Distribution of nitrogen and phosphorus and estimation of nutrient fluxes in the water and sediments of Liangzi Lake, China

Xin Meng [1,2] · Wenqiang Zhang [1,2] · Baoqing Shan [1,2]

Abstract

Water samples and sediments from Liangzi Lake were taken and used to study the vertical distribution characteristics of nitrogen (N) and phosphorus (P) in both the overlying and pore water. Fluxes of ammonia (NH_4^+-N) and phosphate (PO_4^{3-}-P) were calculated using a one-dimensional transport-reaction model based on Fick's First Law. The results showed that the mean NH_4^+-N and NO_3^--N concentrations in the overlying water of Liangzi Lake were 2.59 and 0.46 mg L^{-1}, respectively. The mean PO_4^{3-}-P concentrations were lower than the detection limit. Both N and P displayed peaks at the sediment-water interface. For example, the mean concentration of ammonia in pore water in the surficial layer (0–5 cm) was 4.29 ± 2.74 mg·L^{-1}, which was twice than that of the overlying water. Two PO_4^{3-}-P vertical profile regimes were identified; one had a gradually increasing trend, while the other first increased and then decreased. The mean orthophosphate concentration in the pore water of the surface layer (0–5 cm) was 0.01 ± 0.01 mg·L^{-1}. The spatial distribution of ammonia flux values was highly heterogeneous. Using these data, the annual load contribution of autochthonous ammonia was calculated to be 481 t a^{-1}. Studying N and P pollution and fluxes in the lakes of urban drinking water sources facilitates the provision of protection measures.

Introduction

Drinking water sources such as lakes and reservoirs have been receiving much attention. Many large cities have proposed urban backup water sources in response to water security problems (Li et al., 2020). The main role of the backup water sources is to provide security for urban water supplies. Because of the importance of urban backup water sources, they need to be properly managed. However, the current management and protection of backup water sources in major cities in China is relatively weak, and has not received much attention (Jin et al., 2006; Xie et al. 2003). Wuhan is a rapidly growing city in Central China and has the largest number of lakes within a city in China. There has been relatively little research on the effects of rapid urbanization on the accumulation of pollutants and their diffusion fluxes in the sediments of alternate water sources in this region (Hu et al. 2001). To address this knowledge gap, this paper investigates the endogenous release of nitrogen and phosphorus into drinking water sources of Liangzi Lake, and analyzes the risk characteristics and influencing factors of endogenous nutrient release. An understanding of the risk characteristics of endogenous nutrient release in lake sediments can facilitate the prevention and control of lake water pollution.

N and P are important nutrient elements in lake ecosystems, and also the key influence factors in lake eutrophication. Sediment is an important "source" or "sink" of nutrients in lake water. Sediment can accumulate N and P from overlying water subsidence and particulate matter transport, and can also release N and P into the overlying water (Jeppesen et al. 2005) under appropriate conditions. A large number of dissolved substances in sediments utilize pore water for upward

✉ Wenqiang Zhang
  wqzhang@rcees.ac.cn

✉ Baoqing Shan
  bqshan@rcees.ac.cn

1 State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

2 University of Chinese Academy of Science, Beijing 100049, China

diffusion migration (Frindte et al., 2013). The distribution characteristics of dissolved nutrients in pore water directly determine the nutrient exchange process between sediment and overlying water and affect the chemical properties and composition of lake water bodies. The diffusion of endogenous nitrogen and phosphorus greatly affects eutrophication. Research on lakes, locally and overseas, has mostly focused on hydrochemical composition (Thapanand et al., 2008), characteristics of water pollutants (Yao et al., 2011), and the distribution characteristics of phytoplankton. Little attention has been given to the risk of endogenous nutrient releases on strategic water source reserves.

Liangzi Lake is an emergency water source for Wuhan, and it is therefore important to protect Liangzi Lake's water quality. Because of rapid economic development, ecological problems and pressure on Liangzi Lake's water environment are becoming more pronounced (Zhang and Wang, 2005). In the 1980s, Liangzi Lake's water quality and ecological health was excellent. Subsequent population and economic growth has caused deterioration in water quality and created an environment that is unfavorable for the survival of aquatic organisms. Problems created by soil erosion, industrial and agricultural pollution, domestic waste, and other issues have not been resolved. Studies have shown that Liangzi Lake water quality has remained largely in the III category for many years and has been in a nutrient-rich status (Xiong et al., 2008). Liangzi Lake is an important backup water source in Wuhan, and was therefore selected for analysis. The vertical distribution characteristics of pore water and overlying water and of N and P nutrients were analyzed, and the diffusion fluxes of endogenous N and P in Liangzi Lake were quantitatively estimated using a one-dimensional pore water diffusion model. The determination of the annual nutrient load contribution increases the understanding of the endogenous release process in lakes used for urban water source reserves and provides scientific support for the prevention and control of eutrophication in these lakes.

Materials and methods

Study area

Liangzi Lake is the largest freshwater lake in Hubei Province (it has the largest water storage capacity and covers the largest area). Liangzi Lake is one of the best preserved wetland protection areas on the Asian Wetland Protection List and is listed as a strategic reserve water source for Hubei. Liangzi Lake is also a large permanent freshwater lake; its wetland landscapes and biodiversity are typical features of the Yangtze River (Fig. 1). The Liangzi Lake area is 225 km^2, the average water depth is 2.5 m, and the stored water volume is 650 million m^3. The lake's functions include water storage, a breeding area for wildlife, recreation for tourists, and the supply of water for industry and agriculture. The lake forms an important natural wetland reserve in China. The Liangzi Lake Reserve accounts for 0.29% of the total area of Hubei Province. Using the center of the Lake Liangzi Island town as a boundary, Liangzi Lake can be divided into East Lake, the Qianjiang Lakes, and Central Lake. The Central Lake basin is dominated by aquaculture, the former River Great Lakes support mainly tourism, and activities in the East Lake are mainly based on natural fisheries. Liangzi Lake was designated as a backup source of water for Wuhan City when the Liangzi Lake Natural Wetland Reserve was established in 2004. Liangzi Lake is characterized by biodiversity, genetic diversity, and species scarcity. There are more than 280 species of vertebrates and 92 species of higher aquatic plants in the lake (Gu and Gao, 2014). As a typical lake-type reserve water source, Liangzi Lake's water environment quality characteristics will provide help for other reserve water sources.

