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Effects of Dredging on Nitrogen and Phosphorus Storage Patterns and Retention Mechanisms in Column Core Sediments in the Caohai Region of Dianchi Lake

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Abstract: Dredging is a common technique for managing eutrophication problems in waters, reducing the accumulation of pollutants by removing sediments from the bottom of water bodies. However, dredging can have complex impacts on lake ecosystems, and it is crucial to understand its benefits and mechanisms for the environment. In this paper, the dredged and undredged areas in the Caohai portion of Dianchi Lake were studied to analyze the effects of dredging on nitrogen–phosphorus transport and conversion and changes in nitrogen–phosphorus morphology content and its mechanisms by comparing the nitrogen–phosphorus morphology content and percentage, the nitrogen–phosphorus ratio, and the release contribution of the two areas. It was found that the ratio of stabilized nitrogen (SN) to stabilized phosphorus (SP) in the dredged area was lower than that in the undredged area and the BD-P and TOC content had a large turnaround at the 16–20 cm position of the sediment in the dredged area. The main conclusions were that the dredging would disrupt the internal equilibrium of the lake system for many years, with the greatest effect on the balance of the BD-P in the phosphorus forms of the sediment, and that the column cores of the dredged area at 0 to 16 cm might be newly accumulated sediments after the dredging project. However, with time, the distribution of nitrogen and phosphorus forms in the newly accumulated sediments will gradually reach a new equilibrium. In addition, dredging will also cause significant changes in the retention efficiency of nitrogen and phosphorus in the sediment, and the stable nitrogen and phosphorus forms will be released and transformed into unstable nitrogen and phosphorus forms.

Keywords: dredging project; lake eutrophication; lake ecosystem health; nitrogen form; phosphorus form

Citation: Liu, M.; Yang, Y.; Shao, Z.; Liu, Y.; Wang, Z.; Chen, Z.; Chen, M.; Jiao, L.; Song, D.; Li, J.; et al. Effects of Dredging on Nitrogen and Phosphorus Storage Patterns and Retention Mechanisms in Column Core Sediments in the Caohai Region of Dianchi Lake. *Water* **2024**, *16*, 449. https://doi.org/10.3390/w16030449

Academic Editors: Shengrui Wang, Jingfu Wang and Zhibin Zhang

Received: 7 January 2024
Revised: 26 January 2024
Accepted: 27 January 2024
Published: 30 January 2024

1. Introduction

Lakes in many countries around the world face the problem of eutrophication, caused by exogenous and endogenous pollutants [1,2]. When exogenous pollutants are effectively controlled, the sediments at the bottom of the lake act as a source and sink for pollutants, which are released through molecular diffusion, resuspension, and convection, leading to water quality deterioration and algal blooms. To address this, an environmentally friendly means of controlling eutrophication in lakes has emerged: sediment dredging [3]. Dredging is a common technique for managing eutrophication problems [4], which aims to reduce the level of eutrophic substances and promote self-purification by removing silt and sediment from the bottom of water bodies. The purpose of environmental dredging is to reduce potential risks to human health and the environment; unfortunately, it remains unclear whether environmental dredging alone is effective in reducing such risks [5]. Moreover, dredging can have complex impacts on the ecosystems and environments of water bodies [6,7], mainly including factors, such as the resuspension of sediments due to dredging, release of pollutants from suspended sediments, residual substrate left behind by dredging, and long-term inputs of exogenous pollutants, which can have a great impact on the retention of N and P in sediments. At the end of a dredging project, a series of negative effects on the nascent sediment–water interface are produced, resulting in a short-term effect of dredging [8], and the release of N and P from the interface is restored or even prompted to re-emerge as an endogenous source of pollution [9].

Dianchi is a typical large shallow plateau lake and is one of the most eutrophic lakes in China. In addition, Dianchi is representative of typical lakes that cannot better control eutrophication through the reduction of external nutrient inputs [10]. The natural water exchange of Dianchi takes up to four years, which provides favorable natural conditions for nutrient retention and lake management. The strong internal nutrient cycling in large shallow lakes and the influence of various aquatic habitats on nutrient retention make lake eutrophication management difficult [11–13]. For this study, two areas in the Caohai region—which is the most seriously polluted area of Dianchi Lake—were selected. One of them is the state-controlled point, Caohai Center [14], a more seriously polluted and undredged point with no external interference on sediment accumulation, which has long been polluted by the inflow of an urban river into the lake. The other area is closer to the center of the Caohai Center, farther away from the inflow of the urban river into the lake [15,16], which is relatively less affected by human activities. However, a dredging project was conducted at this site 8 years before the sampling for this study was conducted, changing the N and P morphology and content of the column core sediments [17].

Previous studies have conducted simulation experiments based on the same site/area before and after dredging. For example, Chen, X. et al. [18]. collected sediment and water samples from both dredged and undredged areas around the sea-control inlet of Lake Taihu, China, and analyzed the characteristics of internal nutrient releases between dredged and undredged sediments through simulation experiments. Zhong, J.C. et al. [19] collected sediment cores from two sites with different levels of contamination in Meiliang Bay, Lake Taihu, China, and conducted sediment simulation experiments to analyze the effects of dredging on inland sediments at different times of the year. Jing, L.D. et al. [20] collected sediments from Dongqian Lake, where a real dredging project was carried out, and used them for simulation experiments to understand the effects of dredging on the nitrogen balance. Jing, L.D. et al. [21] conducted a 3-year field investigation on a long-term sediment dredging project in Dongqian Lake, China. The amount of Fe and P forms in sediments from the dredged and nearby undredged areas were monitored and compared. However, the conditions in simulated dredge cores are not fully representative of real dredging projects. For instance, no external loads were applied to the core under field conditions. In addition, For the dredging project that will be carried out in a few years, simulated dredging studies are not effective for assessing the recovery of dredged areas under field conditions. Considering the interactions between dredged and undredged areas, it is difficult to understand the environmental benefits and mechanisms of dredging projects through field monitoring alone.

