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Internal Loads and Bioavailability of Phosphorus and Nitrogen in Dianchi Lake, China

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Abstract: Sediments have a significant influence on the cycling of nutrient elements in lake environments. In order to assess the distribution characteristics and estimate the bioavailability of phosphorus and nitrogen in Dianchi Lake, organic and inorganic phosphorus and nitrogen forms were analysed. The ^{210}Pb radiometric dating method was employed to study temporal changes in the phosphorus and nitrogen pools in Dianchi Lake. The result show that the total phosphorus (TP) and total nitrogen (TN) were both at high concentrations, ranging from 697.5–3210.0 mg/kg and 1263.7–7155.2 mg/kg, respectively. Inorganic phosphorus (IP) and total organic nitrogen (TON) were the main constituents, at percentages of 59%–78% and 74%–95%, respectively, in the sediments. Spatially, there was a decreasing trend in phosphorus and nitrogen contents from the south and north to the lake centre, which is related to the distribution pattern of local economic production. The burial rates of the various phosphorus and nitrogen forms increased in same spatially and over time. Particularly in the past two decades, the burial rates doubled, with that TN reached to 1.287 mg/(cm^2·yr) in 2014. As the most reactive forms, nitrate nitrogen (NO_3-N) and ammonia nitrogen (NH_4-N) were buried more rapidly in the south region, implying that the potential for releasing sedimentary nitrogen increased from north to south. Based on their concentrations and burial rates, the internal loads of phosphorus and nitrogen were analysed for the last century. A TP pool of 71 597.6 t and a TN pool of 81 191.7 t were estimated for Dianchi Lake. Bioavailable phosphorus and nitrogen pools were also estimated at 44 468.0 t and 5429.7 t, respectively, for the last century.
Keywords: sediment; phosphorus; nitrogen; burial rate; internal load; bioavailability; Dianchi Lake

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1 Introduction

Eutrophication is a serious problem globally, in both industrialized and developing countries (Ruban et al., 2001). Phosphorus and nitrogen are both limiting nutrients and supplement the biota growth responsible for lake eutrophication (Mehner et al., 2008; Zhong et al., 2008). Sediments play an important role in determining the distribution, accumulation, release, and final fate of phosphorus and nitrogen (Fytianos and Kotzakioti, 2005). Sediments are both a sink and source of phosphorous and nitrogen in lake environments (Aigars and

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Carman, 2001; Shang et al., 2013; Liu et al., 2015). During transfer from a terrestrial to a lake environment, most nutrient elements accumulate in sediments without any interaction with the freshwater of the biosphere (Meybeck, 1982). However, when the environmental conditions of pH, dissolved oxygen (DO), *etc*. change, some of the nutrients could be release to the water, thus resulting in eutrophication of the lake. With conservation and management causing a reduction in external nutrient inputs, internal pollutant release could become a major cause of eutrophication. According to Søndergaard et al. (2013), endogenous phosphorus release may significantly influence the lake geochemistry dynamics for more than 20 years, especially when controlled exogenously. Knowledge of phosphorus and nitrogen fractions is vital for assessing their bioavailability to be able to pose constructive management schemes.

Many lakes are experiencing eutrophication worldwide, and sedimentary phosphorus and nitrogen have been identified as key factors. Młynarczyk et al. (2013) studied phosphorus forms in the sediments of the Goczałkowice Reservoir using inductively coupled plasma-optical emission spectrometry. Matisoff et al. (2017) quantified the internal load of nutrients and their bioavailability in Lake Winnipeg, and found higher values in the south basin than the north basin. Additionally, there has been much research on factors influencing the distributions of phosphorus and nitrogen in sediments (Zhong et al., 2008; Xiang and Zhou, 2011; Cong et al., 2014; Li et al., 2016; Puttonen et al., 2016). Eutrophication is becoming a serious issue in China, in particular in Taihu Lake, Chaohu Lake, Erhai Lake, and Dianchi Lake. Zhang et al., (2014) probed the impact of pH and DO on nitrogen release from the sediments of Erhai Lake. Jiang and Yuan (2015) quantified phosphorus cycling in the Chaohu watershed and found a 5-fold increase of annual P inputs, about 75% of which was stored. As one of the most serious eutrophic freshwater lakes in China, wide attention has been payed to Dianchi Lake. However, previous studies focused primarily on the distribution of phosphorus or nitrogen forms (Lu et al., 2009; Shi et al., 2013; Xiong et al., 2014). No specific research has demonstrated the temporal distribution and estimated the reserves of phosphorus and nitrogen by form in the sediments, as well as their bioavailability.

Total phosphorous (TP) and total nitrogen (TN) are poor estimates of potential ecological risks because different sediments are composed of different chemical forms and have different contribution values in promoting the deterioration of water quality. Therefore, in order to provide theoretical basis for nitrogen and phosphorus pollution and its treatment in sediments of Dianchi Lake, various phosphorus and nitrogen fractions were analysed along with ^{210}Pb radiometric dating to obtain: 1) the composition of phosphorus and nitrogen in the sediments; 2) the spatial and temporal distribution characteristics of different phosphorus and nitrogen forms; 3) the accumulation and burial characteristics of phosphorus and nitrogen fractions, and 4) the accumulated reserve of various phosphorus and nitrogen forms and their potential bioavailability in the sediments of Dianchi Lake during the last century.