There are more than 30 river ports along the Liangzi Lake, including Xianning, Jiangxia, Daye, and Ezhou. Liangizhu is connected to the Yangtze River by a delta from the former River Great Lakes, through the long harbor of Hukou, and finally through the new waterway. In this study, Liangzi Lake was divided into seven areas: Kuang Linzui (KLZ), Qingshan Island (QSD), Yu Jiazui (YJZ), Nan Beizui (NBZ), Hu Piaozui (HPZ), Gao Tang Lake (GTH), and Shang Dawu (SDW). The QSD, YJZ, and NBZ lake areas are mainly for tourism, and are adjacent to the most densely populated urban areas. The HPZ and GTH lake areas are mainly natural fisheries. The SDW area is fed by a trunk river that carries most of the runoff from the city of Oji. The northern Niushan Lake is isolated from construction and development and is therefore almost exclusively a cultural and recreation area, and thus no sampling points were set up there (Fig. 1).

Field sampling

In October 2014, sediment samples and overlying water were collected simultaneously using a gravity columnar sediment corer (Uwitec, Austria). The sediment sample column was quickly sealed with a rubber plug, placed in a rigid cylindrical sediment transport box to maintain vertical integrity, and sent overnight to the Huazhong Agricultural University Environmental College Laboratory for analysis. The upper overlying water was sampled from the top down at 5 cm intervals by siphoning, with the overlying water being carefully siphoned off. The cylindrical sediment sample was segmented from top to bottom. The top 0–10 cm of sediment was sampled in 1 cm layer, and the remaining sediment below 10 cm was sampled in 2 cm layers.

Fig. 1 Distribution of sediment sampling sites in Liangzi Lake
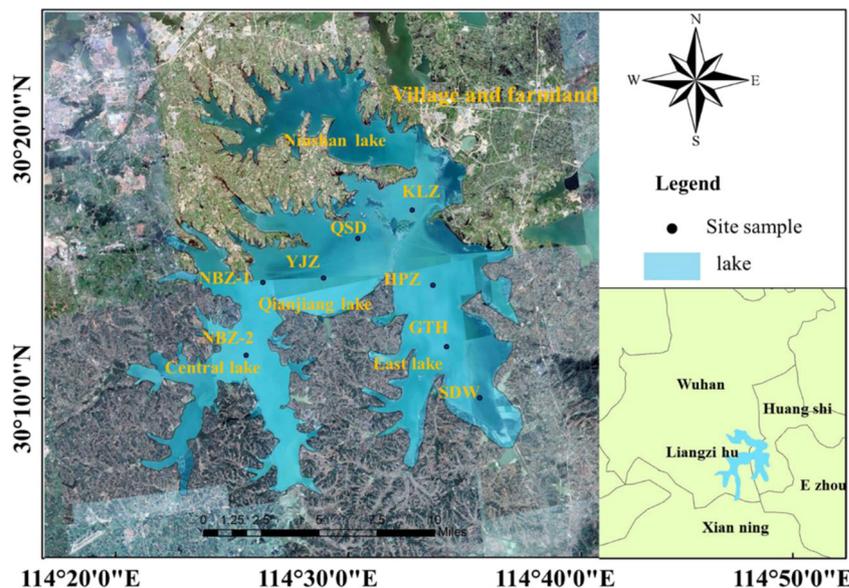
Sample analysis

The pore water was obtained by filtration of the stratified sediment using a 0.45-μm microporous filter membrane. The concentrations of nitrate (NO_3^--N), ammonia nitrogen (NH_3-N), and N-phosphate (PO_4^{3-}-P) in pore water were determined by hydrazine sulfate reduction, indigo blue spectrophotometry, and phosphorus and molybdenum blue spectrophotometry, respectively, using an Automatic Chemical Analyzer (Smart Chem 200,USA). Each sample was analyzed three times, and the results were expressed as a mean value.

The diffusion flux was estimated using a one-dimensional pore water diffusion model (Lavery et al. 2001; Kuwae et al. 2003):

$$F = \phi \times D_s \times \frac{\partial c}{\partial x}$$

where F is the sediment-water interface diffusion flux (mg $(m^2 \cdot d)^{-1}$). For the sediment-water interface material concentration gradient (mg $(L\ cm)^{-1}$), the term D_s ($m^2 \cdot s^{-1}$) is introduced to consider the actual molecular diffusion coefficient of sediment bending effect. The empirical relationship of D_s with porosity (Ullman and Sandstron, 1987) is $D_s = \varphi D_0$ ($\varphi < 0.7$); $D_s = \varphi 2 D_0 (\varphi > 0.7)$ and represents the ideal diffusion coefficient of D_0 in a formula for an infinite dilution solution (Falcão and Vale, 1998). For HPO_4^{2-}, $D_0 = 6.12 \times 10^{-6}$ cm² $\cdot s^{-1}$; and for NH_3-N, $D_0 = 17.6 \times 10^{-6}$ cm² $\cdot s^{-1}$ (Krom and Berner, 1980; Warnken et al., 2000). The term φ is the sediment porosity and is calculated using:

$$\phi(\%) = \frac{[W_w - W_d] \times 100\%}{[W_w - W_d] + W_d/\rho}$$

where W_w is the fresh sediment weight (g); W_d is the dry sediment weight (g); ρ is the ratio of the average surface sediment density to the water density and is generally taken as 2.5. The annual load contribution (W) of sediment nutrient salt is calculated by:

$$W = \sum_i^n F_i \times A_i \times 365/10^9$$

where W is the annual load contribution of nitrogen or phosphorus in the whole lake region (t·a^{-1}); F_i represents the diffusion flux of sediments in area i (mg·$(m^2 \cdot d)^{-1}$); A_i represents area i (m²); the value 10^9 is a unit conversion factor; and 365 d·a^{-1} represents 1 year (Warnken et al., 2000).