For this study, we selected two different locations (dredged and undredged areas) in Dianchi Pond and compared the N and P contents, N and P ratios, N and P form percentages, and release contributions of the two areas, in order to analyze the effects of dredging on the N and P transport, conversion, and changes in N and P form content, It also describes the process and mechanism of the impact of dredging on the biochemical cycle of lakes, with a view to providing a scientific basis for the mechanism of N and P retention in lake ecosystems and the management of eutrophication.

2. Materials and Methods

2.1. Study Area

Dianchi is located in Kunming City, Yunnan Province, in southwestern China, at an elevation of 1886 m (Figure 1). Dianchi is the sixth-largest freshwater lake in China and the largest freshwater lake in Yunnan Province, with a water area of 306 km^2, an average depth of 4.7 m, and a maximum depth of 9.7 m. The water in Dianchi has a residence time of up to 3.5 years, which promotes the accumulation of nutrients [22]. Based on past investigations of the dredging project in Dianchi Pond, dredged and undredged areas were identified (the dredging site belonged to the area of the second phase of the dredging project in 2005) and, in May 2013, a gravity coring pipe (diameter: 9 cm) device was used to extract the nutrients from the undredged area of the Dianchi Pond Caohai (state-controlled point at Caohai center, 102°38′42.36″ E, 24°58′22.44″ N) and the dredged area (outside the Grass Sea Center, 102°38′42.36″ E, 24°58′22.63″ N). Sediment core samples were collected, sealed in the field, and immediately sent to the laboratory. Sediment cores were cut at 1 cm intervals and 50 cm in length under nitrogen, placed in sterile plastic bags, freeze-dried (at −80 °C for 7 days), ground, and then sieved through a 100-mesh sieve for analysis of N and P content [23].

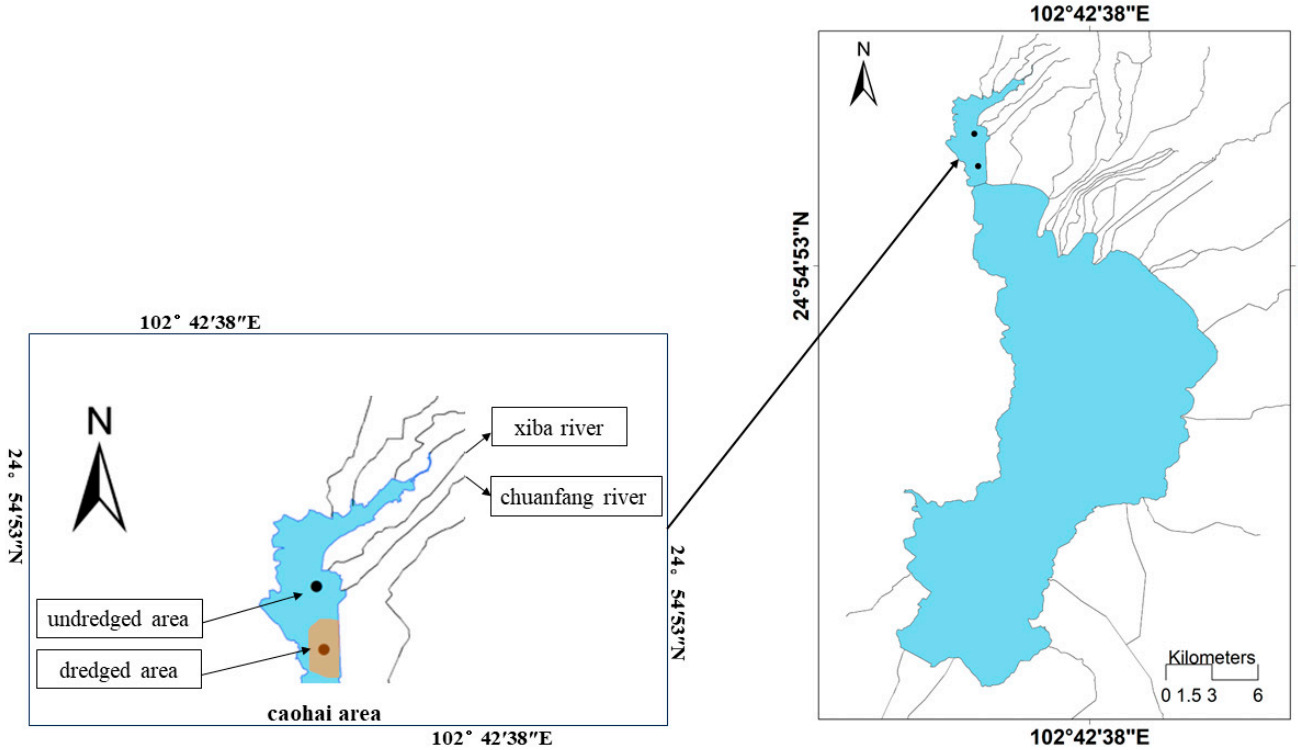

Figure 1. Location of the study area.

2.2. Dredging Project

In order to control the release of internal nutrients in Dianchi Lake and alleviate the eutrophication process, the management of Dianchi Caohai was carried out in 2005 with the implementation of the "Dianchi Caohai Seabed Mud Dredging Continuation Project", which extended to the central part of Caohai Sea and the estuaries of the lower part of the Daguan River, the Shuanfang River, the Xinhe River, the Yungang River, the Wangjiadui Canal, and other rivers that enter the lake, with a total of 191,000 cubic meters of dredged seabed mud and a total of 191 million cubic meters of bottom mud dredged. After a period of continued dredging in Dianchi within the Caohai and Caohai northwestern areas

(4.62 km^2), the water quality was effectively improved. In the Dianchi outside the sea along the north shore and Caohai part of the waters, in order to remove water surface cyanobacteria and water hyacinth, harvesting and disposal were conducted, leading to the total removal of 7,793,500 cubic meters of cyanobacteria algae-rich water and 820,000 tons of water hyacinth.