2 Materials and Methods

2.1 Study area and sample collection

Dianchi Lake, located in the centre of the Yunnan-Guizhou Plateau (24°28' N–25°28' N, 102°30' E–103°00' E), is the largest freshwater lake in Yunnan Province, China (Liu et al., 2011). This lake, containing the Caohai and Waihai basins, has the sixth largest area in China of 330 km^2 (Xin et al., 2016), and is shallow with a mean depth of 4.4 m (Wang et al., 2015). As the most famous plateau freshwater lake in China, it is important as a local water supply, and for fishing, shipping, and climate regulation. Because of industrial and agricultural development around Kunming City in recent decades, the lake has become one of the most seriously eutrophic and contaminated lake in China, with frequent algal blooms (Li et al., 2007; Wang et al., 2015).

Sampling was conducted in July 2014 at six sampling sites located in various river estuaries (Fig. 1). Six sediment cores (50 cm long and 8.3 cm internal diameter, except S4, which was 60 cm long) were collected using a gravity corer and transferred immediately to the laboratory, where they were kept at –50℃ for further analysis. All of the sediment cores were sliced in 1 cm intervals and freeze-dried for determination of phosphorus and nitrogen forms.

2.2 Analysis of phosphorus and nitrogen forms

The standards, measurements, and testing programme proposed by the European Commission (the SMT protocol) was used to quantify five phosphorus forms in the

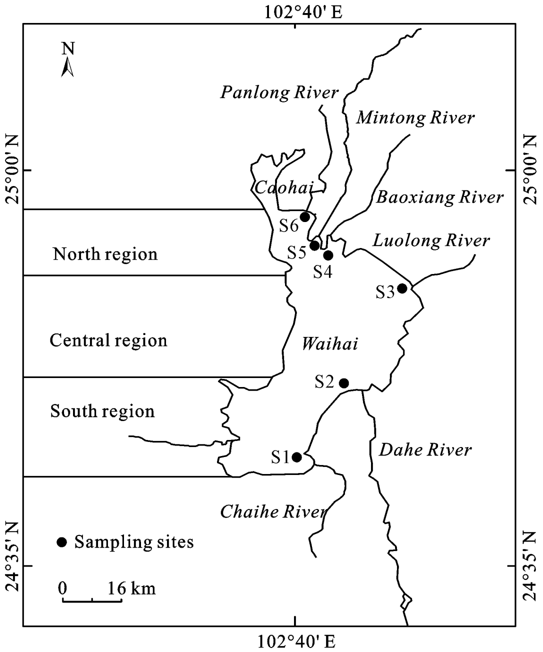

Fig. 1 Location of sampling sites in Dianchi Lake

sediments: TP, inorganic phosphorus (IP), organic phosphorus (OP), phosphorus bound to Ca^{2+} (HCl-P), and phosphorus associated with Fe/Al/Mn oxides and hydroxides (NaOH-P) (Ruban et al., 1999; Jin et al., 2006). The operationally defined scheme was composed of five steps according to the SMT protocol, and the OP content was equal to the difference of TP and IP.

The sedimentary nitrogen forms include TN, ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and total organic nitrogen (TON). TN contents were determined after digestion by persulfate ($K_2S_2O_8$ + NaOH) at 121 °C (Song et al, 2002). NH_4-N contents were measured using salicylic acid and hypochlorous acid salt spectrophotometry (ISO 7150/1-1984) (Hu and Wu, 2005). NO_3-N concentrations were analysed using ultraviolet spectrophotometry directly after acidification with HCl. The TON contents were taken as TON = TN – (NH_4-N + NO_3-N).

2.3 Radionuclide dating method for sediments

The ^{210}Pb radiometric technique was employed to date the sediment cores. The ^{210}Pb specific activities were determined using a high-purity germanium detector (EG&G ORTEC, USA) with a 40 000 s determination time and 62% relative detection efficiency. The constant rate of supply (CRS) model (Appleby and Oldfield, 1992) was applied to date the sediment cores. The chronology (t) of the sediments can be calculated with the function:

$$t = \ln(A_h / A_0) / \lambda \tag{1}$$

where A_h is the content of $^{210}Pb_{ex}$ in each layer of sediment below h depth (Bq/cm^2), A_0 is the total content of ^{210}Pb in the sediment (Bq/cm^2), and λ is the decay constant (Putyrskaya et al., 2015).

According to the sedimentary chronology, the sediment deposition rate, S (g/(cm^2·yr)), and nutrient element burial rate, V, phosphorus and nitrogen reserves, Q, can be obtained as:

$$S = Z/t \tag{2}$$

$$V = S \times C \tag{3}$$

$$Q = V \times t \times \mathrm{A} \tag{4}$$

where the cumulative mass depth Z (g/cm^2) is equal to the sediment mass per unit area above a certain depth, C is the concentration of phosphorus and nitrogen forms, Q is the reserves of phosphorus and nitrogen, and A (km^2) is the area of each region.

