Vertical distribution and release characteristics of nitrogen fractions in sediments in the estuaries of Dianchi Lake, China

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ABSTRACT

Columnar sediment samples were collected from five representative estuaries of Dianchi Lake, China. And the vertical distribution of each fraction of nitrogen (IEF-N, CF-N, IMOF-N, OSF-N) were tested. The results showed that the TN content in sediments from areas A, B, C, D and E gradually decreased with depth between 0 and 15 cm, then sharply decreased with depth between 15 and 30 cm and stabilized at depth below 30 cm, indicating the exogenous input of N in these areas has not been controlled effectively. The proportion of TN occupied by various N fractions in the sediments ranked as follows: OSF-N > IMOF > CF-N > IEF-N. Correlation analysis results showed both IEF-N and IMOF-N were significantly correlated with the content of TFe₂O₃ + MnO + Al₂O₃ in deeper sediments, while no correlation in superficial sediments. The areas A and B have extremely high release risks for N in superficial sediments. However, the N in the sediments of areas C, D and E were in relative equilibrium with the overlying water, indicating release potential risk was relatively low.

1. Introduction

Lake eutrophication has become a major environmental problem worldwide [1]. Algal bloom is a characteristic manifestation of lake eutrophication. Large-scale algal bloom leads to a series of further problems including aquatic hypoxia, death of aquatic organisms, water odor, and release of algal toxins [2,3]. China suffers from lake eutrophication, which is serious in both scale and intensity. By the end of the 1990s, eutrophic lakes represented 77% of the total number of lakes investigated in China and this has become even more severe in recent years [4,5]. Therefore, controlling the input of exogenous nutrients has become incorporated into laws and regulations to help to control water pollution [6].

The key role played by phosphorus (P) in lake eutrophication has long been recognized [7]. Recently, however, besides the role of P, also the importance of nitrogen (N) limitation for lake eutrophication has been more intensively studied and discussed [8–10]. For example, Pearl et al. [11] and Müller & Mitrovic [12] pointed that ecosystem conservation efforts should take a balanced approach to N and P abatement and that the best strategy for lake managers to adopt would be to pursue a double focus on N and P. Thus, N has been also recognized as one of the most critical nutrients limiting lake productivity.

In shallow eutrophication lake, sediment not only stores N in lakes but is also the source of endogenous N [13]. Therefore, even when the exogenous input of N is effectively controlled, endogenous N accumulated in the sediments becomes an important source of N in the water and may continues influence the lake eutrophication [4,6,14]. The sediment N can be released to the overlying water through various physical, chemical, and biological processes such as ion exchange and mineralization [8]. In addition, environmental factors such as temperature, redox potential (Eh), dissolved oxygen (DO), pH value, and the composition of sediments will also seriously affect the release of sediment N [15].

According to previous studies, N existing in sediments is generally divided into inorganic N (i.e. NO₃⁻, NO₂⁻, NH₄⁺) and organic N to characterize the time-space distribution and environmental impacts [16,17]. These work has highlighted the release and transformation of organic N in sediments to evaluate the potential contribution of organic N [18]. This method is necessary for studying background value of nitrogen in sediments, but it can not provide more valuable information about N cycling [19]. In recent years, N is separated into four transferable N fractions (i.e. N in ion-exchangeable fraction (IEF-N), N in carbonate fraction (CF-N), N in iron-manganese...
oxidation fraction (IMOF-N), and N in organic matter-sulfide fraction (OSF-N) and non-transferable nitrogen forms by an improved phosphorus fractional extraction procedure [13]. Although this method is only an operational definition, it would be helpful in the understanding of N of cycling in lake sediments [20].

As the sixth largest freshwater lake in China, Dianchi Lake is located in the central part of the Yunnan–Guizhou Plateau (24°40′–25°02′ N, 102°37′–102°48′ E), downstream of Kunming City (capital of Yunnan province) and once one of the lakes that suffered relatively severe eutrophication in China [21]. Though Dianchi Lake has many inflowing rivers, it has only one water outlet and the water replacement cycle is 3–8 years. As a result, abundant nutrients accumulate in the sediments of the lake and the water quality deteriorates year by year [14,22–24]. Water pollution prevention and control measures in Dianchi Lake were initiated in 1990. During a governance process that has lasted nearly 30 years, a series of measures have been taken including wastewater interception, governance of rivers flowing into the lake, governance of agricultural and rural non-point source pollution, ecological restoration and construction, and desilting. By August 2013, although exogenous pollutants in Dianchi Lake had been essentially controlled, deterioration of its water quality was not improved and blue-green algae and algal blooms continued to occur once per year [25].

