water

MDPI

Article

Effects of Ecological Water Diversion on Internal Nitrogen and Phosphorus Release in a Typical Small Shallow Lake in China

Huaizhi Chen [1,2], Yunben Li [2,3], Anjie Wu [2,4], Yadong Wang [2], Yanping Zhao [1], Guoxiang Wang [1], Chao Han [2] and Qiushi Shen [2,*]

1 School of Environment, Nanjing Normal University, Nanjing 210023, China; 212545006@njnu.edu.cn (H.C.)
2 Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
3 CEWUD Group Company Ltd., Wuhan 430205, China
4 Central & Southern China Municipal Engineering Design and Research Institute Co., Ltd., Wuhan 430010, China
* Correspondence: qsshen@niglas.ac.cn

Abstract: Ecological water diversion is an important method to improve water quality in lakes and reservoirs. But the environmental effects, from the ecological water diversion project (EWDP) to the internal release of sediment nutrients, remain unclear. In this study, an indoor simulation of an EWDP with different treatment scenarios with water transfer proportions of 25%, 50%, 75% and 100% was conducted to study the effects of water diversion on sediment nitrogen and phosphorus release in Lake Wanshandang. Our results showed that the flux of NH_3–N released from the sediments in the western and eastern areas of Lake Wanshandang was significantly reduced after water transfer treatment, and the degree of reduction increased with increased water transfer. Specifically, the release flux of NH_3–N in the sediment in the western area decreased from 18.02 mg/(m^2/d) to −2.25 mg/(m^2/d) when the transferred water reached 100% replacement of the original overlying water. The effect of water transfer treatment on the release flux of SRP from sediment varied greatly throughout the lake. After treatment, the SRP release flux in the western and central areas increased significantly, while it decreased in the eastern area. The NH_3–N and SRP concentrations changed from 0.12–0.27 mg/L and 0.02–0.049 mg/L to 0.28–0.84 mg/L and 0.01–0.066 mg/L before and after the water transfer treatment. Our statistical analysis showed that the change in NH_3–N and SRP release fluxes after treatment was significantly negatively correlated ($p < 0.05$) with concentrations of NH_3–N or SRP in the overlying water before and after water transfer. We suggest the increase in NH_3–N and SRP concentrations in the overlying water after the water transfer treatment led to the subsequent decreased NH_3–N or SRP release flux, while the decrease in SRP concentration in overlying waters enhanced SRP release from the sediment. The differences in the concentrations of nitrogen and phosphorus between the original overlying water and the transferred incoming water are important factors affecting the release of nutrients from sediment.

Keywords: ecological water diversion; sediment; nutrients; internal release

Citation: Chen, H.; Li, Y.; Wu, A.; Wang, Y.; Zhao, Y.; Wang, G.; Han, C.; Shen, Q. Effects of Ecological Water Diversion on Internal Nitrogen and Phosphorus Release in a Typical Small Shallow Lake in China. *Water* **2024**, *16*, 1065. https://doi.org/10.3390/w16071065

Academic Editors: Bommanna Krishnappan and Cesar Andrade

Received: 26 February 2024
Revised: 3 April 2024
Accepted: 5 April 2024
Published: 7 April 2024

1. Introduction

Eutrophication and water quality degradation are major environmental problems facing freshwater lakes globally [1]. In recent years, engineering-based measures to improve lake water quality, such as ecological water diversion projects (EWDPs), have been widely used in the treatment of eutrophic lakes [2–4]. In China, the first inter-basin water diversion project, Yinluaninto Tianjin, effectively improved and maintained better water quality in the Yuqiao Reservoir, thus stopping the long-term issue of more than 700,000 people drinking high-fluoride water [5,6]. An EWDP effectively reduced water pollution in some areas of Lake Taihu, mitigating the effects of a cyanobacteria outbreak in 2007 and improving water quality indicators, such as dissolved oxygen (DO) and ammonia nitrogen (NH_3–N), in the Gonghu Water Plant from lower than Class V to Class III [7,8]. In the United

States, the introduction of Mississippi River water into Lake Pontchartrain reduced the total nitrogen (TN) concentration by 26–30% and the total phosphorus (TP) concentration by 50–59% [9]. In addition, there are other examples of EWDPs globally, such as Lake Da water being introduced into Lake Qin [10], Dathuang [11] and Niulanshan–Dianchi water supplies (China) [12]; Lake Veluwe (Netherlands) [13]; and Lake Tega (Japan) [14]. These EWDPs typically improve water quality conditions in the receiving water body, enhance mobility/overturning, shorten the water displacement cycle and help meet residential needs for safe water.

However, while studies have shown EWDPs can replenish water quantity or improve water quality in the short term, they do not completely solve water pollution problems in lakes [15]. The effects of EWDPs in eutrophicated lakes are easily affected by natural factors, such as lake area, wind direction and flow [16,17]. For small lakes (<50 km^2, e.g., Lake Moses), which are less disturbed by the surrounding environment, TP and chlorophyll-*a* tend to decrease by more than 70% after ecological water diversion, with significant improvements in water quality [2]. However, for large shallow lakes (e.g., Lake Taihu), water quality improvements are less significant because of influences from the scale of water diversion and complex boundary conditions [18]. Ecological water diversion invariably changes nutrient concentrations in the overlying water and will therefore have an impact on sediment nutrient accumulation, transfer and diffusion. The results of one study investigating changes in TP in Jidai and Taihu Lakes showed that ecological water diversion did not show strong correlations with the rebounding TP concentrations in 2016, but longer-term, high-volume water diversion affects the equilibrium between sediment accumulation and the release of nutrients, such as nitrogen (N) and phosphorus (P) [19]. Another study of six small- and medium-sized reservoirs in Zhuhai (China) found that the P concentrations in reservoir sediments tended to increase when more highly polluted rivers were used to divert water into the reservoir [20]. Within a lake environment, particularly eutrophic shallow lakes, sediments are an important place for the transfer and transformation of major pollutants as well as an important internal source and sink of N and P nutrients [21,22]. Thus, large inputs of additional N and P nutrients affect the nutrient concentrations in overlying waters and the internal nutrient load of sediments; this has the potential to disrupt the dynamic balance of nutrients between sediments and overlying water [23], causing changes in the transfer of nutrients between sediments and overlying water. In the medium and long term, the continuous input of incoming water with different water quality affects the existing transfer and transformation state of N and P nutrients in these sediments. However, there are only a few studies investigating how EWDPs affect the release, transfer and transformation of internal nutrients in lake sediments.