3 Results

3.1 Composition of phosphorus and nitrogen forms

The contributions of phosphorus and nitrogen forms within the sediments were very different (Fig. 2). IP was the main phosphorus form in all sediments, at a relative percentage of 59%–78% of TP, and the highest percentage was found in S6. The percentage of IP increased from south to north of the lake, whereas the OP percentage showed the reverse. From south to north, the percentage of NaOH-P showed a stable increase. The HCl-P was the main portion of IP, especially in S2. In contrast to the dominantly inorganic phosphorus fractions, TON was the dominant nitrogen fractionation in sediments, with an average contribution rate of 74%–95%, while NO_3-N and NH_4-N account for only a small portion of the TN. There was a relatively higher percentage of inorganic nitrogen at S6, with 14% NO_3-N and 12% NH_4-N.

3.2 Contents and burial rates of phosphorus forms

The contents (Fig. 3a) and burial rates (Fig. 3b) of phosphorus forms showed an increasing trend during the last century. The concentration of TP changed from

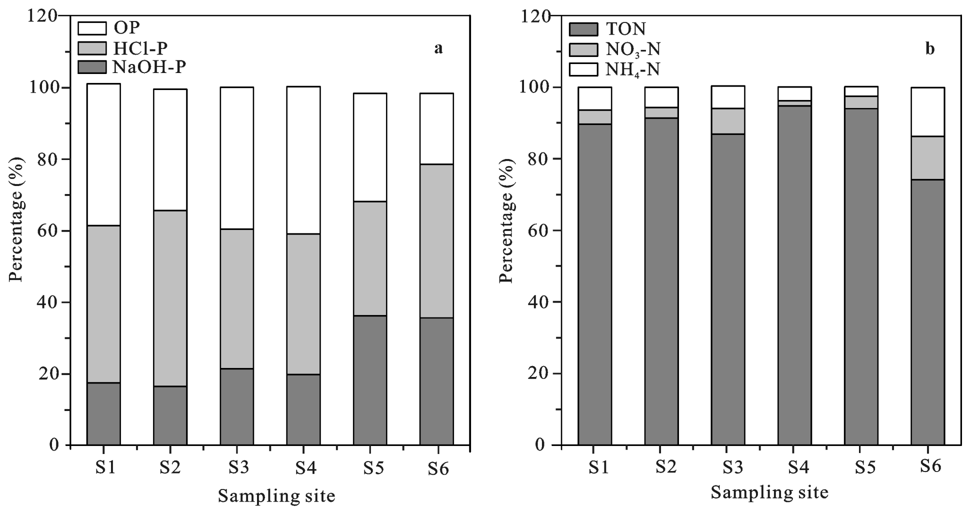

Fig. 2 Relative percentages of phosphorus forms (a, OP, NaOH-P, HCl-P) to TP and nitrogen forms (b, TON, NH_4-N, NO_3-N) to TN in the sediments of Dianchi Lake