In September 2013, the ‘Niulanjiang River—Dianchi Lake Water Diversion Project’ was officially launched. Every day, 2 million cubic meters of clean water are injected into Dianchi Lake, remarkably shortening the replacement cycle of water in Dianchi Lake. At present, the water quality deterioration in Dianchi Lake has been halted, but the water quality itself has yet not been substantially improved. Blue-green algae and algal bloom continued to occur in some areas of the lake in the summer of 2016 for two main reasons. On the one hand, since Dianchi Lake has been polluted for a very long time, its sediments have already become the ‘source’ of nutrients in the water. On the other hand, comparing with the overlying water in Dianchi Lake before the water diversion, the content of Chemical Oxygen Demand (COD), total phosphorus (TP) and chlorophyll a in supply water is lower, but the TN content (3 mg L⁻¹) is higher than the former (<1.5 mg L⁻¹), which could lead to changes in the role of sediments as a source or a sink of N. However, at present, it is still not clear that the sediment of Dianchi Lake is a source or a sink of N. Although the bioavailability of N in the sediments can be quantified by measuring the levels of the various N fractions, each N fraction contributes to the internal loading differently and not all fractions can be released from the sediments. In addition, sedimentation in estuaries of Dianchi Lake occurs at a relatively fast rate with a comparatively high content of TN. Determining the vertical distribution and release characteristics of various N fractions in sediments in estuaries of Dianchi Lake is of great importance to understand the N cycling mechanism in these areas, even after the water supply.

With this background, a sequential extraction method and releasing experiment are carried out to explore the vertical distribution characteristics of various N fractions in sediments in estuaries of Dianchi Lake; the relationship between various N fractions in sediments in estuaries of Dianchi Lake and physicochemical properties of the sediments and the release characteristics of N; and the release efficiency of various N fractions in sediments in the estuaries of Dianchi Lake.

2. Materials and methods

2.1. Study area, sediment sampling and general characteristics

Dianchi Lake once had 35 inflowing rivers; however, with population growth and urbanization, most of these rivers have dried up and been cut off. At present, rivers that constantly supply water to Dianchi Lake throughout the year include Panlongjiang River, Baoxianghe River, Luolonghe River, Laoyuhe River, Yunihe River, Guchenghe River and the Xishan brooks near Guanyinshan Mountain and the Baiyukou Scenic Spot. Among these, Panlongjiang River is the largest river flowing into Dianchi Lake (water transferred from the Niulanjiang River flows into Dianchi Lake via Panlongjiang River). The sedimentation and accumulation of silts in the estuaries of Dianchi Lake lead to a comparatively high content of nutrients in sediments in these estuaries, and thus the release risk is relatively high. Thus, we selected five representative estuaries (Areas A, B, C, D and E) to carry out this research. Area A is the estuary of Panlongjiang River (N from a lot of domestic sewage mainly), Area B is the estuary of Laoyuhe River (N from wastewater from N fertilizer application mainly), Area C is the estuary of Yunihe River (N from a small amount of domestic sewage mainly), Area D is the estuary of Guchenghe River (N from phosphate mining wastewater and a small amount of domestic sewage mainly), and Area E is the estuary of Xishan brooks near Guanyinshan Mountain and the Baiyukou Scenic Spot (Figure 1).

In March 2016, we used a customized columnar sampler (stainless steel tube lined with organic glass column, diameter: 20 cm; height: 50 cm) to collect columnar samples in each of the five study areas, with a sampling depth of 40 cm. The samples were packaged onsite and stored in a sampling box at the temperature of 4 °C. After transport to the laboratory, the samples were cut into 5 cm subsamples using the sample cutter and numbered (for example, samples collected in Area A were numbered A1, A2, …, A8, representing 0–5 cm, 5–10 cm, …, 35–40 cm, …, 40 cm, with a sampling depth of 40 cm and a cutting depth of 5 cm).
respectively). After freeze-drying, some of the samples were used to analyze the contents of clay (0.02–4 µm), silt (4–63 µm) and sand (>63 µm). The remaining samples were ground through a 100-mesh nylon sieve and stored for later use. The total organic carbon (TOC), TN, TP and inorganic element components (Si, Fe, Al, Ca, Mg) of ground samples were measured using the standard methods [26]. In addition, the corresponding overlying water was also collected and parameters such as water temperature, Eh, DO, and pH were measured onsite. TP, TN and the total dissolved N (TDN) within the overlying water were measured in the laboratory according to literature methods [27]. The sampling location and the overlying water parameters were listed in Table 1.