Results

General distribution characteristics of endogenous nitrogen and phosphorus nutrients in Liangzi Lake

The minimum, maximum, and average values of NH_3-N, NO_3^--N, and PO_4^{3-}-P content in the overlying water and pore water of the Liangzi Lake surface sediments (0–5 m) were statistically analyzed (Table 2). The results showed that the content of NH_3-N in eight sampling points was 0.05–6.29 mg, and the average was 2.29 mg. The content of NH_3-N in pore water was 0.72–14.69 mg, and the average was 4.57 mg L^{-1}, which is twice that of the overlying water. In terms of spatial distribution, in the northern Lake area of KLZ and QSD, the values of NH_3-N in the overlying water are higher than in the other areas, while the pore water NH_3-N values in the northern KLZ and the south of the SDW are also high compared with

other areas. The nutrient salts in sediment pore water are mainly derived from debris, shell decomposition, and dissolution of land-based sources. The quantity of nutrients present reflects the balance between their production and consumption. The production of nutrients depends on factors such as the amount of organic matter present in the sediment and its decomposition rate, the degree of impact of land-based sewage, the presence of benthic organisms (especially the number of excavated animals), interfacial hydrodynamic conditions, and mineralization. Because the GTH and HPZ areas have no direct exogenous inputs, the nutrient content of overlying water and pore water NH_3-N is relatively low. However, in the KLZ area, there are many exogenous pollutants, and the pore water and overlying water have relatively high NH_3-N values.

In general, the NO_3^--N content in overlying water was 0.23–1.18 mg·L^{-1}, and the average was 0.51 mg·L^{-1}, while the NO_3^--N content in pore water was 0.22–1.43 mg L^{-1}, and the average was 0.49 mg L^{-1}, which is similar to the average of the overlying water. From the spatial distribution perspective, the YJZ and NBZ areas of the northwest of Liangzi Lake have the highest NO_3^--N values in the overlying water, while pore water NO_3^--N concentrations were relatively high in the northern KIZ (Table 2). The NO_3^--N content in pore water of KLZ is relatively high, mainly as a result of external inputs. The high NO_3^--N content in the YJZ and NBZ areas is caused by water pollution from tourism (Zhu et al. 2019).

By comparing the Liangzi Lake NH_3-N and NO_3^--N values in the present study with the 2005 survey results (Table 1), it can be seen that in the past 10 years, the Liangzi Lake overlying water and pore water NH_3-N values have increased significantly. At the same time, the overlying water and pore water NO_3^--N essentially remained constant. This indicates that exogenous pollution in the Liangzi Lake basin is still increasing and that the sediment is still the sink for the NH_3-N. When compared with the nitrogen and phosphorus content of other lakes in the Yangtze River basin (Table 1), it can be seen that (1) the NH_3-N content in Liangzi Lake was higher than that in the other five lakes, (2) the NO_3^--N content for Liangzi Lake was lower than that of Taihu Lake and Poyang Lake, (3) the NH_3-N pore water for Liangzi Lake was only lower than that of Dianchi Lake, and (4) the pore water NO_3^--N for Liangzi Lake was comparable to that of a typical eutrophic lake. These characteristics show that the NH_3-N pollution problems of Liangzi Lake cannot be ignored.

The phosphate content in the overlying water of Liangzi Lake was less than 0.01 mg L^{-1}, while the pore water phosphate content was between not detectable and 0.09 mg L^{-1}, with an average of 0.01 mg L^{-1}. The concentration of phosphate in the YJZ and NBZ areas of the West Lakes was relatively high (0.01 and 0.02 mg L^{-1}). The detectable phosphate content in pore water was high in the KLZ area in northwest Liangzi Lake. The difference between overlying water and pore water phosphate content was highest in the KLZ, where

the pore water phosphate content was 20 times that of the average of the overlying water. The minimum difference was found in the NBZ area, where the phosphate content in pore water was similar to that of overlying water. It is postulated that the main reason for this small difference is that there is no direct exogenous input in the NBZ area; the substrate is mainly a sandy layer; and the amount of phosphorus adsorbed by sediment is relatively low, and thus the content of phosphate in pore water is the lowest in the study area. Because of the exogenous pollution to the KLZ area, the phosphorus content in the sediment of the delta area and the phosphate content in the pore water are high.

Vertical distribution characteristics of nitrogen at the sediment-water interface