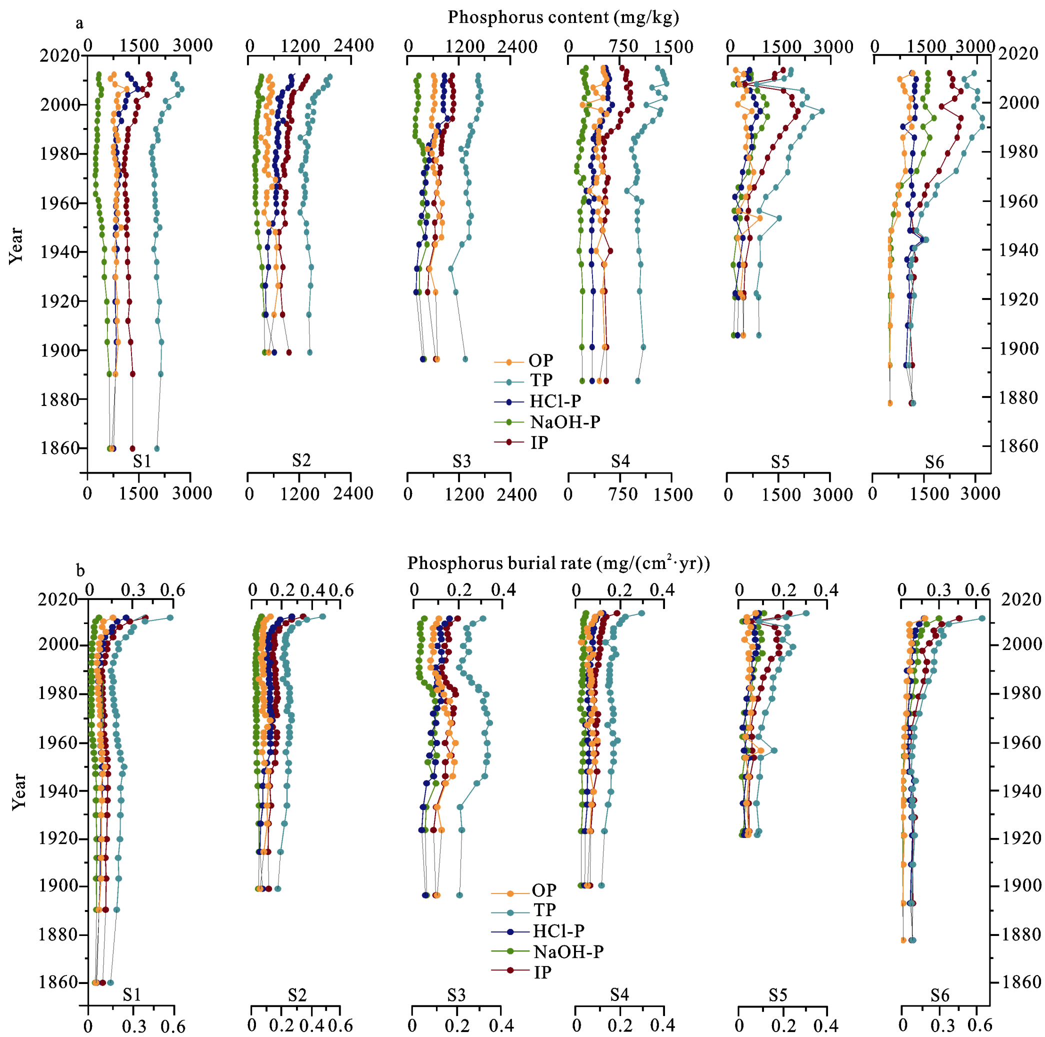

Fig. 3 Content (a) and burial rate (b) variations with age by different phosphorus forms (TP, IP, OP, NaOH-P, HCl-P) in the sediments of Dianchi Lake

697.5 mg/kg to 3210.0 mg/kg. TP contents were observably different among the sampling sites, with the largest average value of 2132.7 mg/kg measured in S1. Spatially, the TP contents were higher in the south, slightly lower in the north, and lowest in the centre of the lake. IP contents mainly consisted of HCl-P in all sediment cores, and increased gradually from the subsurface at 654.3 mg/kg to the surface at 1633.3 mg/kg. NaOH-P and OP had common trends with depth, showing slightly higher contents in the bottom than at the surface in the south of the lake.

According to Fig. 3b, the burial rates of phosphorus forms generally showed an increasing trend with age, and particularly in the most recent two decades, the values almost doubled. However, there was no significant distinction in TP burial among all sampling sites, which had an average rate of 0.224 mg/(cm^2·yr). Dramatically, the burial rates of the other phosphorus forms at all sites exhibited a similar tendency: they were stable before the 1940s, followed by a gradual increase, and then a manifold increase after 1990. In sediments, the IP burial rates were significantly higher, ranging from 0.052 mg/(cm^2·yr) to 0.456 mg/(cm^2·yr), while the OP was deposited to a lesser extent, at 0.002 mg/(cm^2·yr) to 0.194 mg/(cm^2·yr). Burial rates of NaOH-P and HCl-P were 0.004 to 0.294 mg/(cm^2·yr), and 0.024 mg/(cm^2·yr) to 0.277 mg/(cm^2·yr), respectively. In different regions, these two phosphorus forms showed different deposition characteristics. In the south of Dianchi Lake, HCl-P burial dominated while NaOH-P sedimentation was the slowest. In the north of the lake, this pattern was reversed. NaOH-P and HCl-P were buried at almost the same rate, and even at S5, the burial rate of NaOH-P was apparently higher than that of HCl-P.

3.3 Contents and burial rates of nitrogen forms

The vertical profile distribution of the contents (Fig. 4a) and burial rates (Fig. 4b) of nitrogen forms in the sediments show a parallel increasing trend between TN and TP during the last century. The concentration of TN changed from 1263.7 mg/kg to 7155.2 mg/kg, and was observably different among all of the sampling sites. The largest average values of 2816.64 mg/kg were found at S1. Similarly to TP, the TN contents were higher in the south, slightly lower in the north, and lowest in the centre of the lake. According to the standard formulated by the U.S. Environmental Protection Agency (EPA) (U.S. Environmental Protection Agency, 2002), a lake is at a highly polluted level when the TN content in the sediments is above 2000 mg/kg. On this account, there is a serious sedimentary nitrogen contamination in Dianchi Lake that is supported by relevant previous work of our team (Wu et al., 2017). TON was the main fraction of the sedimentary nitrogen, at 1128.5 mg/kg to 2568.0 mg/kg. NO_3-N and NH_4-N were relatively low, with average contents of 50.0 mg/kg and 60.2 mg/kg, respectively, which are the easily bioavailable nitrogen forms in sediments. There was a common spatial distribution of TON and NH_4-N, with their average contents decreasing from the south and north to the centre of the lake. However, the highest NO_3-N contents were observed in the lake centre.