Table 1. Sampling location and the overlying water parameters in Dianchi Lake.

| Sample site | Position | Water depth (m) | pH | DO (mg·L⁻¹) | TP (mg·P·L⁻¹) | TN (mg·N·L⁻¹) | TDN (mg·N·L⁻¹) |
|-------------|----------|----------------|----|------------|--------------|--------------|----------------|
| A           | 24°57'10.99"N 102°40'53.76"E | 3.0 | 7.54 | 6.23 | 0.18 | 1.81 | 1.62 |
| B           | 24°49'40.72"N 102°45'31.68"E | 2.5 | 7.99 | 6.11 | 0.12 | 1.78 | 1.48 |
| C           | 24°46'51.97"N 102°43'51.96"E | 3.0 | 8.10 | 5.85 | 0.15 | 1.70 | 1.52 |
| D           | 24°44'13.07"N 102°36'43.56"E | 3.0 | 7.52 | 5.27 | 0.21 | 1.49 | 1.32 |
| E           | 24°48'20.22"N 102°39'45.00"E | 3.0 | 7.88 | 4.88 | 0.26 | 1.70 | 1.52 |

2.2. N fractions
TN of sediments was determined by the Kjeldahl method. N fractions were determined using the sequential extraction procedure reported by Wang et al. [20] as follows: 1.0 g dry sediment sample was taken accurately, and was subjected to sequential extraction with 1 mol·L⁻¹ MgCl₂, HAc–NaAc (pH = 5), 0.1 mol·L⁻¹ NaOH and K₂S₂O₈ (alkaline). The extracts were centrifuged and N content was determined with spectrophotometer, in which NH₄⁻N was oxidized by sodium hypobromite and NO₃⁻N was reduced by Zn-Cd deoxidation method. This extraction procedure divides N in sediments into four different fractions (i.e. IEF-N, CF-N, IMOF-N and OSF-N).
2.3. N release experiments

N release experiments were performed as follows: 3 g of dried sediment sample was added into 250 mL Pyrex screw cap centrifuge tubes, and to each of them 100 mL 0.02 mol·L⁻¹ KCl solution was then added. The centrifuge tubes were capped and incubated in dark at 25 °C in an orbital shaker at 250 rpm for 24 h, the sampled solution was then immediately centrifuged at 4000 rpm for 10 min, and the content of NH₄⁻N and NO₃⁻N in extracts was determined by the methods described above.

2.4. Quality assurance and control

Data quality was controlled using standard reference materials (GBW07461) and method blanks. The analysis procedure was controlled under the same conditions. The procedure was triplicates and the results were reported as their average. Experiments demonstrated high reproducibility of the methods and the experimental error was <6%.

3. Results and discussions

3.1. Vertical variation of N fractions in core sediments

Figure 2 shows the vertical distribution characteristics of the IEF-N, CF-N, IMOF-N, OSF-N and TN contents and the C/N ratio (by mass) in the sediments. The results indicate that the TN in sediments in the various study areas showed essentially the same vertical variation, namely gradually decreasing from top to bottom. Within the range of 0–15 cm, the TN content slowly decreased as the depth increased, sharply decreased as the depth increased between 15 and 30 cm, and stabilized below the depth of 30 cm. Overall, the TN content in sediments in various study areas ranked from high to low as follows: B ≈ A > D ≈ C > E, with means of 2769, 2613, 1815, 1767, and 1523 mg·kg⁻¹, respectively, which is mainly related to the water quality and quantity of rivers flowing into the lake. For instance, before water was transferred from external drainage basins to Dianchi Lake, Panlong River was the river that supplied the largest quantity of water to Dianchi Lake. Moreover, since it runs through Kunming City, it gathers abundant domestic wastewater and contains a comparatively high TN content. At present, although Nuilanjiang River supplies water to Dianchi Lake via Panlong River, the short water supply time and the relatively high content of TN in the water during the earlier stage (the highest reaches 7 mg·L⁻¹) causes the TN content in sediments in Area A to also be relatively high. The water supplied to Area E mainly originated from the Xishan mountain brooks and rural domestic wastewater of a few villages and the peripheral natural wetland has not yet been completely destroyed. As a result, the TN content in sediments in this area was relatively low. According to the General Standard of Environmental Protection Dredging of Sediments in China, when the TN content in lake sediments exceeds 1000 mg·kg⁻¹, it is considered serious pollution and the sediments should be dredged [20]. Therefore, the sediments in the study areas may be considered seriously polluted by N as a result of the pollution history and pollution level of Dianchi Lake.