The vertical distribution of NH_3-N in sediment pore water and overlying water in different regions of Liangzi Lake are shown in Fig. 2. In Liangzi Lake, the vertical profile of NH_3-N for overlying water and pore water in each region showed a tendency to increase and then decrease. In the QSD area, for example, the concentration in the first cm of sediment was 0.5 mg L^{-1}, the concentrations fluctuated and increased until the maximum value was reached at 6 cm (15 mg L^{-1}), and by 20 cm had decreased to 3 mg L^{-1}. The concentration of NH_3-N in sediment pore water is mainly related to conditions such as overlying water pollution levels, sediment pollution levels, scale of biological action, redox conditions, hydrodynamic influences, and the influence of the surrounding external environment. The QSD area receives a large amount of surface pollution from a large number of point sources, causing relatively serious pollution. In addition, the sediment is rich in organic matter, with a large number of surface microorganisms, significant biological decomposition, and hypoxia near the surface-sediment interface. Thus, a reducing environment is formed, and biological participation in ammonia production is more evident, and the surface pore water can accept more NH_3-N (Grenz et al., 2010). In contrast, the vulnerability of surface sediments to disturbance (underwater submersible flow and biological disturbance caused by tributary recharge) may lead to the release of some NH_3-N into the overlying water body, thus reducing the pore water NH_3-N content of surface sediments to a certain extent. These processes lead to surface sediment forming a maximum NH_3-N value. The underlying sediments are usually more hypoxic than the overlying water, and have a long formation time, a relatively stable environment, and rich microbial communities. Thus, part of the NH_3-N produced is absorbed by microorganisms. In addition, because the bottom sediment is less affected by hydrodynamic disturbances, it is more favorable than surface sediments for the preservation of NH_3-N in sediments. As a result, the NH_3-N content in the pore water of the
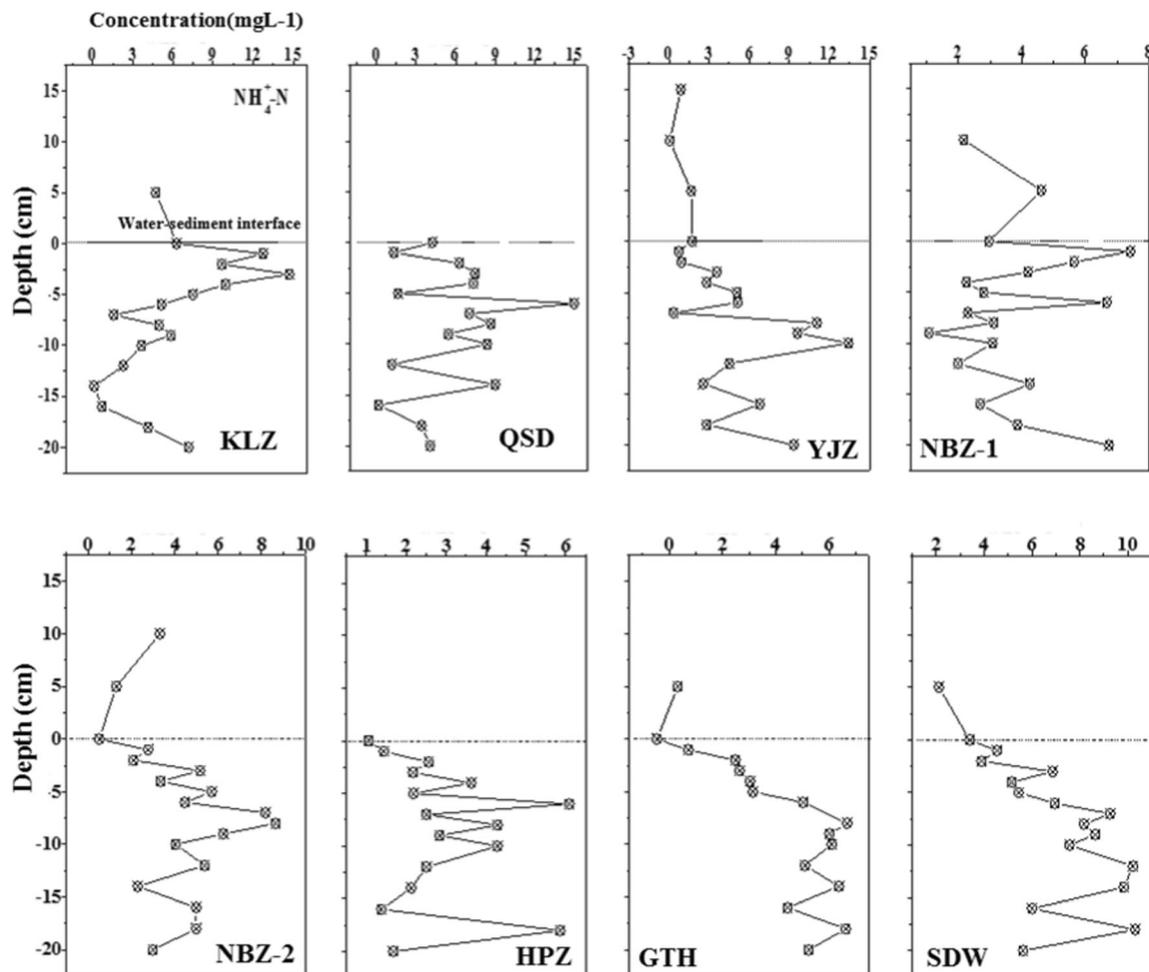
Fig. 2 Vertical distribution of NH_4^+-N in the overlying water and pore water in sediments from Liangzi Lake

bottom sediment decreased relatively to the surface sediment (Cermelj et al., 1997).

The vertical distribution of NO_3^--N in sediment pore water and overlying water in different areas of Liangzi Lake is shown in Fig. 3. The change in NO_3^--N from overlying water to increased depth of sediment pore water followed three main patterns. The first pattern occurred in the KLZ, YJZ, NBZ-2, and SDW areas, where the general pattern (ignoring fluctuations) was for NO_3^--N to be broadly stable before reaching the sediment-water interface, then increase to a peak, decrease, and remain stable. For example, in the KLZ area, the surface layer had a concentration of 0.4 mg L^{-1}; the concentration then increased to 1.5 mg L^{-1}, decreased, and stabilized at 0.2 mg L^{-1}. This pattern may be related to the occurrence of benthic organisms in these areas, as well as interfacial hydro-dynamic conditions (Urban et al., 1997). This leads to a redox environment and microbial nitrification of the near surface of sediments, which can be verified by analyzing the porosity and redox potential of the vertical profile of the sediments. Organic matter is decomposed by anaerobic microorganisms to produce a large amount of NH_3-N, but because of oxygen

limitations, it cannot be converted into NO_3^--N by nitrification. At the same time, NO_3^--N in pore water will be reduced to NO_2^--N or N_2 under the action of denitrification bacteria.