Considering the significance of ecological water diversion projects, the effects of diversion projects on sediment nutrients release in terminal lakes are of great importance, which have not been well studied yet. Nowadays, in China, local governments and construction units are increasingly implementing ecological water diversion projects to deal with ecological problems such as eutrophication in lakes and reservoirs [3,5–8]. These projects have enhanced the water quality and lessened the degradation of the water environment of lakes [5–8] but have also raised new potential problems including disruption to the original physical and chemical balance of lake water, affecting various geochemical cycles of important nutrients. Moreover, most of the lakes involved in these projects are eutrophic and shallow, which often face internal pollution from nitrogen and phosphorus nutrients. A reasonable hypothesis is that water diversion projects are expected to influence the natural transfer and transformation patterns of internal nutrients across the sediment–water interface in lakes. However, it is still unclear to what extent and in which way water diversion can affect internal release. To our knowledge, there are still no relevant studies to answer these questions to date.

This study was based on the Yangtze–Taihu Water Diversion, a large-scale ecological water diversion project (EWDP) involving the Wangyu River and small lakes located to the west of its west bank. The effects of Wangyu River water diversion on internal N and P nutrient release from Lake Wanshandang sediments were studied, and a causal relationship between internal nutrient release from shallow lake sediments and ecological water diversion was suggested. This study provides a theoretical basis for the control and management of internal pollution in sediments underlying water bodies at the receiving end of EWDPs.

2. Materials and Methods

2.1. Sample Area and Collection

Lake Wanshandang (31°34′–31°36′ N, 120°29′–120°33′ E) is located within the dense water network of Taihu Plain in the Yangtze River Delta. The total lake area is about 1.68 km^2, with an average water depth of about 2.1 m; it is a typical small, shallow lake on the outskirts of a city (Wuxi, Jiangsu Province, China). The Wanshandang region is located in the subtropical humid climate zone, with an annual average temperature of 14–22 °C and annual average precipitation of 1052.8 mm. Lake Wanshandang is long and narrow with upstream areas receiving incoming water from the Wuxi Jiuli River and other urban rivers and downstream effluent flowing into the Wangyu River through Jialingtang and finally into Gonghu Bay (Lake Taihu). Due to the influence of industrial wastewater in upstream areas, urban sewage and agricultural non-point source pollution, the water quality in Lake Wanshandang has deteriorated annually and has not reached a satisfactory surface water standard in the past three years; the main pollution factors are NH_3–N and TP. In addition, there are many tributaries that flow into Lake Wanshandang, and these have poor water quality. Pollution then flows into the Wangyu River via Lake Wanshandang, and then into Lake Taihu, threatening its drinking water safety and ecological security. In response, the local government has initiated the Xishan '263' Water Control Project, which includes constructing a gate and a dam at the east entrance of Lake Wanshandang. Subsequently, water from the Wangyu River is pumped into Lake Wanshandang using high-power water pumps, creating a flow from the southeast to the northwest in the lake. This project aims to enhance the water quality in the lake.

In this study, three sediment sampling sites (WSD1, WSD2 and WSD3) were set up in the west, central and east areas of Lake Wanshandang for sediment and water sampling, respectively (Figure 1). In situ sediment cores and overlying water samples were collected for the incubation experiment at each sampling site in March 2020. And another water sampling site was set up in Wangyu River for the collection of the overlying water used for water transfer. All the sampling sites were set up under the consideration of the hydrodynamic conditions, the area and the shape, as well as the inflows and the outflows of the lake. A gravity corer (50 cm length, internal Ø 8.4 cm) was used to collect sediment cores (depth greater than 20 cm) during sediment sampling. The sampling process ensured a visibly undisturbed sediment–water interface. In total, 15 sediment column samples were collected at each sampling site. Furthermore, a plexiglass water collector (1 L) was used to collect in situ water samples at the depth of 20 cm under the surface of each sampling site in Lake Wanshandang and Wangyu River. In total, 15 × 20 L in situ overlying water samples were collected at each sampling site at Lake Wanshandang, and an additional water sampling site in Wangyu River recovered 40 L of in situ overlying water. All collected water samples were packed in 25 L polyethylene buckets. Water subsamples were placed into 50 mL polypropylene bottles for the analysis of TN and TP; further subsamples (50 mL) were filtered through disposable filter heads (aperture 0.45 μm, Ø 2.5 cm) at the sampling site and placed into 50 mL polypropylene bottles for the analysis of total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), NH_3–N and soluble reactive phosphorus (SRP). Three parallel samples were set up over each sampling site and refrigerated in an incubator at −4 °C. All water and sediment samples were immediately transported back to the State Key Laboratory of Lakes and Environment, Nanjing Institute of Geography and Limnology (Chinese Academy of Sciences), for analysis and simulation experiments.

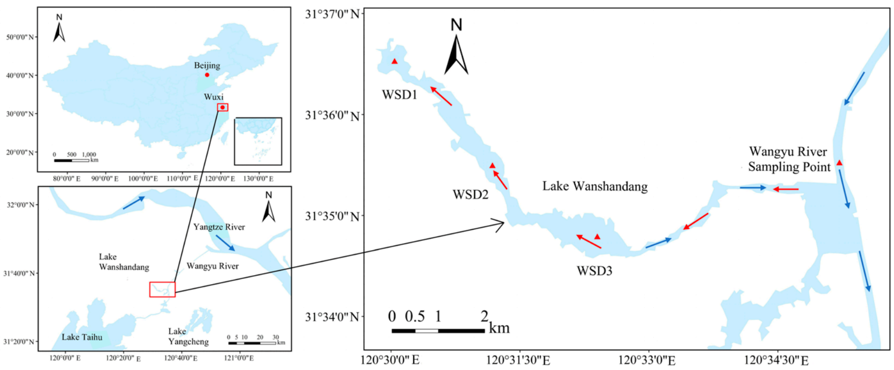

Figure 1. Sampling sites in Lake Wanshandang and Wangyu River (the red dots represent cities and the red triangles represent sampling sites; the blue arrows represent the natural flow direction of rivers and channels and the red arrows represent the flow direction of water diversion).

2.2. Experimental Design

To better study the release of N and P nutrients from Lake Wanshandang sediments under different water transfer conditions from Wangyu River, a total of five sediment internal release simulation experiments were set up; there was one control (CK) group where the replacement volume of water was 0% and four different water transfer treatment groups with three parallel experiments set up for each treatment group. The four different water transfer treatment groups were T1 (25% replacement volume); T2 (50% replacement volume); T3 (75% replacement volume); T4 (100% replacement volume). All water samples for the water transfer experiment were filtered by using a nylon sieve (−400 mesh) to remove large particles and algae. This kind of filtered water was used for the replacement water. In this study, the focus was on the static release of N and P from sediments [24].