2.3. Experimental Method

TN in sediments was determined by alkaline potassium persulfate digestion. NH_4^+-N, NO_3^--N, and NO_2^--N were extracted with 0.5 mol/L K_2SO_4 solution, and the solid:liquid ratio was kept at 1:10. The contents of NH_4^+-N, NO_3^--N, and NO_2^--N in the extract were determined by Nano reagent spectrophotometry, ultraviolet spectrophotometry, and diazoazo spectrophotometry, respectively. For details, please refer to the fourth edition of "Methods for Monitoring and Analysis of Water and Wastewater" [24]. NH_4^+-N, NO_3^--N, and NO_2^--N are usually regarded as exchangeable nitrogen (EN). Potential mineralizable organic nitrogen (PMON), which represents a fraction of the organic nitrogen in the sediment, was detected by incubating a 5 g sediment sample at 40 °C for 7 days and then conducting extraction with K_2SO_4 solution [25]. PMON and EN are considered as potentially mobile nitrogen (PMN), and the amount of stable nitrogen (SN) is equal to the amount of TN minus the amount of PMN.

The P-bound form is usually extracted using the sequential extraction method [26]. A 1 g dry sediment sample was placed in a 100 mL centrifuge tube, 50 mL of NH_4Cl solution (1 mol/L) was added, and the phosphorus in the adsorbed form (NH_4Cl-P) was extracted using a thermostatic shaker (25 °C, 200 r·min) for 30 min. The residue from the previous step was added to a BD solution (0.11 mol·L^{-1} $NaHCO_3$-0.11 mol·L^{-1} Sodium dithionite), followed by shaking at 40 °C for 1 h to extract the ferromanganese chelate phosphorus (BD-P). The residue was added to 50 mL of 1 mol/L NaOH at 25 °C for 16 h to extract the ferroaluminum oxidized phosphorus (NaOH-rP), diluted to 25 mL and added to 4 mL of potassium peroxysulfate (0.18 mol/L) to obtain the NaOH-TP, which was extracted by subtracting NaOH-rP from NaOH-rP. NaOH-nrP was obtained by subtracting NaOH-rP. The residue was added to 50 mL of 0.5 mol/L HCl and shaken at 25 °C for 16 h to extract calcium and phosphorus (HCl-P), and the final residue was added to 50 mL of 1 mol/L NaOH to obtain the inert phosphorus (Res-P). The sequential extraction method gave recoveries ranging from 88% to 119%. NH_4Cl-P, BD-P, and NaOH-nrP were defined as mobile phosphorus (MP), whereas NaOH-rP, HCl-P, and Res-P were defined as stabilized phosphorus (SP). TP levels in sediments were measured using standard measurements and tests [27]. The total organic carbon (TOC) content was determined using a total organic carbon analyzer (Shimadzu TOC-L, Tokyo, Japan).

2.4. Release Contribution of N and P

The release contribution equation can be expressed as [28]:

$$\text{Release contribution} = \frac{|C_{surface} - C_{other}|}{\sum_{i=1}^{n} |C_{surface} - C_{other}|} \times 100\%,$$

where $C_{surface}$ indicates the content of N- and P-bound forms in the upper layer of sediment, while C_{other} indicates the concentration of N- and P-bound forms in the other layer of sediment. If the difference between $C_{surface}$ and C_{other} is positive, the material is predominantly released; conversely, the material is predominantly retained.

3. Results

3.1. Basic Properties of Sediment Column Cores in Dredged and Undredged Areas

The basic properties of sediments in the undredged and dredged areas are shown in Figure 2, where TN is in the undredged area, and the distribution of sediment column cores in the dredged area is shown in the figure. The TN concentration in the dredged area showed little change in general and decreased gradually with depth. Meanwhile, the TN concentration in the undredged area presented greater change, with an overall fluctuating upward state. Notably, there was a huge inflection point at 5–8 cm, where the TN concentration increased from 9826 mg/kg at 5–8 cm to 14,879 mg/kg at 12–16 cm. The difference in the TN concentration between the undredged area and the dredged area ranged from 2891 to 9589 mg/kg, and the TN concentration in the undredged area was higher than that in the undredged area as a whole.

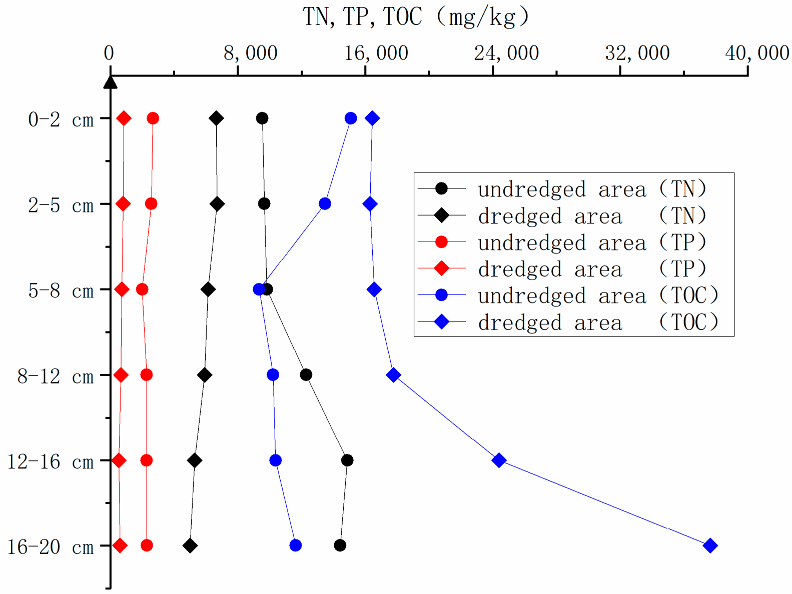

Figure 2. Variation of TN, TP, and TOC content with depth in dredged and undredged areas.

The TP concentration in the dredged area and the distribution of sediment column cores in the undredged area are also shown in Figure 2. The concentration of TP in the undredged area decreased gradually with depth, then suddenly decreased to 1999 mg/kg at 5–8 cm. The concentration of TP at 8–20 cm was relatively stable (the concentration was 2270 ± 20 mg/kg). The concentration of TP in the dredged area decreased gradually with depth at 0–16 cm. Then, the concentration of TP in the range of 16–20 cm inverted and increased to 600 mg/kg. The TP concentrations in the undredged area ranged from 2000 to 2500 mg/kg, while those in the dredged area ranged from 500 to 1000 mg/kg, with an overall difference of about 1500 mg/kg between the two points.