The second pattern in the change of NO_3^--N concentrations with depth was found in the QSD and HPZ areas. Here, the maximum value was reached soon after entering the sediment. The value then decreased and remained stable until the 15-cm layer was reached, when a sudden increase occurred. In the QSD area, for example, the surface value was 0.3 mg L^{-1}, then increased to 0.9 mg L^{-1}, and decreased to 0.35 mg L^{-1}, before suddenly increasing to 1.0 mg L^{-1} at 15 cm. Abrupt increases in the lower layers may be associated with benthic organisms and pollution sources. The third pattern in the change of NO_3^--N concentrations with depth was found in the NBZ-1 and GTH areas. Here the NO_3^--N concentration decreased sharply in the first few cm of sediment and then increased to a stable, high value. For example, in the GTH area, the surface layer had a NO_3^--N value of 0.36 mg L^{-1}, which subsequently decreased to 0.21 mg L^{-1}, and then increased and remained stable at 0.33 mg L^{-1}. The surface sediment from 0 to 5 cm has been recently affected by
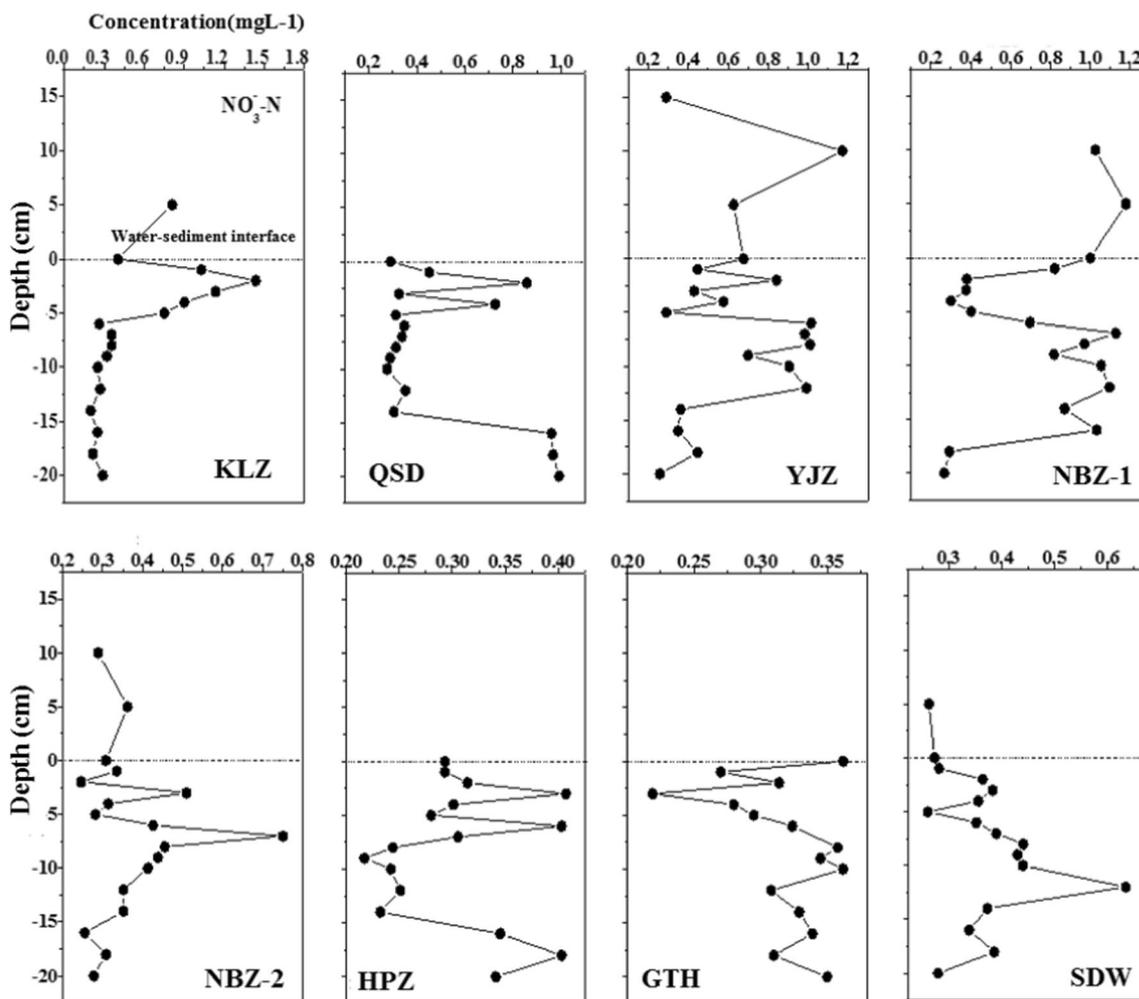
Fig. 3 Vertical distribution of NO_3^--N in overlying water and pore water in sediments from Liangzi Lake

NO_3^--N pollution from external water bodies, which has largely been retained by the surface sediment. The bottom sediment is relatively hypoxic; the environment is stable, has the ability to accumulate NO_3^--N, and thus the low NO_3^--N concentration increases and then remains stable.

Vertical distribution characteristics of phosphate at the sediment-water interface

The vertical distribution characteristics of phosphate in the pore water of sediment in different areas of Liangzi Lake can be split into two broad categories. In the first category, phosphate increases, then decreases, and then remains stable. The maximum value occurs in the pore water part of the profile (Fig. 4). For example, in the case of YJZ, the concentration of phosphate in the overlying water was maintained at 0.01 mg L^{-1} until the sediment-water interface was reached, and then the phosphate concentration increased significantly and peaked at 4 cm below the sediment-water interface, reaching a value of 0.1 mg L^{-1}. Then, as the depth increased, the concentration of PO_4^{3-}-P gradually decreased, and

stabilized at 5 cm below the interface, with a concentration of 0.01 mg L^{-1}.