First, in situ sediment was placed in the incubating column (50 cm length, internal Ø 8.4 cm), and the sediment depth was set at 20 cm. Then, the above-mentioned filtered water was carefully introduced with small drops at the very beginning, and then with a very small flow along the column wall into the corresponding incubating column by a siphon in order to keep the sediment–water interface undisturbed throughout. During the experiment, the height of the water column in the culture column was maintained at 20 cm. The ambient temperature of sediment release was set at room temperature, which was consistent with the average temperature at Lake Wanshandang and the experimental season. The incubation was conducted indoors under dark conditions to prevent influence from light. During the incubation, all sediment columns were maintained in open-mouth static conditions. Dissolved oxygen was measured 5 cm below the water surface with a portable dissolved oxygen meter. During the experiment period, the water column was kept oxic with a DO > 5 mg/L. During the experiment, 50 mL of water from each culture column was collected at 0, 12 h, 24 h, 36 h, 48 h, 60 h and 72 h after release; these were then filtered through 0.45 µm acetate fiber filters and frozen at −8 °C. After all samples were collected, NH_3–N and SRP concentrations were analyzed.

After each sampling process, 50 mL of the filtered water samples from the original sampling site and the filtered water samples with different water replacement volumes were added into each corresponding culture column to maintain the integrity and stability of the simulation system. The calculation of sediment release flux is shown in Formula (1) [25].

$$r = \left[V(C_n - C_0) + \sum_{n=1}^{n} V_{i-1}(C_{i-1} - C_0)\right] / A \cdot t \tag{1}$$

where r is the release flux [mg(m^2·d)]; V is the volume (L) of overlying water in the column; C_n, C_0 and C_{j-1} are concentrations (mg/L) of a substance at the initial and $j-1$ sampling steps, respectively; V_{j-1} is the $j-1$ sampling volume (L); A is the contact area between water and sediment in the sample (m^2); t is the release time (d).

2.3. Analysis and Detection

2.3.1. Water Body Physical Parameters

In this study, while collecting samples, a multi-parameter water quality analyzer (Horiba U 50) was used to monitor the basic physical indicators, including DO, pH, redox potential (ORP), electrical conductivity (EC), total dissolved solids (TDS), turbidity and salinity, of the water at each sampling site.

2.3.2. Water Body Chemical Parameters

Chemical measurements made in this study included TN, TDN, TP, TDP, NH_3–N and SRP. TN and TDN were determined by alkaline potassium persulfate digestion and ultraviolet spectrophotometry. TP and TDP were determined by potassium persulfate digestion and molybdenum–antimony resistance spectrophotometry. NH_3–N was determined by Nessler reagent colorimetry and SRP was determined by molybdenum–antimony resistance spectrophotometry. The spectrophotometer used was a UV–visible spectrophotometer (UV-2750, Shimadzu, Japan), and all analyses were carried out with reference to corresponding water and wastewater monitoring methods [26].

2.3.3. Data Processing and Statistical Analysis

In this study, all graphs and statistical analyses were created and conducted by using OriginPro 2022 (OriginLab Corporation, Northampton, MA, USA). Pearson correlation analysis was employed to test the relation between the fluxes of NH_3–N and SRP changes before and after the water transfer treatment and the release flux of internal NH_3–N and SRP. One-factor analysis of variance (ANOVA) was employed to analyze the difference in TN, TDN, TP, TDP, NH_3–N and SRP in the original water samples of Lake Wanshandang and Wangyu River as well as the release fluxes of NH_3–N and SRP nutrients at each sediment sampling site. Paired Comparison Plot APP in OriginPro 2022 was employed for post hoc multiple comparison tests for parameters with significant differences after the ANOVA to analyze differences in tested factors among different treatments or sampling sites.

3. Results

3.1. Basic Physicochemical Characteristics of Water Bodies

The basic physical properties of the water at the sampling sites in Lake Wanshandang and Wangyu River are shown in Table 1. The monitoring results showed that the DO at each sampling site was sufficient to support an aerobic state. The pH showed spatial variations, where pH was higher in the northwestern lake area and lower in the eastern lake area and Wangyu River. Spatial differences in ORP in Lake Wanshandang were small, but the redox conditions were relatively poor. The ORP of Wangyu River was obviously higher, and it showed a weak oxidation state. The EC, TDS and turbidity of Lake Wanshandang showed a decreasing trend from northwest to southeast. The turbidity in Wangyu River was similar to that in the middle area of Lake Wanshandang, which was significantly higher than that in the eastern area of Lake Wanshandang. Meanwhile, compared with Lake Wanshandang, the pH, EC and TDS in Wangyu River were lower.

Table 1. Basic physical parameters of Lake Wanshandang and Wangyu River.

Sampling Site	DO (mg/L)	pH	ORP (mV)	EC (mS/cm)	TDS (g/L)	Turbidity (NTU)	Salinity (%)
WSD1	11.23	8.35	73	0.397	0.243	36.6	0.02
WSD2	13.32	8.22	79	0.341	0.207	31.4	0.02
WSD3	10.54	7.62	81	0.284	0.171	17.8	0.01
Wangyu River	12.45	6.94	285	0.257	0.167	31.1	0.01

The concentrations of N and P nutrients in the waters of Lake Wanshandang and Wangyu River are shown in Figure 2. The concentrations of TN and TDN in Lake Wanshandang were 1.51–2.19 mg/L and 1.40–1.95 mg/L, respectively, whereas the TN and

TDN concentrations in Wangyu River were higher (2.54 mgL and 2.42 mgL, respectively). The TN of WSD1 was in the state of Class V, while the TN of WSD2, WSD3 and Wangyu River were lower than Class V, which indicated a poor state (Table S1) [27]. In the overlying waters across all sites, N was mainly dissolved (89.04–93.69% in Lake Wanshandang, 95.28% in Wangyu River). The distributions of TP and TDP in Lake Wanshandang were relatively uniform, with TP concentrations ranging from 0.13 to 0.14 mg/L and TDP concentrations ranging from 0.06 to 0.07 mg/L. However, concentrations of TP and TDP in Wangyu River were lower (0.07 mgL and 0.05 mgL, respectively). Despite this, the TP of Lake Wanshandang was in the state of Class V, while the TP of Wangyu River was in the state of Class II (Table S1) [27]. The proportion of dissolved P in Lake Wanshandang was 42.86–53.85%, accounting for about half of TP, while the proportion of dissolved P in Wangyu River was higher (71.43%). The NH_3–N concentrations in Lake Wanshandang and Wangyu River were 0.12–0.27 mg/L and 0.28 mg/L, respectively. The NH_3–N concentration at WSD2 was closer to the Wangyu River value. The NH_3–N of WSD2, WSD3 and Wangyu River were in the state of Class II, while the NH_3–N of WSD1 was in the state of Class I (Table S1) [27]. The SRP concentration in Lake Wanshandang was 0.020–0.049 mg/L, and that in Wangyu River was 0.037 mg/L. Specifically, the SRP concentrations at WSD1 and WSD2 were higher than that in the Wangyu River, while the SRP concentration at WSD3 was lower.