The vertical variation trends of the content of IEF-N, IMOF-N and OSF-N were essentially the same as the results for TN (gradually decreasing from top to bottom). However, the content of CF-N did not show a clear vertical variation trend and it even began to increase as the depth increased (Figure 2). The CF-N was greatly affected by the pH value and thus the limited variation with sediment depth may be because pH value in Dianchi Lake is relatively stable (Table 1).

The sediment TOC contents reveal the primary productivity level of the lake system. A relatively high TOC reflects the input of terrestrial sources and an increase in the lake's primary productivity. In addition, TOC levels can also reflect the type and intensity of human activities [28]. The C/N ratio of sediments can be used to infer the source of organic matter and the productivity of a lake to reveal the influences of human activities on the evolution of lake eutrophication [29]. The C/N (by mass) in sediments of different depths in the five study areas indicated that C/N in the deeper sediments (20–40 cm) of Areas A and C were relatively stable and were characterized by a relatively small variation range (Figure 2). This

![Figure 2. Vertical variations of IEF-N, CF-N, IMOF-N, OSF-N, TN and C/N in core sediments.](image-url)
indicates that organic matter in the deeper sediments of the two study areas mainly originate from endogenous aquatic organisms rather than terrestrial plants. The C/N in sediments within the range of 0–40 cm in Areas B, D and E was higher than that in Areas A and C. This implies that terrestrial plants make a relatively large contribution to organic matter in sediments in Areas B, D and E [23,29]. Differences between the C/N ratios of sediments in different study areas indicate that different areas have different sources of organic matter.

Figure 3 shows the proportions of various N fractions in the TN of the sediments. As the depth increases, the contents of IEF-N and TN in the sediments gradually decreased with different speeds. The content of TN significantly decreased as the depth of the sediment increased (Figure 2), thus, as the depth of sediments increased, the proportion of IEF-N in TN exhibits an opposing increasing trend (Figure 3). As one of the fractions with seasonal variation in the N pool of sediments, IEF-N is extremely likely to participate in the N cycle of the lake. Therefore, IEF-N in superficial sediments is more likely to participate in the N cycle of the lake.

CF-N fraction is relatively sensitive to pH variation. When the pH in the environment decreases, the CF-N is easily released and then participates in the N cycle of the sediments [20]. The overlying water and sediments in Dianchi Lake are alkaline (Table 1), which creates a favorable environment for the stability and enrichment of CF-N. Therefore, in this study, the proportion of CF-N in TN was slightly higher than that of IEF-N in TN. The IMOF-N fraction represents N combined with oxides such as iron and manganese in the sediments. Compared with IEF-N and CF-N, IMOF-N is more difficult to release, and is relatively sensitive to Eh variation. Similar to IMOF-P (phosphorus in iron-manganese oxide fraction), when Eh in the environment declines, this N fraction becomes more easily release and is able to participates in the N cycle of the lake [9].

The OSF-N fraction refers to N that combines organic matters and sulfides. In this study, OSF-N occupied the highest proportion among the four N fractions, which agrees with the research conclusions of Wang et al. [20]. The IEF-N, CF-N, IMOF-N and OSF-N fractions are likely to take part in the N cycle of the lake, thus, the sum total of the four N fractions may be regarded as total transferable N (TT-N). The difference between TN and TT-N is the non-transferable N (NT-N). Results in sediments of various eutrophic lake, OSF-N > IEF-N > IMOF-N > CF-N [20]. Nevertheless, in this study, IEF-N represents the lowest proportion; lower than that of CF-N and IMOF-N. The distribution of sediment N among these different N fractions is affected by multiple factors including pH and Eh values of the environment and the mineral composition of the sediments [9]. The final distribution of different N fractions within the sediment TN is a result of the synthetic action of multiple factors. Overall, the proportions of various N fractions in the TN contained in the sediments of the study areas rank as follows: OSF-N > IMOF-N > CF-N > IEF-N.