The burial rates of TN showed an increasing trend with age, particularly after 1970. Deposition of sediment TN remained stable before the 1970s, and sharply increased after that due to human activities and economic, industrial, and agricultural growth. The maximum sedimentary TN burial rate increased to 1.287 mg/(cm^2·yr) in 2014 at S1. For the TN content spatial distribution, there was also a decreasing trend from south to north, while the lowest value was observed at the centre (S3). The burial rates of TON in sediments were homogeneous with an average value of 0.258 mg/(cm^2·yr). At various sampling sites, NO_3-N and NH_4-N burial rates fluctuated separately, at 0.041–24.667 μg/(cm^2·yr) and 0.026–23.309 μg/(cm^2·yr), respectively. NO_3-N was buried the fastest at S3, and there was a higher rate of NO_3-N and NH_4-N deposition in the south of than in the north. As the most active nitrogen fractions, even at low contents, these can be readily released to the water when the environment changes. As in the study by Wang et al. (2016) on nitrogen pollution in the sediments of Dianchi Lake, the risk of sedimentary nitrogen release increases from north to south of the lake. Hence, the relevant department should attach more importance to endogenous nitrogen contamination and take corresponding measures.

4 Discussion

4.1 Phosphorus and nitrogen composition and distribution characteristics

Dianchi has become the most seriously polluted fresh-

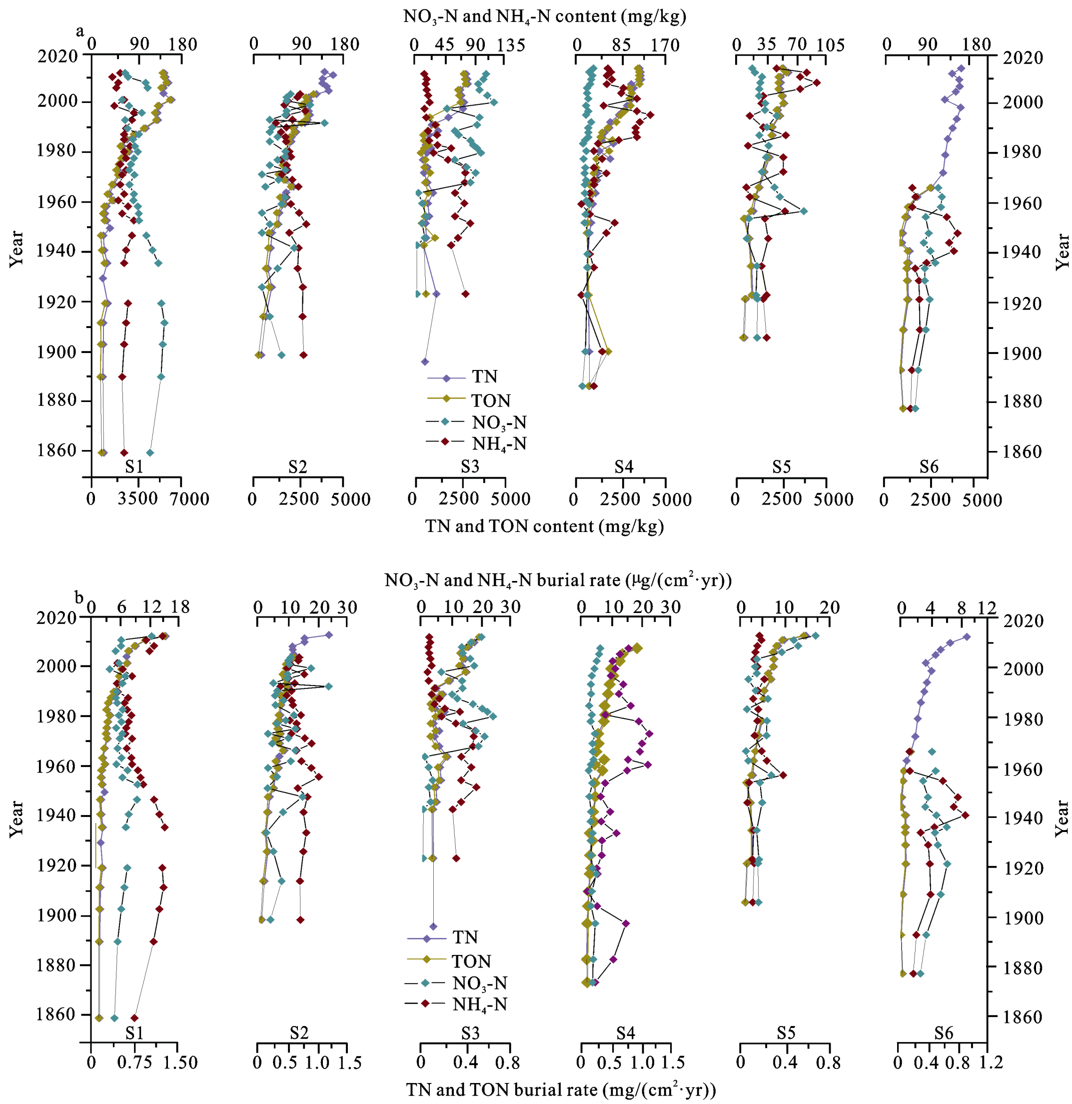

Fig. 4 Content (a) and burial rate (b) variations with age by nitrogen form (TN, TON, NH_4-N, NO_3-N) in the sediments of Dianchi Lake