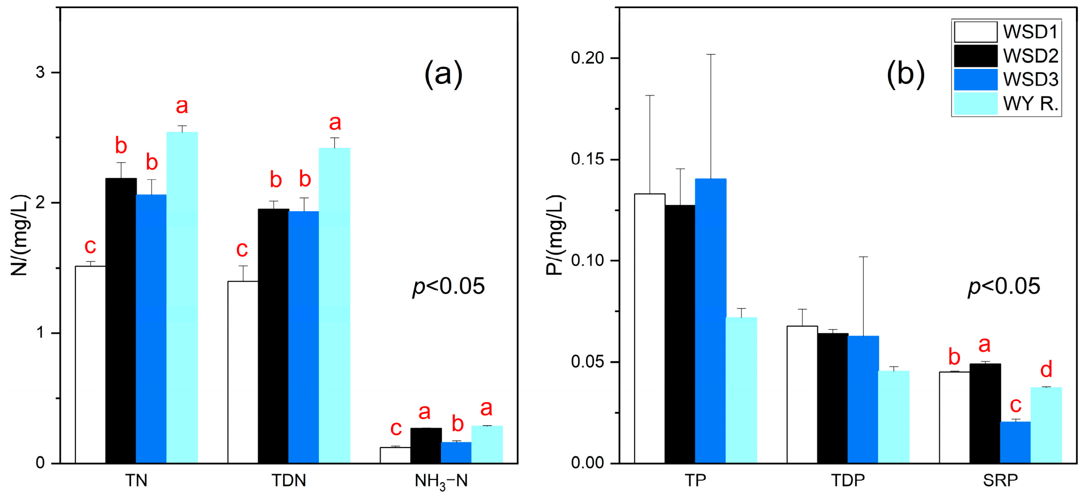

Figure 2. Characteristics of nitrogen and phosphorus nutrient concentrations in Lake Wanshandang and Wangyu River water ((**a**) shows the concentrations of TN, TDN, and NH_3–N, and (**b**) shows the concentrations of TP, TDP, and SRP. Different letters indicate whether there are significant differences in nutrient levels among different sites).

The analysis results (Figure 2) showed that there are significant differences in TN, TDN and NH_3–N between Wangyu River and Lake Wanshandang. The concentrations of the above indicators in Wangyu River were significantly ($p < 0.05$) higher than those in Lake Wanshandang. The SRP concentration in Wangyu River was significantly higher than that in the eastern area of Lake Wanshandang ($p < 0.05$), but also significantly lower than that in the western area of Lake Wanshandang ($p < 0.05$). However, there were no significant differences in TP and TDP concentrations in the two water bodies ($p > 0.05$).

3.2. Static Release

The internal N and P release characteristics of Lake Wanshandang sediments after different water transfer treatments are shown in Figure 3. The NH_3–N and SRP concentrations changed from 0.12–0.27 mg/L and 0.02–0.049 mg/L to 0.28–0.84 mg/L and 0.01–0.066 mg/L before and after the water transfer treatment (Figure 2). With increasing proportions of water transference from Wangyu River, the release flux of sediment NH_3–N gradually decreased. After water transfer treatment, the NH_3–N release flux at WSD1 gradually decreased from 18.02 mg(m^2·d) (T1 treatment) to −2.25 mg(m^2·d) (T4 treatment). Meanwhile, the water transfer treatment at WSD2 had little effect on the NH_3–N release flux, with fluxes ranging from 14.43 mg/(m^2·d) to 18.37 mg/(m^2·d). Similar to WSD1, the NH_3–N release flux at WSD3 decreased from 17.83 mg(m^2·d) (T1 treatment) to 8.02 mg(m^2·d) (T4 treatment). For WSD1, when the proportion of replaced water increased from 25% to 100%, the changing rate of NH_3–N release flux decreased from −48.34% (T1 treatment) to −112.49% (T4 treatment). Similarly, it decreased from −-13.47% (T1 treatment) to −55% (T4 treatment) at WSD3.

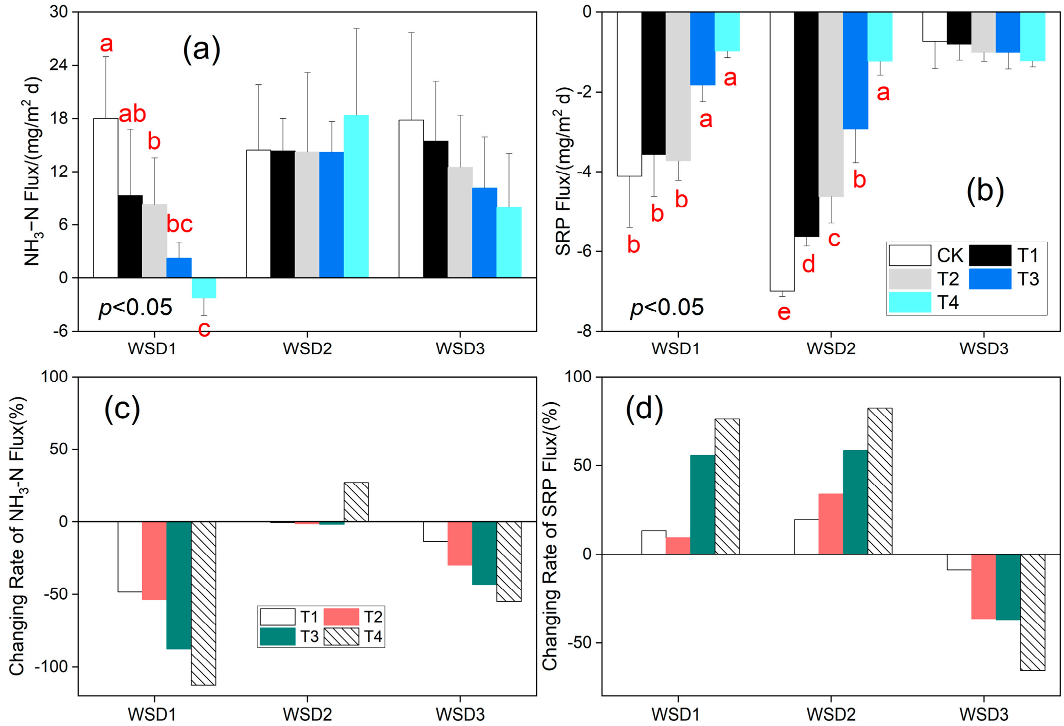

Figure 3. Characteristics of internal nitrogen and phosphorus release from Lake Wanshandang sediment after four different water transfer treatments. CK = 0% water transfer replacement; T1 = 25% water transfer replacement; T2 = 50% water transfer replacement; T3 = 75% water transfer replacement; T4 = 100% water transfer replacement (positive values in (**a**,**b**) represent the direction of the release flux as an upward release from the sediment to the overlying water, and negative values represent the direction of the release flux as a downward diffusion from the overlying water to the sediment. The changing rate of flux in the *y*-axis in (**c**,**d**) is the increase or decrease percentage in the release flux of NH_3–N and SRP after water transfer treatment compared to the release flux of NH_3–N and SRP from CK. Different letters indicate whether there are significant differences in nutrient levels among different sites).