The TOC in the dredged area was relatively stable, fluctuating in the range of 16,300 ± 300 mg/kg, at the depth of 0–12 cm, then increased rapidly to 37,653 mg/kg in the range of 12–20 cm. The TOC content in the undredged area first decreased and then increased with depth, and the inflection point was found in the range of 5–8 cm (9336 mg/kg). The TN and TOC contents were very close (difference of about 5%) at this depth. The TOC content in the dredged area was always higher than that in the undredged area, and the difference between the TOC content at the two points gradually increased with depth.

3.2. Nitrogen and Phosphorus Fate of Column Core Sediments in Dredged and Undredged Areas

The distribution of nitrogen forms in the sediment cores from the undredged and dredged areas is shown in Figure 3. SN accounted for the majority of the nitrogen forms in the two regions (more than 82%), while the NO_2^--N content in the two regions was always very low (close to 0); as such, it is not shown here. The SN in the undredged region increased with depth (mainly divided into two parts: 83% at 0–8 cm and 89% at 8–20 cm), and the proportion of PMON gradually decreased with depth (mainly divided into two parts: 10% at 0–8 cm and 4% at 8–20 cm), and the proportions of NO_3^--N and NH_4^+-N remained stable and low with depth, never exceeding 5%. The proportion of SN in the dredged area as a whole fluctuated with depth, and the change in the proportion was not significant (95–98%). The proportion of PMON increased with depth (83% at

0–8 cm, 89% at 8–20 cm), and the proportion of NO_3^--N increased with depth (89% at 0–8 cm). The percentage of SN in the dredged area fluctuated with depth (85–89%), the percentage of PMON increased with depth (fluctuating at 0–12 cm, increasing at 12–20 cm, accounting for about 12%), the percentage of NH_4^+-N was low and fluctuated with depth, and the percentage of NO_3^--N decreased steadily with depth (almost 0% at 16–20 cm). The difference between the two regions is that the NO_3^--N and NH_4^+-N ratios in the undredged region were significantly higher than those in the dredged region, and the PMON ratio in the dredged region was significantly higher than that in the undredged region(at 12–20 cm).

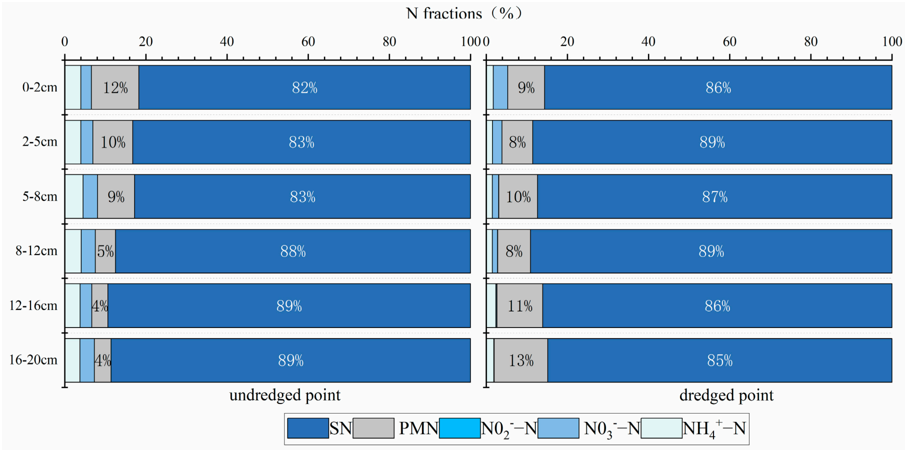

Figure 3. Sediment nitrogen form percentage variation with depth in dredged and undredged areas.

The distribution of phosphorus forms in the column core sediments in the undredged and dredged areas is shown in Figure 4. The percentage of MP fluctuated between 0 and 16 cm, with the percentage of NaOH-nrP in the dredged area being higher than that in the undredged area (21–29% for MP in the dredged area and 11–16% for MP in the undredged area). The percentage of BD-P in the two areas was similar, and the percentage of BD-P in the dredged area rapidly increased to 50% at 16–20 cm. The NH_4Cl-P ratio in the two areas was very low (less than 0.3%), so it is not shown here. SP accounted for most of the phosphorus forms in both regions (more than 65% in SP in both regions, except for the dredged region at 16–20 cm, where the percentage of SP was smaller). The percentage of NaOH-rP was higher in the undredged region than in the dredged region (33–43% in the undredged region and 10–17% in the dredged region), while the percentage of HCl-P was similar in both regions (except for the 16–20 cm dredged area, which was lower at 11%). The percentage of Res-P was slightly higher in the dredged area than in the undredged area (8–10% Res-P in the undredged area and 15–18% Res-P in the dredged area).

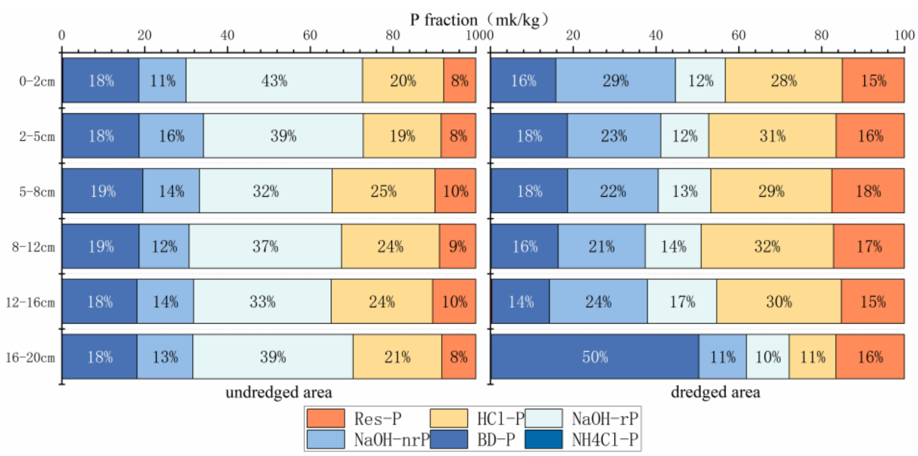

Figure 4. Sediment phosphorus form percentage as a function of depth in dredged and undredged areas.