3.2. The relationship between different N fractions and sediment properties

The TN content and C/N ratio in superficial sediments (0–15 cm) were considerably higher than in the deeper sediments (15–40 cm) and it is known that nutrients in superficial sediments are more likely to participate in the N cycle of the lake [5,22]. Therefore, we divided the columnar samples of the sediments into superficial sediments (0–15 cm) and deeper sediments (15–40 cm) and analyzed the correlation between various N fractions in sediments at different depths and the correlation
between various N fractions and the various physicochemical properties of the sediments. The results of these analyses are summarized in Tables 2 and 3 respectively.

IEF-N refers to N in a weakly adsorbed state and its content is determined by various factors that affect the sediments’ adsorption process of N. The higher the TOC content and the smaller the grain size is, the stronger the adsorption capacity of N in the sediment [31]. This explains our finding that IEF-N was significantly positively correlated with the content of TOC, clay and silt but significantly negatively correlated with the sand and SiO₂ contents (Tables 2 and 3).

The distribution and release of CF-N in the sediments is typically determined by the carbonate and organic matter contents. The higher the carbonate and organic matter content, the higher the CF-N content [20,31]. However, in this study, CF-N was only positively correlated with the content of silt and C/N in superficial sediments (Table 2), but was not significantly correlated with the remaining N fractions (i.e. IEF-N, IMOF-N and OSF-N) and various physicochemical properties of the sediments (Tables 2 and 3). In reality, there are many environmental factors that affect the distribution of N fractions in the sediments. The final distribution of N fractions reflects the synthetic action of various environmental factors. Further studies are needed to determine the concrete influences of various environmental factors on the distribution of N fractions.

Similar to IMOF-P in the sediments, IMOF-N mainly refers to N combined by Fe-hydroxides and Mn compounds in the sediments. This N fraction is relatively sensitive to Eh [32]. When DO in the water is exhausted, IMOF-N can be released from the sediments to the overlying water and becomes the endogenous source of N in the lake [33]. Factors such as DO, pH, bacterial activity, and TOC affect the content of IMOF-N in the sediments; low DO, high pH and high bacterial activity accelerate the release of IMOF-N. As a result of the competitive adsorption between TOC and Fe/Mn oxides, high TOC will lead to low IMOF-N [34]. In the current study, IMOF-N was not significantly correlated with the content of TFe₂O₃ + MnO and TFe₂O₃ + MnO + Al₂O₃ in superficial sediments (Table 2). However, in the deeper sediments, IMOF-N was significantly positively correlated with the content of TFe₂O₃ + MnO and TFe₂O₃ + MnO + Al₂O₃ in superficial sediments (Table 3). This might be caused by the obstruction of clay and ooze, which weakens the release of IMOF-N in the deeper sediments [35]. In addition, TOC content in the sediments was also characterized by a gradually decreasing trend vertically from top to bottom. The decrease of the TOC content reduces the competitive adsorption between TOC and Fe/Mn oxides; in sediments of the same depth, the higher the TOC content, the higher the OSF-N content and the lower the IMOF-N content [31].

The regeneration and distribution of OSF-N is related to factors such as TOC, percentage of different grain size fractions, and Eh. The higher the TOC content, the smaller

**Table 2. Pearson inter-correlation coefficients between the N fractions and sediment properties in superficial core sediments (n = 15)**

|        | IEF-N | CF-N | IMOF-N | OSF-N | TT-N | NT-N | TT  | NT  |
|--------|-------|------|--------|-------|------|------|-----|-----|
| IEF-N  | 1.00  | 0.30 | 0.91** | 0.81** | 0.88** | 0.92** | 0.89** | 0.92** |
| CF-N   | 0.30  | 1.00 | 0.43   | 0.45   | 0.54** | 0.56*  | 0.47 | 0.57* |
| IMOF-N | 0.91**| 0.43 | 1.00   | 0.83** | 0.78*  | 0.82** | 0.83** | 0.88** |
| OSF-N  | 0.81**| 0.45 | 0.83** | 1.00   | 0.92** | 0.97** | 0.89** | 0.92** |
| TT-N   | 0.88**| 0.54** | 0.78*  | 0.92** | 1.00   | 0.94** | 0.90** | 0.92** |
| NT-N   | 0.92**| 0.56*  | 0.82** | 0.89** | 0.97** | 1.00   | 0.94** | 0.97** |
| TT     | 0.89**| 0.54** | 0.83** | 0.78*  | 0.92** | 0.94** | 1.00   | 0.94** |
| NT     | 0.92**| 0.57*  | 0.89** | 0.92** | 0.97** | 0.90** | 0.94** | 1.00   |