water lake in China, and is characterised as moderately eutrophic (Ni et al., 2016). The spatial average contents of TP and TN in the sediments of 6 cores from Dianchi Lake were 1128–2124 mg/kg and 1267–3625 mg/kg, respectively, higher than most lakes in China, including Taihu Lake, Erhai Lake, and Chaohu Lake, and even than some lakes in other countries (Table 1). Lake Winnipeg in Canada and the Goczałkowice Reservoir in Poland are both eutrophic lakes. Both phosphorus and nitrogen contents were only slightly lower in these two lakes than those in Dianchi Lake. Therefore, Dianchi Lake can be regarded as representative of eutrophication lake.

Table 1 TP and TN contents in the sediments of different lakes in China and other countries

	Dianchi [a]	Taihu [b,c]	Chaohu [d]	Erhai [e,f]	Winnipeg [g]	Goczałkowice [h]
TP (mg/kg)	1128–2124	420–3408	220–770	2354–6147	670–1050	470–2640
TN (mg/kg)	1267–3625	1748	450–1250	418–1108	–	920–3060

Notes: a, This study; b, Jin et al., 2006; c, Gao et al., 2009; d, Wu et al., 2016; e, Zhao et al., 2013a; f, Zhao et al., 2013b; g, Matisoff et al., 2017; h, Młynarczyk et al., 2013.

According to Fig. 2, there was a significant difference in phosphorus and nitrogen fractionation between the south and north regions of Dianchi Lake. Both OP and TON were higher in the south and lower in the north. The organic phosphorus and nitrogen were seriously influenced by input fractions, sedimentary environment, diagenesis, and human activities (Liu et al., 2001). S6 is located at the north of the lake, where there is a higher eutrophic level relative to the south region. The organic components originating from autochthonous sources was higher at this site compared to that in the south region. Organic matter in sediments mainly originates from autochthonous sources (phytoplankton product), and will degrade quicker than sediment from allochthonous sources (Gudasz et al., 2012; Chmiel et al., 2015; Watanabe and Kuwae, 2015), which may have led to lower OP and TON at S6.

Based on the above research, phosphorus and nitrogen in sediments shared common spatial distribution features. Both phosphorus and nitrogen contents were high in the south and north of the lake (Figs. 3 and 4). The south area of Dianchi basin is an agriculturally intensive region, and the north area is near Kunming City, and therefore influenced by anthropogenic activities. Agricultural non-point sources and urban point sources of pollution are becoming the most important sedimentary nitrogen and phosphorus sources to Dianchi Lake (Mcdowell and Asbury, 1994; Wu et al., 2014). As shown in Fig. 5, the Gross Domestic Product (GDP) of Kunming City increased from 1970, and agricultural and industrial development increased accordingly. From the 1990s to 2010, the total GDP, industrial GDP, and agricultural GDP increased by 18.40, 15.76, and 8.44 times, respectively. Furthermore, the south region was a phosphate ore (mainly bound to calcium) gathering site for a mining factory that directly contributed to the higher proportion of HCl-P than that found other regions. Hence, this distribution pattern can mostly be attributed to improved industrial and agricultural productivity and the subsequent disturbance by humans.

4.2 Reserve estimations of phosphorus and nitrogen forms in sediments

According to Wang et al. (2016), the Waihai Basin of Dianchi Lake can be divided into three regions (Fig. 1): the south, centre, and north, with respective areas of 101.185 km^2, 133.806 km^2, and 51.602 km^2. After 1900,

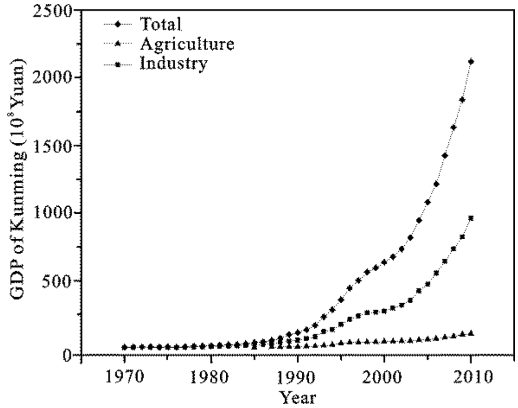

Fig. 5 Total GDP (Gross Domestic Product) and industrial GDP (from 1970 to 2010), agricultural GDP (from 1985 to 2010) of Kunming City (from the Kunming City Statistical Yearbook. Yunnan Provincial Bureau of Statistics, 1970–2010.)