With an increase in water transfer proportions, the release of sediment SRP at WSD1 and WSD2 gradually increased. After water transfer treatment, the SRP release flux at WSD1 gradually increased from −4.11 mg(m^2·d) to −0.98 mg(m^2·d). Similarly, the SRP release flux at WSD2 gradually increased from −7.00 mg(m^2·d) to −1.23 mg(m^2·d), showing a more pronounced increase. However, the release flux of SRP at WSD3 showed a gradually decreasing trend as a whole, from −0.74 mg (m^2·d) to −1.22 mg (m^2·d). The changing rate of SRP release flux from the sediments at each site in Lake Wanshandang also varied with the increasing proportion of water transfer. After water transfer treatment, the changing rate of SRP release flux from WSD1 and WSD2 sediments showed a gradual increase with increased water transfer, with an opposite trend for WSD3 sediments. The change in SRP release at WSD1 gradually increased from 13.26% (T1 treatment) to 76.23% (T4 treatment). Similarly, it increased from 19.62% (T1 treatment) to 82.43% (T4 treatment) at WSD2;

this was in contrast to WSD3 sediments, where it gradually decreased from −8.79% (T1 treatment) to −65.67% (T4 treatment) at WSD3.

After the water transfer treatment, an increase in the volume of water transfer resulted in a noticeable decrease in the NH_3–N release flux in the sediments of both the western and eastern areas of Lake Wanshandang. The reduction in NH_3–N release flux was particularly pronounced in the western area of Lake Wanshandang. Notably, when the water transfer volume exceeded 50%, the release flux was significantly lower compared to the CK ($p < 0.05$). On the contrary, after the water transfer treatment, an increase in the water transfer volume led to a clear rise in the SRP release flux in the sediments of the western and central parts of Lake Wanshandang. Specifically, when the water transfer volume exceeded 50% and 25%, the sediment SRP release flux was significantly higher than that of the CK at WSD1 and WSD2 ($p < 0.05$) (Figure 3a,b).

4. Discussion

A large number of studies have shown that in eutrophic shallow lakes, the release of internal N and P from sediments is an important factor leading to high concentrations of N and P in overlying waters and affecting eutrophication status [28,29]. The average contents of sediment TN and TP of Lake Wanshandang reached 2129 mg/kg and 2456 mg/kg, respectively, indicating relatively highly polluted water [30]. A previous study conducted by Yunben Li [30] found that the release potential of internal dissolved N and P nutrients in Lake Wanshandang sediments was high but that release fluxes of NH_3–N and SRP were minimal in spring. This study found relatively lower P release flux compared with previous research [30], but the N release flux was still higher than most lakes. After water transfer treatment, the release of NH_3–N and SRP from Lake Wanshandang sediments obviously changed, with different sediment characteristics across the sampling sites. Results regarding the static release of N and P before and after water transfer showed that the NH_3–N concentration ratio ($[NH_3–N]_{mixed}$: $[NH_3–N]_{original}$, where mixed represents after water transfer) was significantly negatively correlated with NH_3–N release flux and flux changing rate ($r = -0.95$, $p < 0.01$; $r = -0.99$, $p < 0.01$; Figure 4). This indicated that increasing NH_3–N concentrations in overlying waters after water transfer resulted in a decrease in the internal NH_3–N release flux and the release potential of sediments and, specifically, the greater the increase in NH_3–N concentrations in overlying waters, the greater the decrease in the release flux. Before water transfer ($[NH_3–N]_{mixed}$:$[NH_3–N]_{original}$ was 1.0), sediment NH_3–N throughout the study area was in a state of release from the sediment to the overlying water. Since NH_3–N concentrations in the Wangyu River were higher than in Lake Wanshandang, following the water transfer experiment, NH_3–N concentrations in the overlying water increased because of introduced water from Wangyu River. This then affected the original dynamic release balance of NH_3–N and reduced the release flux of NH_3–N from the sediment. The results of this study showed that the differences in original NH_3–N concentrations in the overlying waters of the Wangyu River and Lake Wanshandang sampling sites were WSD1 > WSD3 > WSD2 (Figure 2c). Specifically, ($[NH_3–N]_{mixed}$:$[NH_3–N]_{original}$) at WSD1 represented the maximum (1.55–2.36), while ($[NH_3–N]_{mixed}$:$[NH_3–N]_{original}$) at WSD2 represented the minimum (1.01–1.06) after water transfer. With an increase in water transfer proportions, the release flux and flux changing rate of sediment NH_3–N decreased most obviously at WSD1, while those did not decrease significantly at WSD2 (Figure 3a,c). Ion diffusion is one important pathway for the release of dissolved NH_3–N from sediments to overlying water [31,32], and the NH_3–N concentration difference between sediments and overlying water is the main driving force for this diffusion [33]. The results of this study confirmed that the transfer of water from Wangyu River increased the NH_3–N concentrations in the overlying water of Lake Wanshandang, and this process reduced the concentration difference of NH_3–N between the sediment and overlying water. Thus, this reduced the static release capacity of NH_3–N in Lake Wanshandang sediments.

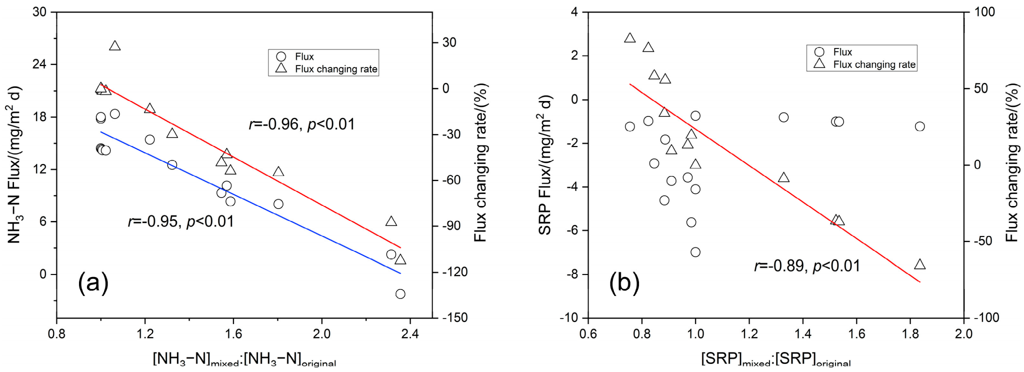

Figure 4. Release flux and flux changing rates of (**a**) NH_3–N and (**b**) SRP in relation to the corresponding N or P concentration ratios before and after water transfer.