The other broad category shows fluctuating phosphate concentrations as sediment depth increases, but the overall trend is an increase in concentration with depth. Studies have shown that the release of P in sediments is closely related to the redox conditions of sediments and iron compounds, and that an aerobic environment promotes the adsorption of phosphorus by sediments, while anaerobic conditions help the release of phosphorus from sediment to pore water. Phosphate is most likely to originate from anaerobic degradation of organic matter, while the various iron hydroxides and oxides in sediments have a high adsorption force on phosphorus (Cha et al., 2005). Thus, ferric hydroxide in the oxidation zone below the sediment-water interface absorbs phosphorus from pore water, resulting in a low phosphorus content near the surface water. However, when the oxidizing conditions change to reducing conditions at a certain depth, the soluble phosphorus is dissolved into the pore water again as a result of the reduction of the iron hydroxide, thereby leading to an increase in the phosphorus concentration in the pore water. The distribution
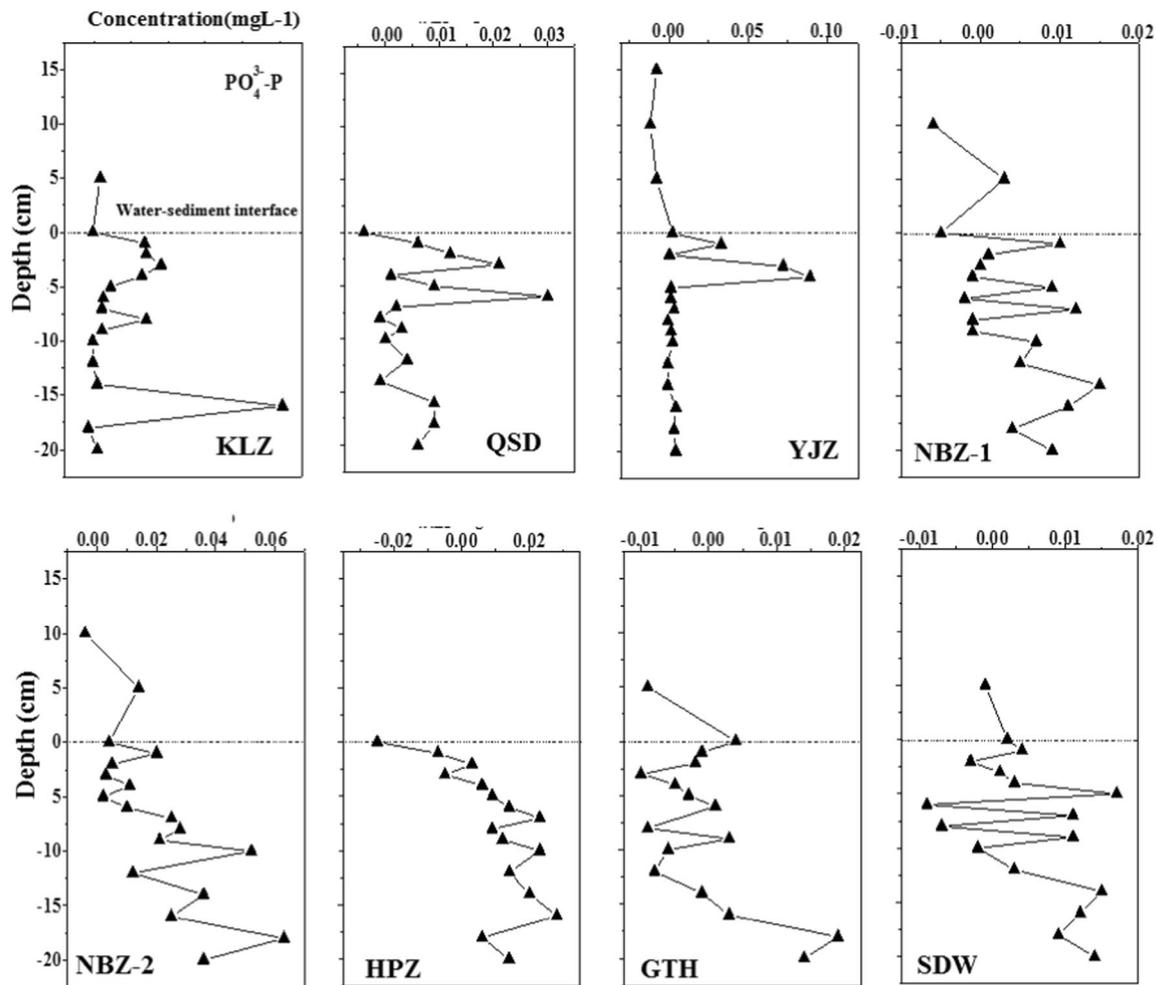
Fig. 4 Vertical distribution of PO_4^{3-}-P in overlying water and pore water in sediments from Liangzi Lake

characteristics of nitrogen and phosphorus in pore water are related to the distribution characteristics of nitrogen and phosphorus in sediments, which are mainly controlled by the content of nitrogen and phosphorus in sediments (Sakurai and Haruta, 2006). The distribution characteristics of endogenous N and P, and of the overlying water nitrogen and P in the vertical direction, enables a preliminary understanding of the vertical distribution characteristics of nitrogen and phosphorus in sediment.