sediment has become a bulk stockpile of nutrient elements in the lake. Combining the contents and burial rates of phosphorus and nitrogen with the basin areas, sedimentary phosphorus and nitrogen reserves were estimated (Table 2). The calculated values of TP and TN storage reached 71 597.6 t and 81 191.7 t, respectively, over the last century, higher than that found by Wang et al. (2016) (a TN pool of 5757.9 t in the 20 cm surface sediments). In this research, all sampling sites were located in river estuaries, resulting in higher content and burial rates. Moreover, the depth of the sediment cores was deeper, therefore, a larger pool is reasonable. The distribution of burial capacities of phosphorus forms in the region was consistent with that of TP, with centre > south > north. The south region was the dominant pool of TN, TON, and NO_3-N, but the largest NH_4-N storage was at the centre. The north region close to the city has been receiving 62% of the city sewage (Li et al., 2010). As a severely polluted region, abundant ammonium and nitrate ions were absorbed by microorganisms and plants, leading to the lowest inorganic nitrogen reserves in the northern sediments.

Since the 1970s, the time of the largest pollutant discharge to the lake (Li, 2012), the government has developed large-scale industries around the Dianchi basin (Lu et al., 2009), inducing a great proportion of phosphorus and nitrogen deposition (Table 3). Over half of the phosphorus reserves were buried during this time, except for OP. Similarly, most of the nitrogen reserves were also buried since the 1970s, with a minimum of 37.62% (for NH_4-N) of the reserve accumulating during this time. In the meantime, mining of phosphate ore

Table 2 Phosphorous and nitrogen fraction reserves in sediments of Dianchi Lake for the last century (t)

Region	IP	NaOH-P	HCl-P	OP	TP	NO_3-N	NH_4-N	TON	TN
South	15503.9	4086.0	11418.9	8950.6	24454.6	1194.0	782.9	30559.1	32536.0
Center	20292.5	8438.4	13831.1	16827.4	37119.9	1190.9	1702.2	20052.9	22946.0
North	6902.0	3029.4	3776.2	3136.2	10023.1	326.9	232.8	25150.0	25709.8
Total	42698.5	15553.8	29026.1	28914.2	71597.6	2711.8	2717.9	75762.0	81191.7

Table 3 Contribution of phosphorus and nitrogen reserves after 1970s relative to 1900–2014 (%)

Region	IP	NaOH-P	HCl-P	OP	TP	NO_3-N	NH_4-N	TON	TN
South	68.01	60.74	68.61	63.85	66.49	42.01	58.83	67.48	66.33
Center	46.28	37.09	50.69	38.55	42.77	79.69	16.86	69.65	66.25
North	59.09	68.27	51.49	51.32	56.98	46.26	79.06	34.25	34.81
Total	56.26	57.71	51.40	41.08	50.23	44.32	37.62	62.27	60.84

Note: Contribution rate of phosphorus and nitrogen is the ratio of content in each region to the total

directly accelerated phosphorus deposition, especially in the south of the lake. Since the 1990s, Dianchi Lake has been in a drastically deteriorated condition, with serious eutrophication and algal blooms. From 1990 to 2010, anthropogenic nitrogen inputs increased linearly more than 2 fold, from approximately 5500 kg/(km^2·yr) to 12 600 kg/(km^2·yr) (Gao et al., 2015). Subsequently, the government has attached more attention to the situation, and extensive countermeasures have been implemented to mitigate the pollution. However, the internal load has not been alleviated. The retention of sedimentary phosphorus and nitrogen is related to the sedimentation rate, physical and chemical properties of the sediments, amount and kinds of organic matter, and the intensity of mineralization (Graca and Bolałek, 1998; Lu et al., 2016). Based on the contribution of phosphorus and nitrogen in different regions in the recent 50 years, all forms were higher in the south part of lake, which may indicate that the nutrient pollution by phosphorus and nitrogen compounds has transferred gradually from north to south in the lake. This could be attributable to the comprehensive influence of external inputs and the above factors.

4.3 Bioavailable potential of phosphorus and nitrogen in sediments

Sediments are both a sink and a source of phosphorus and nitrogen in the overlying water environment, and subsequently control the primary productivity (Broecker and Peng, 1982). The conversion from sink to source depends on environmental conditions and the composition of nutrient forms. Different forms of phosphorus and nitrogen have different effects on biology. When the sedimentary environment changes, phosphorus and nitrogen can be released into the water, but not all forms are labile and desorb. Hence, it was necessary to explore the bioavailability of phosphorus and nitrogen forms in the sediment. A simple TN or TP concentration does little to illuminate the processes of nutrient uptake during algal growth. Phosphorus bound to Fe, Al, and Mn oxides and hydroxides was active and vulnerable. DO, pH, bioturbation, and sediment suspension were all critical factors controlling the combined process of phosphorus sorption and desorption, especially when DO concentration was low (Jin et al., 2006; Mattila et al., 2006; Puttonen et al., 2014). OP was the primary phosphorus form found in the sediments, and was complicated in composition and structure. Although it cannot be utilized directly by algae, research has shown that half of the OP can be converted into algal-available phosphorus species, especially in anoxic conditions (Rydin, 2000). The mineralization of organic matter in sediments induced OP release, and this process can be sustained long-term.