The water transfer treatment also significantly changed the release of P from sediments. After water transfer treatment, the internal SRP release flux of sediments at WSD1 and WSD2 increased significantly, while the internal SRP release flux of sediments at WSD3 decreased significantly (Figure 3b). In contrast to NH_3–N, no statistically significant correlation was found between the release flux of the sediment SRP and SRP concentration ratio in overlying water before and after water transfer ($[SRP]_{mixed}$: $[SRP]_{original}$; $p > 0.05$), but there was a significant negative correlation between the flux changing rate of sediment SRP and ($[SRP]_{mixed}$: $[SRP]_{original}$; $r = -0.89$, $p < 0.01$). With the increase in ($[SRP]_{mixed}$: $[SRP]_{original}$), the flux changing rate of sediment SRP was exhibited as a linear decreasing trend. Higher SRP concentrations in the overlying water after water transfer resulted in a greater decrease in the flux changing rate of sediment SRP. SRP concentrations in the overlying water of WSD1 and WSD2 were the same as and higher than the Wangyu River before water transfer, while the SRP at WSD3 was lower (Figure 2d). Following the transfer of Wangyu River water, SRP concentrations in overlying water under different water transfer experiment conditions decreased significantly at WSD1 and WSD2, compared to the original water. Conversely, the SRP concentration at WSD3 showed an increase to varying degrees. Specifically, ($[SRP]_{mixed}$: $[SRP]_{original}$) decreased (0.82–0.98) at WSD1 and WSD2, while ($[SRP]_{mixed}$: $[SRP]_{original}$) increased significantly at WSD3 after water transfer (1.33–1.84). This was a direct result of the introduction of higher SRP-containing Wangyu River water to sediments from the three study sites. Thus, the transfer of water from Wangyu River changed the SRP concentration of overlying water in Lake Wanshandang and then affected the release of internal P from sediments. This effect was regulated by the SRP concentrations of the overlying water in each area. Where the SRP concentration of the original water body was higher (higher than the inflow), internal SRP release flux from sediment was significantly accelerated after water transfer because of the increase in the concentration gradient of P from sediment to the overlying water. In areas where the SRP concentration of the original water body was low (lower than the incoming water), sediment SRP release flux was reduced after the water transfer because of the decrease in the concentration gradient of P from sediment to the overlying water.

In eutrophic shallow lakes, internal sediments act as both a source and sink of N and P, and internal dissolved N and P migrate between soil and water interfaces through static diffusion, biological irrigation, physical disturbance and other processes [34,35]. In most lakes, static release is the main mechanism of the interfacial transfer of internal N and P pollutants. Important factors affecting the internal static release from sediments include water temperature, pH, redox potential, sediment moisture content, porosity, N and P load and N and P nutrient salt forms, but the main driving factor is the concentration gradient of corresponding ions at the sediment–water interface. The ideal static release mode is that target ions in interstitial water migrate between the sediment–water interface, as driven by the concentration gradient, and the direction of transfer can be either from the sediment upward to the overlying water or from the overlying water into the sediment.

Therefore, concentration gradients play a crucial role in the release of internal pollutants from sediments.

After ecological water transfer introduces water with different characteristics, the concentration of N and P in the original overlying water of the receiving water body changes, followed by a different concentration gradient between the original overlying water and the interstitial water at the sediment–water interface. This can produce changes in the diffusion direction and flux of corresponding chemical species at the sediment–water interface. Thus, release fluxes change (Figure 5). Specifically, if the concentration of NH_3-N or SRP in overlying water is unchanged after water transfer, the concentration balance between overlying water and sediment is unchanged, and the release flux of corresponding sediment is unchanged. However, if the concentration of NH_3-N in overlying water increases after water transfer, the flux of NH_3-N from sediment will decrease to a large extent. The slight increase in NH_3-N release from sediments in some cases can be attributed to minimal differences in NH_3-N concentration before and after water diversion, along with the complex transfer and transformation processes of NH_3-N itself. In fact, this is demonstrated at WSD2, where the NH_3-N concentration of original water was the same as the Wangyu River used for water transfer (Figure 2c), while the release flux changed little after water transfer treatment (Figure 3a). Similarly, if the SRP concentration in overlying water increases after water transfer, the SRP release flux decreases. Although the transfer of Wangyu River water can increase NH_3-N concentrations in the overlying water of Lake Wanshandang in the short term, it reduces sediment NH_3-N flux into Lake Wanshandang, which controls NH_3-N concentrations in the overlying water. In contrast, effects on the flux of SRP from Lake Wanshandang sediments were different at different sites, and thus, a consistent effect of reducing the release from sediments cannot be achieved after water transfer.

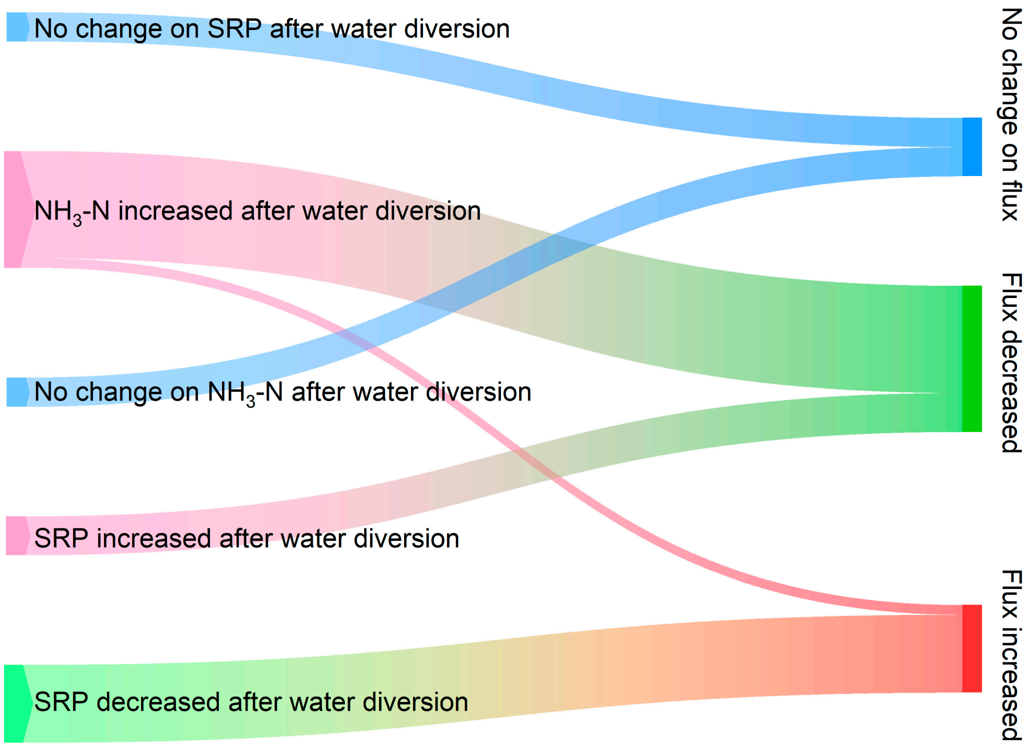

Figure 5. Relationship between changes in NH_3-N and SRP concentrations and sediment release after water transfer.