Nutrient diffusion flux and annual load contribution

Because of the extremely low flow rate of overlying water at the sediment-water interface, diffusion, caused by concentration gradients, is the main migration process of nutrient salt. The results of the calculation of the diffusion flux and annual load contribution of NH_3-N at the sediment-water interface are shown in Table 2. In most areas, NH_3-N is shown to be released by sediment and to move upward, which indicates that there is a risk that endogenous nutrient salt (NH_3-N) release will affect the Liangzi Lake water quality. The NH_3-N

diffusion flux in the GTH area is low (less than 6.0 mg ($m^2 \cdot$ d)$^{-1}$). However, there are obvious exogenous pollution inputs in the KLZ and NBZ areas, where the diffusion fluxes are 79.71 and 51.95 mg ($m^2 \cdot d$)$^{-1}$, respectively The order of NH_3-N diffusion flux in the Liangzi Lake area is essentially consistent with the degree of sediment pollution, and the Lake areas adjacent to its main tributaries (KLZ and NBZ) have poor water quality, while particulate matter is deposited in slow-flowing areas such as KLZ and YJZ. The sediments in these areas are blackened and have smelly peat layers, while the pore water has a high organic matter and NH_3-N content. The lake-bottom sediments in the GTH area are mostly sandy, and the relatively light pollution in this area causes the pore water NH_3-N content to be lower. Our calculations indicate that the annual load contribution of NH_3-N in the whole lake area is 481 t·a^{-1}, and the contribution rate for the KLZ area is 75%, which is clearly the main contributor to endogenous NH_3-N release (Fig. 5).

As can be seen from Table 3, in the Liangzi Lake sediment-water interface, the GTH area has a negative value for phosphate flux, while the diffusion fluxes for KLZ and YJZ are the
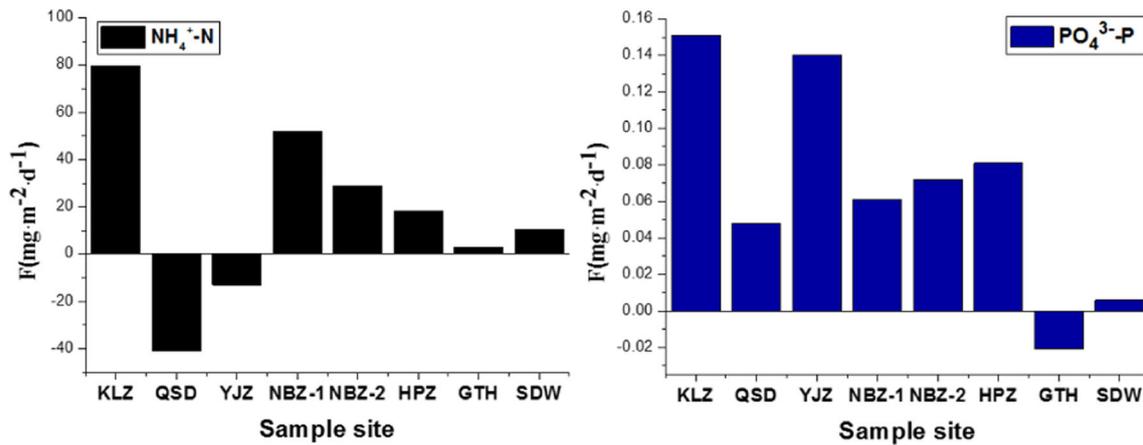
Fig. 5 Fluxes of NH$_3$-N and PO4^{3-}-P for different areas of Liangzi Lake

largest: 0.15 and 0.14 mg (m^2·d)$^{-1}$, respectively. The origins of phosphate in GTH is characterized by the diffusion of overlying water to sediment, and the diffusion flux is − 0.02 mg· (m^2·d)$^{-1}$. These areas have a shallow water level, and more surface sediments are affected by hydrodynamic disturbance than in the rest of Liangzi Lake. As a result, the suspended surface particles are oxygen-rich and have a high temperature, and small and medium molecular weight organic matter is fully decomposed. The mineral structure mainly comprises iron, silicon, and other inorganic macromolecular colloids, which creates a large specific surface. When anionic phosphate sources in water bodies are in contact with the surface of undisturbed sediments, physical and chemical adsorption can occur (Pagès et al., 2011). In addition, this area is relatively far away from land sources, and thus the mineralization of organic matter is more significant, and there is a higher proportion of inorganic mineral particles, and a relatively calm environment so that PO$_4$$^{3-}$-P in the overlying water is taken in by the sediments, resulting in the formation of internal sinks (Christophoridis and Fytianos, 2006).

In general, in terms of the upward release of sediment from Liangzi Lake, the annual load contribution of phosphate was 1.72 t·a^{-1}, while the contribution rates for KLZ and YJZ were 40%, and 27%, respectively. As can be seen from Table 3, the diffusion flux for NH$_3$-N and phosphate in GTH is low; this may be related to the short history of the formation of sediments in such areas and the low amounts of exogenous input. The NH$_3$-N and PO$_4$$^{3-}$-P diffusion fluxes in KLZ and YJZ are large, and the main contributing areas to the Liangzi Lake NH$_3$-N and phosphate loads.

Conclusions

Values of NH$_3$-N at the Liangzi Lake sediment-water interface showed an increasing trend with depth in vertical sections, and the concentrations of NH$_3$-N in the sediment

pores were 4.29 ± 2.74 mg L^{-1}, which was twice that in the overlying water. The vertical distribution characteristics of phosphate were divided into two categories. In the first category, the phosphate concentrations show a gradually increasing trend with depth. In the second category, the phosphate concentrations first increased (reaching a maximum value in the first 5 cm from the surface) and then decreased to an average value of 0.012 ± 0.020 mg L^{-1}. In the QSD and YJZ areas, ammonia moved from the overlying water to the sediment, and the diffusion flux was 41.1 and − 12.9 mg (m^2·d)$^{-1}$, respectively. The other areas are characterized by the upward movement of nutrients. These areas included KLZ and NBZ, where the fluxes were as high as 79.7 and 51.9 mg (m^2·d)$^{-1}$, respectively, while the flux in other regions was less than this. The GTH area is characterized by the diffusion of phosphate from the overlying water to sediment, and the diffusion flux was − 0.021 mg (m^2·d)$^{-1}$. Other lake areas were characterized by the upward movement of nutrients, with diffusion fluxes of 0.006–0.150 mg (m^2·d)$^{-1}$. The annual contribution of NH$_3$-N in the whole lake area was 481 t·a^{-1}, while 75% of the contribution was from KLZ. The contribution of the phosphate annual load was 1.72 t·a^{-1} for the whole area, while the contribution rates for KLZ and the YJZ were 40% and 27%, respectively. The overall results of this investigation indicate that it is necessary to manage and control nutrient loading of the Liangzi Lake to avoid eutrophication. The determination of the annual nutrient load contribution increases the understanding of the endogenous release process in lakes used for urban water source reserves, and provides scientific support for the prevention and control of eutrophication in these lakes.