3.3. Sediment Nutrient Balance Characteristics

Box line plots of nitrogen:phosphorus ratios in the dredged and undredged areas are shown in Figure 5. The mobile nitrogen:phosphorus ratio in the dredged area was higher than that in the undredged area overall (minimum in the dredged area > maximum in the undredged area), the anomalies in the dredged area were higher (up to 2.98 at 12–16 cm), the median value in the undredged area was 0.98, the median value in the dredged area was 1.86, and the range of the IQR in the undredged area was slightly larger than that in the dredged area. The stabilized nitrogen:phosphorus ratio was overall higher in the dredged area than in the undredged area (minimum value of 12.16 in the dredged area and maximum value of 8.60 in the undredged area), the anomalies were higher in the dredged area (up to 18.56 at 16–20 cm), the median value was 6.45 in the undredged area and 12.61 in the dredged area, and the range of the IQR in the undredged area was larger than that in the dredged area. The TN and TP ratios were overall higher in the dredged area than in the undredged area (minimum value of 7.85 in the dredged area and maximum value of 8.86 in the undredged area), whereas the anomalies in the undredged area were close to their median values. The median value was 5.16 in the undredged area and 8.42 in the dredged area, and the range of the IQR was larger in the undredged area than in the dredged area.

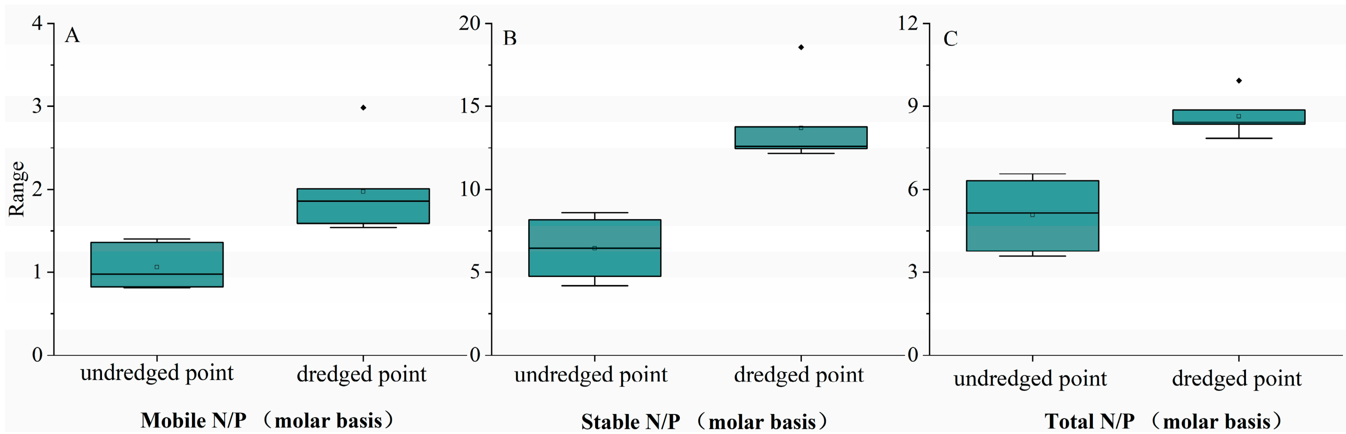

Figure 5. (**A**) Mobile nitrogen:phosphorus ratio in sediment column cores; (**B**) stabilized nitrogen:phosphorus ratio in sediment column cores; and (**C**) total nitrogen:phosphorus ratio in sediment column cores.

In summary, the nitrogen:phosphorus ratios in the dredged areas were higher than those in the undredged areas, and there were higher anomalies in the dredged areas and a larger IQR in the undredged areas. It is known from the previous section that the effect of dredging makes the nitrogen content greater than that of phosphorus, as dredging causes the nitrogen content to increase while the phosphorus content is changed insignificantly. Therefore, the nitrogen:phosphorus ratios are higher in the dredged areas. A high nitrogen:phosphorus ratio leads to the massive growth of aquatic plants, which is the reason why the TOC in dredged areas was higher than that in the undredged areas.

The contributions of N and P release are shown in Table 1. The release contributions of EN and PMON in the undredged site were 60.17% and 39.83%, respectively, with EN accounting for 20% more N release than PMON. The contributions of MP and SP to P release were 22.87% and 77.13%, respectively, and NaOH-rP and HCl-P were the main contributors to P release. The contributions of EN and PMON to N release in the dredged area were 18.46% and 81.54%, respectively, with PMON contributing almost entirely to N release. The contributions of MP and SP to P release were 43.03% and 56.97%, respectively and, unlike in the undredged area, the contributions of BD-P and HCl-P to P were larger, whereas NaOH-rP contributed less.

Table 1. Contributions to N and P release in dredged and undredged areas.

Nitrogen and Phosphorus Form		Release Contribution (%)	
		Undredged Point	**Dredged Point**
N	NH_4^+-N	32.54	14.32
	NO_3^--N	27.58	3.96
	NO_2^--N	0.04	0.18
	PMON	39.83	81.54
P	NH4Cl-P	0.08	0.23
	BD-P	18.59	25.50
	NaOH-rP	34.05	13.09
	NaOH-nrP	14.43	17.31
	HCl-P	23.36	26.65
	Res-P	9.50	17.23