*p < 0.05; **p < 0.01.
the grain size and the lower the Eh, the higher the OSF-N content. In this study, OSF-N was significantly positively correlated with TOC and silt contents in both superficial and deeper sediments, which is in accordance with the findings of Lü et al. [31] and Wang et al. [20]. Research has shown that Fe, Mn and Al oxides in the sediments can improve the bioavailability of N by reducing the efficiency of CEC in immobilizing N [20]. Nevertheless, in the current study, there was no significant correlation between the TFe$_2$O$_3$ + MnO + Al$_2$O$_3$ content and various N fractions (except IMOF-N in sediments at the bottom) (Tables 2 and 3). In fact, the content of Fe, Mn and Al oxides is only one of many factors affecting the distribution of N fractions and the final distribution of N fractions is a result of the synthetic action of the various factors [20].

### 3.3. N release

When the exogenous input of N is controlled, the N release in the sediments is the main factor that affects the content of N in the overlying water of the lake. The contribution rates of the various N fractions to N release can be estimated using a comparison of the variation of distribution proportions of various N fractions in the sediments before and after the release experiment (Figure 4).

Release experiment results indicated that there was no apparent variation trend in sediments in the five study areas (A, B, C, D and E) relating to the contribution of various N fractions at different sediment depths to the total amount of N released. As the main N fraction released, the release of IEF-N and OSF-N represented about 66 and 19% of the total amount of N released respectively. However, CF-N and IMOF-N contributed comparatively little to the total amount of N released (Figure 4). The contribution rates of various N fractions to the total amount of N released ranked from high to low as follows: IEF-N > OSF-N > IMOF-N > CF-N, which agrees with the findings of Wang et al. [20].

According to the extraction ability of the extracts, the difficulty levels for various N fractions to be released in the sediments decreased in the order IEF-N > CF-N > IMOF-N > OSF-N [20,31]. However, in this study, it was easier for OSF-N to be released than CF-N and IMOF-N (Figure 4). Organic matter in sediments is mainly composed of humic substances and other organic matters. Though there is only a small organic matter content in the sediments of the study area, it has a relatively large impact on the exchange of nutrient substances between the sediments and the water interface [24]. At present, controversies remain on how organic matter affects the immobilization of inorganic N in the sediments. Some research has shown that organic matter plays a leading role in immobilizing inorganic N in the sediments [36]. However, other studies have indicated that the obstruction action of the organic matter layer...
whether the sediments in the estuaries are a source or sink of N in Dianchi Lake. Suppose N in superficial sediments (0–15 cm) can sufficient exchange with the overlying water, then according to the results of the release experiment, the TN concentration (average value) in the extracts of superficial sediments in the five study areas (A, B, C, D, and E) after the release experiment were 2.91, 2.89, 1.30, 1.10, and 1.00 mg·L⁻¹, respectively. The TDN concentrations in the overlying water in the five study areas were 1.62, 1.48, 1.52, 1.32, and 1.52 mg·L⁻¹, respectively (Table 1). It is clear that the TN concentration in the extracts (the release experiment) of superficial sediments in Areas A and B was much higher (about 1.8 times higher) than the TDN concentration in the overlying water. Therefore, Areas A and B have extremely high release risks for N in superficial sediments. However, the N in the sediments of areas C, D and E were in relative equilibrium with the overlying water, indicating release potential risk was relatively low. According to the Environmental Quality Standards for Surface Water of the People’s Republic of China [38], only when TN content in the overlying water is less than 1.5 mg·L⁻¹ can water quality of Dianchi Lake reach the class IV level which can be used for industrial application. Therefore, with

weakens the function of the sediments in immobilizing inorganic N [37]. Further research into the influences of the type and content of organic matter on OSF-N release is required.