References

Cermelj B, Bertuzzi A, Faganeli J (1997) Modeling of pore water nutrient distribution and benthic fluxes in shallow coastal waters (Gulf of Trieste, Northern Adriatic) [J]. The Interactions Between Sediments and Water 99:435–444

Cha HJ, Lee CB, Kim BS et al (2005) Early diagenetic redistribution and burial of phosphorus in the sediments of the southwestern East Sea (Japan Sea) [J]. Mar Geol 216:127–143

Christophoridis C, Fytianos K. Conditions affecting the release of phosphorus from surface lake sediments[J]. J Environ Qual, 2006, 35(4): 1181–1192

Falcão M, Vale C (1998) Sediment-water exchange of ammonium and phosphate in intertidal and subtidal areas of a mesotidal coastal lagoon (Ria Formosa) [J]. Hydrobiologia 373:193–201

Frindte K, Eckert W, Attermeyer K et al (2013) Internal wave-induced redox shifts affect biogeochemistry and microbial activity in sediments: a simulation experiment [J]. Biogeochemistry 113(1–3):423–434

Gu Z, Gao F (2014) Water environmental function zoning and water quality status analysis in Liangzi Lake basin, [J]. Chinese Journal of Environmental Management 6(5):32–36 in Chinese

Grenz C, Denis L, Pringault O et al (2010) Spatial and seasonal variability of sediment oxygen consumption and nutrient fluxes at the sediment water interface in a sub-tropical lagoon (New Caledonia) [J]. Mar Pollut Bull 61(7):399–412

Hu W, Lo W, Chua H, Sin S, Yu P (2001) Nutrient release and sediment oxygen demand in a eutrophic land-locked embayment in Hong Kong. Environ Int 26:369–375

Jeppesen E, Soendergaard M, Jensen JP et al (2005) Lake responses to reduced nutrient loading- an analysis of contemporary long-term data from 35 case studies [J]. Freshw Biol 50(10):1747–1771

Jin X, Wang S, Pang Y, Wu FC (2006) Phosphorus fractions and the effect of pH on the phosphorus release of the sediments from different trophic areas in Taihu Lake, China. Environ Pollut 139:288–295

Kuwae T, Kibe E, Nakamura Y (2003) Effect of emersion and immersion on the porewater nutrient dynamics of an intertidal sandflat in Tokyo Bay [J]. Estuar Coast Shelf Sci 57(5):929–940

Krom M D, Berner R A. The diffusion coefficients of sulfate, ammonium, and phosphate ions in anoxic marine sediments[J]. Limnol Oceanogr, 1980, 25(2): 327–337

Lavery PS, Oldham CE, Ghisalberti M (2001) The use of Fick's first law for predicting porewater nutrient fluxes under diffusive conditions [J]. Hydrol Process 15(13):2435–2451

Li T, Wang SX, Wang Y et al (2020) Landscape pattern variation, protection measures, and land use/land cover changes in drinking water source protection areas: a case study in Danjiangkou reservoir, China [J]. Global Ecol Conserv 21

Pagès A, Teasdale PR, Robertson D, Bennett WW, Schäfer J, Welsh DT (2011) Representative measurement of two-dimensional reactive phosphate distributions and co-distributed iron (II) and sulfide in seagrass sediment porewaters [J]. Chemosphere 85(8):1256–1261

Sakurai Y, Haruta S (2006) Characteristics of sediments in a newly constructed reservoir in Japan [J]. Water Sci Technol 53(2):73–78

Thapanand T, Jutagatee T, Wongrat P et al (2008) Trophic relationships and ecosystem characteristics in a newly-impounded man-made lake in Thailand [J]. Fish Manag Ecol 16(2):77–87

Ullman WJ, Sandstron MW (1987) Dissolved nutrient fluxes from the nearshore sediments of Bowling Green Bay, central great barrier reef lagoon (Australia) [J]. Estuar Coast Shelf Sci 24(3):289–203

Urban NR, Dinkel C, Wehrli B (1997) Solute transfer across the sediment surface of a eutrophic lake: I. Porewater profiles from dialysis samplers [J]. Aquat Sci 59:1–25

Warnken KW, Gill GA, Santschi PH et al (2000) Benthic exchange of nutrients in Galveston Bay, Texas [J]. Estuar Coasts 23(5):647–661

Xie L, Xie P, Tang H (2003) Enhancement of dissolved phosphorus release from sediment to lake water by Microcystis blooms—an enclosure experiment in a hyper-eutrophic, subtropical Chinese lake. Environ Pollut 122:391–399

Xiong H-F, Tan QL, Yun-hua (2008) Distributions of nitrogen and phosphorus in the sediment from Liangzi [J]. J Huazhong Agric Univ 27(2):235–238 (in Chinese)

Yao H, Feng XB, Guo YN et al (2011) Mercury and methylmercury concentrations in two newly constructed reservoirs in the Wujiang River, Guizhou, China [J]. Environ Toxicol Chem 30(3):530–537

Zhang W-m, Wang Z-b (2005) Water quality assessment for Liangzi Lake [J]. Environ Sci Technol 28:0102–0102 (in Chinese)

Zhu YY, Jin X, Tang WZ et al (2019) Comprehensive analysis of nitrogen distributions and ammonia nitrogen release fluxes in the sediments of Baiyangdian Lake, China. [J]. J Environ Sci (China):76