4. Discussion

4.1. Pollution Components of Dredging and Reversion Phenomenon

The considered undredged area was located at the Dianchi state-controlled point Caohai center, closer to the city center, which is strongly affected by human activities and located at a point with a number of rivers near the mouth of the lake (Xiba River and Chuanfang River). In the 1980s, two urban rivers—the Xiba River and Chuanfang River—were constructed. In this time period, with the two rivers flowing through the area, the region was characterized by an expanding scale of urbanization, industrialization, and agricultural production. Urban sewage and industrial wastewater became the main sources of pollution in the Xiba and Chuanfang Rivers, and the inflow of these rivers caused pollution of the lake [28]. The dredged area is far from the inflow of the rivers and, so, is less affected by human activities. Consequently, the N and P concentrations in the undredged area were much higher than those in the dredged area. With the full implementation of governmental governance measures [29] and the improvement of urban management in Kunming, the environmental governance and ecological restoration of the areas around the Xiba and Chuanfang Rivers have gradually strengthened and improved. For example, measures such as sewage treatment and the construction of artificial wetlands have been implemented to reduce the volume of pollutants discharged into Dianchi. Meanwhile, improvements in planning and construction, land use, and agricultural production in the areas surrounding Dianchi have also positively affected the ecological environment of the Xiba and Chuanfang River basins [30]. The N and P concentrations in the undredged area gradually showed a decreasing trend and, so, the surface sediment N and P concentrations in the undredged area were relatively lower than those in the deeper (8–20 cm) area. The TOC concentration in the undredged area showed an inflection point at 5–8 cm, probably due to the fact that exogenous pollution was controlled at a later stage, while the endogenous pollution of lake sediments was greater than the external load [31,32], producing a large amount of organic matter, and cyanobacterial outbreaks have frequently occurred in the undredged area of Dianchi Pond. In recent years, the intensity of cyanobacterial outbreaks has not decreased but, rather, increased somewhat and a large volume of dead algal residues has decayed and been deposited, gradually becoming part of the substrate and contributing to the increased TP, TN, and TOC content of the surface substrate [33].

According to relevant data, the dredging area was in the region subjected to dredging in 2005, while the sampling was conducted in 2013. The control effect on endogenous loads in the initial stage of surface sediment dredging is generally more significant, leading to a greater reduction of the target pollutant content in the lake; however, with the extension of time, both general dredging and precision-dredging techniques may result in a jump in the reduction of the endogenous pollution loads in the lake, followed by reversion of some of the pollutant loads [34]. Due to the reversion of pollutants after dredging, the TN concentration in the dredged area was higher than that in the deeper area of 8–20 cm, while that in the undredged area gradually increased with depth. The TOC content in the dredged area was higher than that in the undredged area, due to the fact that dredging can provide more suitable habitat conditions, inducing the proliferation of aquatic plants and the production of a large amount of organic matter. With the passage of time, the new sediment began to pile up and the habitat conditions gradually declined; thus, the TOC in the dredged area at 12–20 cm decreased with decreasing depth, whereas the TOC content of the surface layer at 0–12 cm reached a new level. The TOC content reached a new stable equilibrium, similar to the previously mentioned phenomenon of contaminated fractions reverting back after dredging. Reddy et al. [35]. have found that removing the top 30 cm of sediment removed about 65% of the sediment storage of TP and, thus, the TP content in the dredged area was lower than that in the undredged area by 1500 mg/kg or so. The total phosphorus concentration in the dredged area decreased gradually with depth at 0–16 cm, while the total phosphorus concentration reversed and increased to 600 mg/kg at 16–20 cm. As such, it can be inferred that the sediment at a depth of 0–16 cm in our dredged area was newly deposited after dredging; this inference will be validated in the following section.

4.2. Mechanisms by Which Dredging Affects Nitrogen and Phosphorus Storage Patterns in Lake Sediments

4.2.1. Mechanism by Which Dredging Affects the Nitrogen Storage Pattern in Lake Sediments

Subsoil dredging has a large impact on the physical, chemical, and biological properties of surface sediments, thus affecting the denitrification process in the sediments. Due to the low water content and low porosity of dredged sediments, the dredged sediments are relatively dense (as opposed to the undredged sediments, which are loose), and it is difficult to recover the physical properties of the dredged sediments in the short term [36]. Furthermore, the dredging activity promotes the oxidation and morphological transformation of nitrogen, causing the nitrogen in the sediments to become oxidized and transformed. Nitrogen oxidation and morphology transformation are promoted by the dredging activity, which leads the nitrogen morphology in the sediments to be more inclined towards the nitrate nitrogen morphology. Figure 3 shows that the proportion of NO_3^--N in the dredged area at 16–20 cm was almost zero, while, with the accumulation of new sediments, the content of NO_3^--N gradually increased, similar to the study of Jing, L.D. et al. [20]. The NH_4^+-N occupancy and release contribution of the dredged area were lower than those in the undredged area, due to the fact that the undredged area was affected by the exogenous pollution of the inlet river, while the dredged area, with less external pollution loads, consistently maintained a low level of the release rate; furthermore, the dredging of the substrate allowed for better control of the release of NH_4^+-N from the sediments.

In the most seriously polluted area of Dianchi Pond, Caohai, the PMON release contribution was higher at both monitoring sites. The influence of human activities on this area cannot be ignored, and the long-term anthropogenic disturbance has led to the massive accumulation of organic matter in the bottom sediment, from which PMON originates. An in-depth study revealed that the contribution of PMON release was higher than 80% in the dredged area and that PMON in nitrogen form was significantly higher in the dredged area than in the undredged area (with the contribution of release being less than 40% in the undredged site), while the EN content in the dredged area was significantly lower than that in the undredged area. These results suggest that dredging not only converted the EN in the sediments to PMON but also disrupted the internal equilibrium of the lake system that had been maintained for many years.

Through the act of dredging, the organic matter in the lake substrate further decomposes, releasing more PMON. This will lead to a sharp increase in the concentration of nitrogen nutrients in the water body, placing a serious burden on the ecosystem. As PMON is in a form that is not easily released, the bioeffectiveness of nitrogen in the water body will be reduced. This directly affects the growth of algae in the lake, which, in turn, will affect the stability of the entire food chain and species diversity. In addition to the contribution of PMON release, dredging also leads to the spillover of other pollutants into the lake water. The release of soluble phosphorus, heavy metals, and other harmful substances will further degrade the water quality of Dianchi Lake, posing a potential threat to aquatic organisms and human health. In order to protect the stability of the Dianchi ecosystem, we should control the input of pollutants into the lake from the source.