According to the results of this study, the effect of transferred water on the release of internal N and P nutrients from Lake Wanshandang sediments mainly depends on the quality of the inflow from Wangyu River and the concentration of N and P nutrients in different areas of Lake Wanshandang. As a result of the spatial and temporal heterogeneity of N and P distribution in lake water and sediment, the effects of trans-water transfer on the release of N and P nutrients in receiving water bodies are complex. The biggest advantage of an EWDP is the obvious improvement in overlying water quality in a short period of time. This leads to improvements in the hydrodynamic conditions of water bodies, as well as the self-purification capacity of water bodies [17]. However, in the long run, changes in the dynamic balance of N and P between overlying water and sediments can cause the release of corresponding pollutants from in situ sediments. Thus, we recommend conducting long-term multi-angle (such as time, space and types of pollutants) observations and assessments of the transfer and transformation of key pollutants in various water bodies and sediments affected by EWDPs to scientifically evaluate and efficiently manage the environmental benefits. To be clear, nutrient release from sediments in shallow lakes can be affected by many bio-physical processes such as mechanical disturbances like wind–wave disturbance and bioturbation. Therefore, more complicated responses of nutrient release imposed by water diversion should be carefully studied in the future.

5. Conclusions

The effects of ecological water transfer on the release of internal N and P nutrients from Lake Wanshandang sediments were analyzed. The results showed that the transfer of Wangyu River water had significant effects on the release of internal N and P from Lake Wanshandang sediments under different water transfer experimental conditions. After water transfer treatment, the release flux of NH_3-N from sediments in the western and eastern areas decreased significantly, and this decrease increased with greater water transference. The SRP release flux from sediments in the western and central areas increased significantly after water transfer treatment, while it decreased in the eastern area. Water transfer treatment obviously changed the concentrations of NH_3-N and SRP in the overlying water, which affected the dynamic balance between the sediment and the overlying water and led to the corresponding changes in N and P concentrations. The results of this study showed that increases in NH_3-N and SRP concentrations in overlying water after water transfer treatment reduces the release of NH_3-N and SRP from sediments. EWDPs are complex and long-term initiatives, with an expectation that environmental effects will be larger scale and last for a longer period than demonstrated here. To clarify the impact and mechanism of ecological water diversion on the internal release of pollutants from shallow lake sediments, it is necessary to conduct more intensive and long-term studies.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w16071065/s1, Table S1: Environmental quality standards for TN, TP and NH_3-N for surface water of China (C represents the concentrations of TN, TP and NH_3-N in each row).

Author Contributions: Conceptualization, Q.S.; investigation, Y.L. and Y.W.; formal analysis, Q.S., Y.L. and A.W.; writing, H.C. and Q.S.; review, Q.S., C.H., Y.Z. and G.W.; project administration, Q.S.; funding acquisition, Q.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the National Key Research and Development Program of China (2022YFC3202703), the National Natural Science Foundation of China (U22A20616) and the Science and Technology Program of Bayan Nur (K202324).

Data Availability Statement: The data used in this study are available upon request.

Acknowledgments: We thank Sev Kender for editing the English text of a draft of this manuscript.

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

References

1. Zhai, S.; Hu, W.; Zhu, Z. Ecological impacts of water transfers on Lake Taihu from the Yangtze River, China. *Ecol. Eng.* **2010**, *36*, 406–420. [CrossRef]