The amount of N released in the sediments is not only determined by the storage proportions of various N fractions, but also is related to the TN content [20]. Figure 5 shows the correlation between the release amount of various N fractions and the TN content in the sediments. As indicated by the correlation analysis results, the release amount of CF-N did not increase as the TN content increased. However, the release amount of IEF-N, IMOF-N and OSF-N increased as the TN content increased. Although OSF-N is an N fraction that is more difficult to release under the extraction experiment condition, the TN content is relatively high in the sediments and thus its release amount was accordingly high. This explains why IEF-N and OSF-N were the main N fractions release in the sediments (occupying more than 80% of the total release amount).

At present, as a result of the implementation of the water diversion project from the external drainage basin, the eutrophication status of Dianchi Lake has been slightly relieved. However, it remains unknown whether the sediments in the estuaries are a source or sink of N in Dianchi Lake. Suppose N in superficial sediments (0–15 cm) can sufficient exchange with the overlying water, then according to the results of the release experiment, the TN concentration (average value) in the extracts of superficial sediments in the five study areas (A, B, C, D, and E) after the release experiment were 2.91, 2.89, 1.30, 1.10, and 1.00 mg·L⁻¹, respectively. The TDN concentrations in the overlying water in the five study areas were 1.62, 1.48, 1.52, 1.32, and 1.52 mg·L⁻¹, respectively (Table 1). It is clear that the TN concentration in the extracts (the release experiment) of superficial sediments in Areas A and B was much higher (about 1.8 times higher) than the TDN concentration in the overlying water. Therefore, Areas A and B have extremely high release risks for N in superficial sediments. However, the N in the sediments of areas C, D and E were in relative equilibrium with the overlying water, indicating release potential risk was relatively low. According to the Environmental Quality Standards for Surface Water of the People’s Republic of China [38], only when TN content in the overlying water is less than 1.5 mg·L⁻¹ can water quality of Dianchi Lake reach the class IV level which can be used for industrial application. Therefore, with

![Figure 4](image1.png)

**Figure 4.** The contribution of the N released from different N fractions to total released N in core sediments.

![Figure 5](image2.png)

**Figure 5.** The relationship between the N released of different N fractions and TN concentrations in core sediments.
the improvement of water quality in Dianchi Lake. N in sediments in estuaries of Dianchi Lake continues to have a potential release risk.

4. Conclusions

With a relatively high content of TN in sediments, estuaries of Dianchi Lake suffer from comparatively severe pollution. We found that the TN content in the sediments gradually decreased from top to bottom. At 0–15 cm sediment depth, TN content slowly decreased as the depth increased; at 15–30 cm, it sharply decreased as the depth increased and stabilized at depths >30 cm, indicating that the exogenous input of N in these areas has not been controlled effectively in recent years. The vertical variation trend of the content of IEF-N, IMOF-N and OSF-N was essentially the same as that of TN. However, the CF-N content showed no clear vertical variation. The proportions of various N fractions in TN in sediments of Dianchi Lake ranked as follows: OSF-N > IMOF > CF-N > IEF-N.

As shown by the correlation analysis results, IEF-N, IMOF-N, OSF-N, TT-N and TN were significantly positively correlated with the contents of TOC, clay and silt but were significantly negatively correlated with the contents of sand and SiO₂. In the superficial sediments (0–15 cm), both IEF-N and IMOF-N were not significantly correlated with the content of TFe₂O₃ + MnO + Al₂O₃, but in deeper sediments (15–40 cm), both IEF-N and IMOF-N were significantly correlated with the content of TFe₂O₃ + MnO + Al₂O₃.

The release experiment results indicated that the contribution rates of various N fractions to the total N release decreased in the order IEF-N > OSF-N > IMOF-N > CF-N. As the main N fractions released, IEF-N and OSF-N occupied more than 80% of the total release amount, whereas CF-N and IMOF-N contributed relatively little to the total N release. In the environment, the probabilities of the exchange between the sediments at different depths and overlying water were different, and the exchange between superficial sediments and overlying water was stronger than that between deep sediments and overlying water. However, in the laboratory experiment, there was a sufficient exchange between the sediment sample and the extracts, which may lead to overestimated release rates of various fractions of N in deep sediments. At present, the release risk of N in superficial sediments in Areas A and B is higher than that in Areas C, D and E. However, it is likely that with the advance of remediation, the TDN concentration in the overlying water will gradually decrease, and the N in sediment in the Estuaries of Dianchi Lake will develop a release risk.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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