4.2.2. Mechanisms by Which Dredging Affects Phosphorus Storage Patterns in Lake Sediments

In lake sediments, large amounts of organic matter and nutrients are sometimes stored in a stable form. Dredging will break this balance, and the SP after dredging is transformed into MP, with the proportion of MP in the dredged area being higher than that in the undredged area by more than 10%; in particular, the proportion of MP at 16–20 cm in the dredged area reached as high as 61% (the proportion of BD-P at this depth). The ratio of various phosphorus forms in the column core of the dredged area at 0–16 cm and the column core of the undredged area at 0–20 cm is relatively stable, which may be due to the specific location of dredging (the TOC and TP in the dredged area at 16–20 cm also presented a large turn). Thus, it can be deduced that the column core of the dredged area at 0–16 cm was the newly accumulated sediment after the dredging project. The contribution of SP release in the undredged area is much larger than that in the dredged area, as the sediments in the undredged area were not disturbed by the dredging project (the phosphorus form would be relatively stable), whereas the undredged area—which is more seriously polluted—had higher organic matter due to the adsorption of N, phosphorus, and other nutrients, resulting in their not being easy to release, thus accumulating a large amount of SP. Dredged areas have a higher contribution of MP than undredged areas, as dredging leads to the degradation of organic matter in the sediment, which reduces the retention of N and P in the sediment and converts part of the SP into mobile phosphorus (MP).

Overall, the N and P form content in the undredged area was higher than that in the dredged area, while the N and P form percentage varied greatly with depth between the two: the SP percentage in the dredged area was lower in the 16–20 cm position, but increased with time, similar to the study of Jing, L.D. et al. As most macrobenthic fauna live in the top 30 cm of the sediment, sediment dredging significantly reduces the diversity and density of benthic organisms. Microbial activity in the dredged area begins to gradually recover as new sediment accumulates, and several studies have shown that benthic disturbance and burrowing processes lead to an increase in the dissolved oxygen penetration capacity of the near-surface sediment at the sediment–water interface [37], which leads to the increase in high-valent Fe–Mn content in the surface sediment, allowing for the sequestration of phosphorus and reducing its release at the sediment–water interface.

According to the data in Figure 4, it can be clearly seen that dredging had a greater impact on the phosphorus storage pattern. This was also true in the study of Liu, C. et al. [38], who found that the control of phosphorus release after dredging was better than that of nitrogen, while the control of nitrogen was maintained longer than that of phosphorus under the influence of external pollution loads. In contrast, both the nitrogen form percentage and the phosphorus form percentage at the undredged sites remained relatively stable with depth changes. It can be seen that dredging disrupts the internal equilibrium that has been established in the lake system over many years, which may be very difficult to re-establish. In addition, disruption of the sediment–water interface has a direct and severe impact on nutrient cycling in the lake system, which may have a dramatic effect on the system. The specific mechanisms of N and P retention are shown in Figure 6.

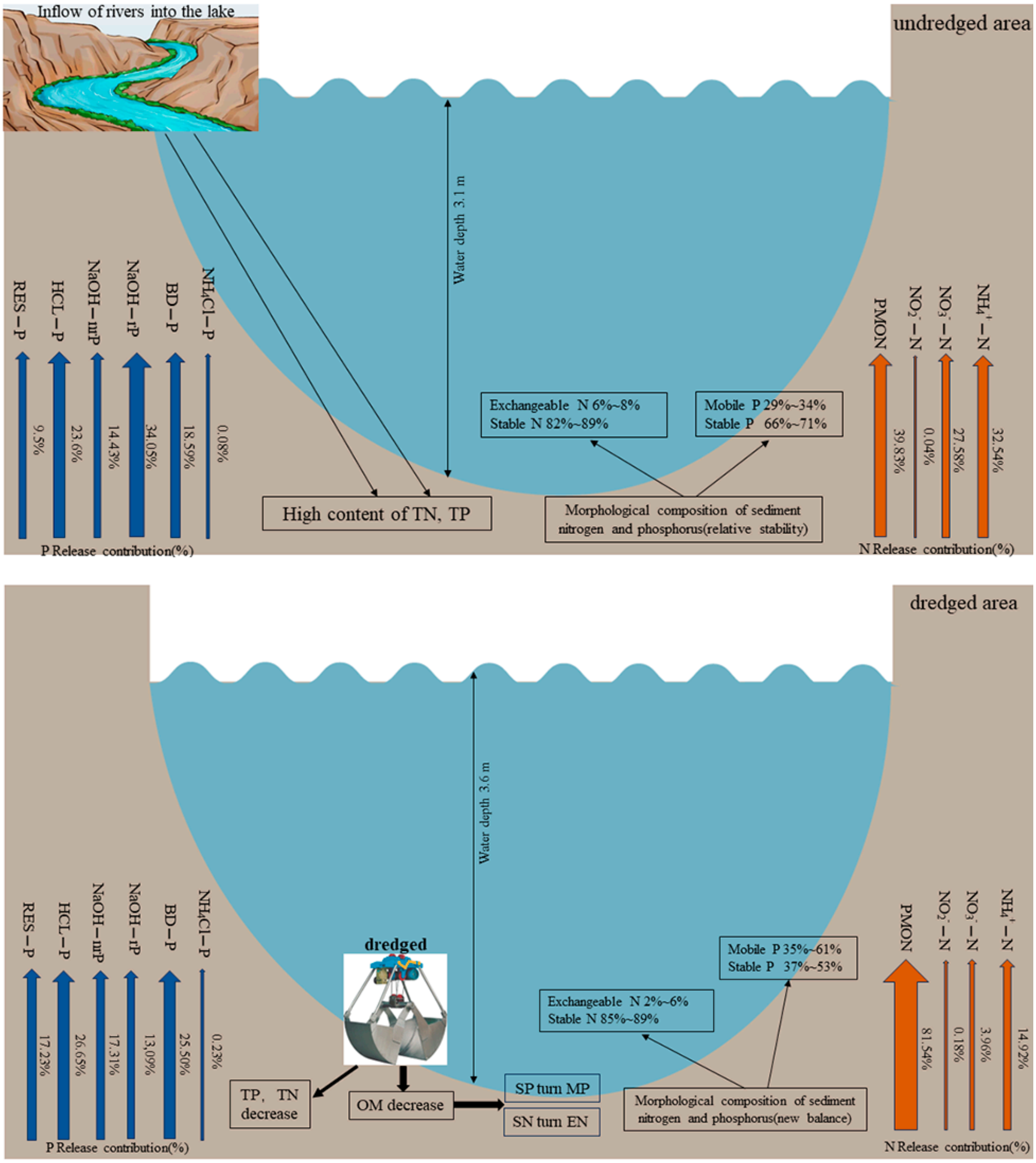

Figure 6. Mechanisms of N and P retention in dredged versus undredged areas. Sections 3.2 and 3.3 describe the relevant data in the figure.