NaOH-P and OP can be released from sediments to the water in certain environmental conditions, of which the contents reflect the algal-available capacity to some degree (Rydin, 2000; Gao et al., 2005; Zhu et al., 2013). Consequently, the estimated content of potential bioavailable phosphorus was 44 468.0 t, at a percentage of 62.11% to TP, and showed significant spatial variation. In the north region of Dianchi Lake, these two phosphorus forms increased with time (Fig. 3a), responding to algal blooms and high eutrophication conditions. In comparison with another lightly eutrophic lake in China, Taihu Lake (Ni et al., 2016), this bioavailable phosphorus reserve was very large. Zhu et al. (2013) studied the sediments at the depth of 21 cm in Taihu Lake and demonstrated that there was 5156 t of bioavailable phosphorus. If this was all released to the water, the phosphorus concentration in the lake water would increase almost 7 times. DO concentrations (Fig. 6) in the water showed a significant decreasing trend from south to north in Dianchi Lake, and the average pH value was 8.42 with a standard deviation of 0.03. Naturally, there was a higher risk of phosphorus being released from the sediments in the northern region due to influence from DO. According to Jin et al (2006), a higher pH will promote release of NaOH-P in alkaline conditions, and thus the water pH in the north aided the release of NaOH-P. In addition, the area of Dianchi Lake is much smaller than that of Taihu Lake (2338 km^2) (Li et al., 2007), while the bioavailable phosphorus pool was much higher. Thus, the internal phosphorus load problem in Dianchi Lake is very serious and needs to be addressed.

Apart from phosphorus, nitrogen is a crucial element restricting algal growth. NH_4-N and NO_3-N were the most active components and were accessible by algae. Zhang et al. (2014) indicates that inorganic nitrogen can be released to water, regardless of the DO concentration. NH_4-N was the main fraction desorbed from sediments in anoxic conditions. In this situation, the mineralization of organic matter and ammonification of organic nitrogen

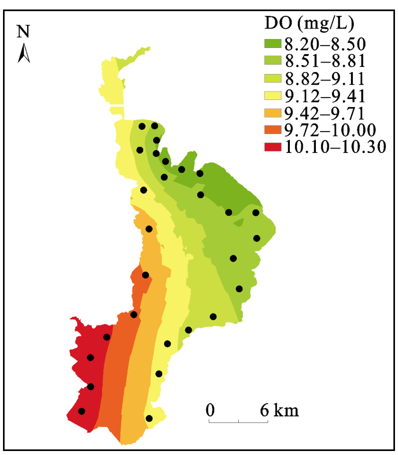

Fig. 6 Spatial distribution of DO concentrations in the water of Dianchi Lake (as determined by Yunnan Institute of Environmental Science)

supplied nitrogen release. In contrast to the anaerobic environment, NO_3-N dominated in the dissolved nitrogen pool in aerobic conditions. Bai et al. (2002) demonstrated that when the DO concentration was below 1.5 mg/L, the NH_4-N release quantity reached 10 mg/(m^2·d), while as DO concentration increased to 2.8 mg/L, the value decreased sharply. This study assessed the bioavailable nitrogen pool at 5429.7 t during the last century, without regard to TON. TON was complicated in composition and structure, and its release and translation processes are still unknown and need further study.

According to this study, there was a very large phosphorus and nitrogen bioavailability capacity in the sediments of Dianchi Lake. Internal phosphorus and nitrogen were assumed the notable parameters for eutrophication (Rydin et al., 2011). Internal phosphorus and nitrogen loads need to be highlighted, particularly when the external pollutants are controlled. Currently, dredging is believed to be a useful measure for rehabilitating the aquatic ecosystem by removing the polluted surface bottom layers and reducing the release of nutrients (Zhong et al., 2008). However, dredging is not always successful because no single method can completely eradicate release of phosphorus and nitrogen contents. The associated DO, pH, temperature, bioturbation, and other factors codetermine the transformation of nutrients in sediments to algae. It is still unknown how to sustain or improve the lake status by reasonable regulation of these factors. Much work is still needed to explore the relationships among different nutrient forms, their bioavailability, and environmental factors.

5 Conclusions

Accumulation of phosphorus and nitrogen in sediments showed an increasing trend over time. The distribution and deposition in sediments were influenced by human activities. In the north and south of Dianchi lake, where are respectively dominated by agriculture and urban life, phosphorus and nitrogen contamination was the most serious. Since 1970, rapid economic development has accelerated phosphorus and nitrogen accumulation with the reserves during this time accounting for over half of the pool accumulated during the last century. Sediments are a large pool of nutrients, of which the bioavailable components can provide long-term supplements for algae and other planktons. Therefore, we need to take immediate effective actions to control and manage internal phosphorus and nitrogen contamination of Dianchi Lake.

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