2. Welch, E.B.; Barbiero, R.P.; Bouchard, D.; Jones, C.A. Lake trophic state change and constant algal composition following dilution and diversion. *Ecol. Eng.* **1992**, *1*, 173–197. [CrossRef]
3. Liu, Z.J.; Xiao, Q.T.; Hu, Z.H.; Zhang, M.; Wang, W.; Xiao, W. Effects of water diversion from Yangtze River to Lake Taihu on N2O flux in Gonghu Bay, Lake Taihu. *China Environ. Sci.* **2020**, *40*, 5229–5236. [CrossRef]
4. Smit, J.T.; Steinman, A.D. Wetland Sediment Phosphorus Flux in Response to Proposed Hydrologic Reconnection and Warming. *Wetlands* **2015**, *35*, 655–665. [CrossRef]
5. Ge, L.T. The construction of transboundary water pollution prevention and control model of river basin from the perspective of collaborative management—A case study in Water Pollution Prevention and Control in Luanhe-Tianjin Water Diversion Project. *China Rural. Water Hydropower* **2018**, *2018*, 60–63. [CrossRef]
6. Chen, G.Y.; Li, W.; Wang, J.; Lu, F.; Zhao, Y. Progress on Eco-compensation Mechanism Pilot Between Upstream and Downstream of Luanhe River. *Environ. Prot.* **2017**, *45*, 24–27. [CrossRef]
7. Lu, H.M.; Zou, Y.; Feng, H.L. Analysis and inspiration of ecological and environmental impacts of typical water diversion projects at home and abroad. *Water Resour. Plan. Des.* **2018**, *2018*, 88–92, 166. [CrossRef]
8. Zhou, X.P.; Zhai, S.H.; Yuan, L. Influences of water diversion from Yangtze River to Taihu Lake on water quality of Taihu Lake between 2007 and 2008. *Water Resour. Prot.* **2010**, *26*, 40–43. [CrossRef]
9. Lane, R.R.; Day, J.W.; Kemp, G.P.; Demcheck, D.K. The 1994 experimental opening of the Bonnet Carre Spillway to divert Mississippi River water into Lake Pontchartrain, Louisiana. *Ecol. Eng.* **2001**, *17*, 411–422. [CrossRef]
10. Sun, K.Y.; Niu, Z.R.; Wang, J.W.; Zhang, X.Y. Optimal allocation of water resources from Datong River-to-Qinwangchuan Basin Water Diversion Project addressing water supply object transformation. *J. Water Resour. Water Eng.* **2023**, *34*, 93–100.
11. Wu, Y.Y. Application of water ecological facilities in engineering design of transfering water from Datong river to Huangshui river. *Yellow River* **2020**, *42*, 67–68.
12. Mao, J.Z.; Sun, Y.L.; He, K.D.; Kong, G.F.; Yang, Z.L. Study of water environment improvement effect by Niulan River-Dianchi Lake Water Supplement Project in Waihai area of Dianchi Lake. *Water Resources Protection.* **2017**, *33*, 47–51. [CrossRef]
13. Hosper, H.; Meyer, M.-L. Control of phosphorus loading and flushing as restoration methods for Lake Veluwe, The Netherlands. *Hydrobiol. Bull.* **1986**, *20*, 183–194. [CrossRef]
14. Amano, Y.; Sakai, Y.; Sekiya, T.; Takeya, K.; Taki, K.; Machida, M. Effect of phosphorus fluctuation caused by river water dilution in eutrophic lake on competition between blue-green alga Microcystis aeruginosa and diatom *Cyclotella* sp. *J. Environ. Sci.* **2010**, *22*, 1666–1673. [CrossRef]
15. Zhang, L.L.; Chen, L.; Guo, X.F.; Gu, M. Economic analysis of water transfer and security of drinking water in water-scarce cities. *Water Wastewater Eng.* **2018**, *54*, 49–52. [CrossRef]
16. Li, Y.; Acharya, K.; Yu, Z. Modeling impacts of Yangtze River water transfer on water ages in Lake Taihu, China. *Ecol. Eng.* **2011**, *37*, 325–334. [CrossRef]
17. Lu, X.; Wu, S.; Zhang, Y.; Dai, J.; Li, D. Progress of ecology and environment effect of water diversion project. *J. Water Resour. Water Eng.* **2015**, *26*, 38–45.
18. Hu, L.; Hu, W.; Zhai, S.; Wu, H. Effects on water quality following water transfer in Lake Taihu, China. *Ecol. Eng.* **2009**, *36*, 471–481. [CrossRef]
19. Wei, Z.; Zongpu, X.; Yuanming, Z.; Shuhua, Z.; Ganyu, F.; Ruochen, W.; Huaimin, C.; Siyuan, H.; Shuai, Z.; Ya, Z. Effect of water diversion from the Yangtze River to Lake Taihu on total phosphorus rebound after 2016. *J. Lake Sci.* **2020**, *32*, 1432–1445. [CrossRef]
20. Nie, X.; Lin, Z.W.; Gu, J.G.; Han, B.P. Phosphorus fractions and their release from sediments of middle and small sized reservoirs for drinking water in the south of China. *Ecol. Environ. Sci.* **2008**, *3*, 903–908. [CrossRef]
21. Tendaupenyu, P.; Magadza, C.H.D. Nutrient concentrations in the surface sediments of Lake Chivero, Zimbabwe: A shallow, hypereutrophic, subtropical artificial lake. *Lakes Reserv. Res. Manag.* **2017**, *22*, 297–309. [CrossRef]
22. Schindler, D.W.; Carpenter, S.R.; Chapra, S.C.; Hecky, R.E.; Orihel, D.M. Reducing Phosphorus to Curb Lake Eutrophication is a Success. *Environ. Sci. Technol.* **2016**, *50*, 8923–8929. [CrossRef]
23. Wang, Y.; Jiang, X.; Li, Y.; Wang, S. Spatial and Temporal Distribution of Nitrogen and Phosphorus and Nutritional Characteristics of Water in Dongting Lake. *Res. Environ. Sci.* **2014**, *27*, 484–491. [CrossRef]
24. Li, Y.B.; Kuang, S.; Wang, Z.Y.; Shen, Q.S.; Wang, Y.D.; Kang, D.J. Characteristics and significance of nitrogen, phosphorus and oxygen transportation at the sediment-water interface in east Lake Chaohu. *J. Lake Sci.* **2020**, *32*, 688–700. [CrossRef]
25. Liu, C.; Zhong, J.; Wang, J.; Zhang, L.; Fan, C. Fifteen-year study of environmental dredging effect on variation of nitrogen and phosphorus exchange across the sediment-water interface of an urban lake. *Environ. Pollut.* **2016**, *219*, 639–648. [CrossRef]
26. Editorial Committee of "Determination Methods for Examination of Water and Wastewater", State Environmental Protection Administration. *Determination Methods for Examination of Water and Wastewater*, 4th ed.; Monographs; China Environmental Press: Beijing, China, 2002.
27. *GB 3838-2002*; Surface Water Environmental Quality Standards. National Environmental Protection Agency. China Standard Press: Beijing, China, 2002.
28. Yao, J.; Wang, G.; Xue, B.; Wang, P.; Hao, F.; Xie, G.; Peng, Y. Assessment of lake eutrophication using a novel multidimensional similarity cloud model. *J. Environ. Manag.* **2019**, *248*, 109259. [CrossRef]

29. Zhang, T.-N.; Zhou, S.-L.; Chen, Z.-Y.; Zhang, Z.-W.; Sun, Y.; Yao, B.; Cui, J.-S.; Li, Z.-X.; Luo, X. Analysis of Water Quality and Exchange Flux of Interstitial Water-Overlying Water in Sediments of Baiyangdian Entrance Area in Summer. *Environ. Sci.* **2021**, *42*, 3176–3185. [CrossRef]
30. Li, Y.B. Research on Characteristics and Controlling of Sediment Internal Phosphorous Release from a Small Urban Shallow Lake. Master's Thesis, Fuzhou University, Fuzhou, China, 2020. [CrossRef]
31. Hu, W.; Lo, W.; Chua, H.; Sin, S.; Yu, P. Nutrient release and sediment oxygen demand in a eutrophic land-locked embayment in Hong Kong. *Environ. Int.* **2001**, *26*, 369–375. [CrossRef]
32. Zhu, Y.Y.; Jin, X.; Meng, X.; Zhang, C.; Tang, W.Z.; Shan, B.Q.; Zhao, Y. Study on ammonia nitrogen release flux in the sediment-water interface of Baiyangdian Lake. *Acta Sci. Circumstantiae* **2018**, *38*, 2435–2444. [CrossRef]
33. Cui, H.F.; Chen, S.Y.; Yang, C.H.; YANG, C.H.; Tang, W.J.; Yin, P.; Yin, H.B. Internal Pollution and Release Characteristics of Bottom Sediments of Hengshan Reservoir in Yixing City. *Environ. Sci.* **2020**, *41*, 5400–5409. [CrossRef]
34. Portielje, R.; Lijklema, L. Estimation of sediment–water exchange of solutes in Lake Veluwe, The Netherlands. *Water Res.* **1999**, *33*, 279–285. [CrossRef]
35. Liu, J.; Zheng, X.L.; Chen, L.; Wu, C.C. Study on flux and release law of nitrogen and phosphorus of sediment in reservoir. *J. Hydraul. Eng.* **2012**, *43*, 339–343. [CrossRef]