4.3. Impact of Dredging on Lake Ecosystems

Eutrophication is the most common type of lake pollution (Dianchi is a typical eutrophic lake); however, domestic and foreign environmental protection dredging is one of the most important water environment problems to be solved. Part or most of the phosphorus and nitrogen in the lake sediment is usually regarded as the source of phosphorus or nitrogen in the water column: the N and P dissociate into the interstitial water through desorption or biogeochemical transformation, then migrate into the water column through the sediment–water interface. This has an impact on the eutrophication process of the lake [39], and control of N and P pollution through dredging can effectively control and reduce eutrophication of the lake. Dredging removes a large amount of the N, P, and organic matter pollutants deposited at the lake bottom, directly reducing endogenous pollution of the lake. As the effect of bottom dredging on endogenous reduction and water quality improvement is significantly affected by exogenous inputs [40], if the exogenous pollution of the dredged area is better controlled, the newly accumulated N and P pollutants can be maintained at a low level. Controlling N and P pollution in lakes through dredging not only can control endogenous pollution, but also improve water quality. The bottom sediments of lakes are rich in organic matter and nutrients, which are further released into the water column with the spreading of bottom sediments and suspension of mud, leading to water quality deterioration. Dredging can effectively reduce the nutrient and organic matter content of the substrate, thereby slowing the process of water quality deterioration.

Dredging is an effective environmental measure that reduces the accumulation of pollutants and prevents their further release into the water through the removal of sediments from the bottom of a water body. During bottom dredging, with the goal of improving water quality, a series of measures need to be taken to reduce the amount of pollutant accumulation in the sediments and the risk of their release into the water body [41]. The results of this paper indicate that substrate dredging can change the original N and P cycling patterns in sediments. N and P in sediments are usually bound to organic matter to form a complex, which is difficult to dissolve and release into water. Dredging can disrupt this bonding state, allowing some of the N and P to be released from the sediments. In addition, bottom dredging can strip the surface layer of sediments, reducing the extrusion and diffusion of surface sediments into the water column and reducing the release of pollutants at the sediment–water interface [42]. By slowing down the turnover rate of N and P in sediments, substrate dredging can reduce N and P concentrations in water bodies, which is essential for the health and stability of water body ecosystems. High concentrations of N and P can lead to eutrophication in water, triggering excessive algal growth and eutrophic oxidation of the water body, disrupting the ecological balance. As such, the implementation of substrate dredging can effectively control the supply of N and P, reduce the occurrence of eutrophication, and protect the ecological integrity of water bodies.

In conclusion, environmental protection through dredging for the purpose of improving water quality allows for a reduction of the amount of pollutants in the sediment and the release of pollutants at the sediment–water interface. Substrate dredging changes the N and P cycling pattern in the sediment and slows down the turnover rate of N and P, thus helping to reduce the N and P concentration in the water body, improve the water quality, and protect the health of the water ecosystem.

5. Conclusions

Based on the findings of this paper, several main conclusions were drawn:

1. Dredging disrupts the internal balance in the lake system for many years, having the greatest impact on the BD-P balance in the sediments, which greatly affects nutrient cycling in the lake system and effectively reduces the nitrogen and phosphorus content of the sediments. However, over time, the distribution of nitrogen and phosphorus forms in the newly accumulated sediments will reach a new equilibrium, and nitrogen and phosphorus pollution can rise back to predredging levels.

2. Dredging affects nitrogen and phosphorus retention. Nitrogen and phosphorus are mainly found in sediments through adsorption and precipitation, whereas, after dredging, nitrogen and phosphorus reach downstream water bodies mainly through diffusion and convective transport. The retention efficiency of nitrogen and phosphorus in the sediments was found to change significantly, where stable nitrogen and phosphorus forms were released and transformed into unstable nitrogen and phosphorus forms.

3. The column cores at 0–16 cm in the dredged area may be newly deposited sediments following the dredging project.

Author Contributions: Software, Z.S. and Y.L.; Validation, D.S.; Formal analysis, Y.Y. and M.C.; Investigation, Z.W. and Z.C.; Writing—original draft, M.L.; Writing—review and editing, J.W.; Visualization, J.L.; Funding acquisition, L.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Yunnan Provincial Department of Science and Technology Major Science and Technology Special Program (202302AE090012), Key Laboratory Project of Pollution Process and Governance of Plateau Lake Basin in Yunnan Province (2021004), National Major Science and Technology Program for Water Pollution Control and Treatment (No. 2012ZX07102004).

Data Availability Statement: Data available on request due to privacy or ethical restrictions. The data presented in this study are available on request from the corresponding author.

Acknowledgments: We sincerely thank our colleagues at Yunnan Agricultural University and the Chinese Research Academy of Environmental Sciences for their support and assistance. We are very grateful to the anonymous reviewers for their valuable comments and efforts to improve this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

N	Nitrogen
TN	Total nitrogen
EN	Exchangable nitrogen
SN	Stabilized nitrogen
PMN	Potentially mobile nitrogen
PMON	Potential mineralizable organic nitrogen
P	Phosphorus
TP	Total phosphorus
MP	Mobile phosphorus
SP	Stabilized phosphorus
TOC	Total organic carbon

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