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Distribution Characteristics of Carbon, Nitrogen, and Phosphorus and Pollution Load Estimation of Sediments in Danjiangkou Reservoir, China

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Abstract: Danjiangkou Reservoir is a world-famous large artificial freshwater lake that offers water resources for the middle route of the South-to-North Water Diversion Project in China. In this study, the distribution of carbon, nitrogen, and phosphorus in reservoir sediments and their pollution assessments were elucidated at different water periods. The average TN (total nitrogen), TP (total phosphorus), and TOM (total organic matter) contents were 794.8 mg/kg, 807.2 mg/kg, and 8.7% in the nonflood season, respectively. When the time comes to flood season, with the large amount of nitrogen pollution inputted from peripheral nonpoint sources and phosphorus released by the accelerated exchange of water bodies, the average TN concentration increased to 1061.2 mg/kg. In addition, the average TP and TOM contents were reduced to 559.5 mg/kg and 6.3%. Nutrient pollution fluctuated between the safe and lowest level. Reservoir eutrophication risk was low. There was a certain nitrogen enrichment in the Danjiangkou Reservoir, and the flood season was the main period of nitrogen pollution input. Water exchange during flood season might accelerate organic matter degradation. Near the dam, sediment organic matter content increased significantly, reaching severe pollution levels. The results of the simulated sediment nutrient release test showed that the nitrogen and phosphorus in the reservoir would release slowly. Moreover, their annual release flux was calculated as 470.4 t and 87.9 t, respectively. It illustrated that the internal pollution of Danjiangkou Reservoir was light, and the release amount was small, so it was not the main pollution source of the reservoir at present.

Keywords: Danjiangkou Reservoir; sediment; temporal-spatial distribution; pollution assessment; pollution load estimation

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1. Introduction

Carbon, nitrogen, and phosphorus are the nutritional material basis of the geochemical cycle and are closely related to the health of the water ecological environment [1]. Nitrogen and phosphorus are the limiting factors causing water eutrophication, and their contents are often used as the core indices to evaluate the eutrophication level of reservoirs [2,3]. Therefore, great efforts have been made to understand the spatial pattern and influencing factors of sediment nutrients, especially carbon, nitrogen, and phosphorus, considering the increasing occurrence of eutrophication in reservoirs worldwide [4,5].

As the once largest artificial freshwater lake in Asia, the Danjiangkou Reservoir is now also an important water source for the middle route of the South-to-North Water Diversion Project in China [6]. By the end of 2019, the Danjiangkou Reservoir transferred nearly 30 billion cubic meters of water to the north of China. The water quality of the Danjiangkou Reservoir is directly related to the health and safety of residents in the water demand area [7]. Moreover, the current anthropogenic pollution of this reservoir is a great public health concern. The increase in carbon, nitrogen, and phosphorus content in reservoir water and the deterioration of water quality are usually attributed to the input of point and nonpoint source pollutants within the basin, but the release of carbon, nitrogen, and phosphorus in reservoir sediments is also an important reason that cannot be ignored [8,9]. As a matter of fact, climate change around the world has enhanced upward fluxes of nutrients across the sediment–water interface into the hypolimnion by extending stratification, which has caused internal nutrient loading to play a more substantial role [1]. Sediment always acts not only as a sink of nutrients but also as a source [10]. The enrichment of carbon, nitrogen, and phosphorus in sediments would also increase the primary productivity of the reservoir [11]. Therefore, it is necessary to investigate the occurrence characteristics of sediment nutrients in the Danjiangkou Reservoir to master the current situation of conventional pollution, alleviate streambed pollution, and formulate strategies for water quality safety [12].

The internal nutrient release of sediments is affected by the surrounding hydrodynamics and water environment conditions [4]. The differences in water depth, nutrient species, water temperature, pH, concentration gradient, oxidation-reduction potential, organisms, and hydrodynamics can change the sediment nutrient distribution [13,14]. Among these factors, the importance of hydrodynamics has been frequently confirmed. In addition, many studies have focused on the effects of hydrodynamics on the internal nutrient release of large deepwater reservoirs [14–16]. In contrast to shallow lakes, deepwater reservoirs form a seasonal or permanent thermodynamic stratification due to their physical and structural characteristics [17]. Seasonal hypoxia is usually reported in those deepwater reservoirs, and it could accelerate the release of P rather than N from the sediments in warm seasons in the latest study [1,18]. Therefore, it is not reasonable to talk about the sediment nutrition distribution of deepwater reservoirs in a single water period or season. Moreover, it is worth noting that there are many investigations and studies on the enrichment of nitrogen and phosphorus nutrients in reservoir sediments, but there are few studies on how much nitrogen and phosphorus in these sediments will eventually release pollution loads into the reservoir [19]. Previous studies on nitrogen and phosphorus nutrients in Danjiangkou Reservoir sediments are rare, and there is no report on pollution load estimation [20,21]. Thus, more attention should be paid to the source apportionment and probabilistic risk of internal nutrition release in this deepwater reservoir [22].

Danjiangkou is a typically regulated reservoir with an annual fluctuation in water level of nearly 20 m. The flood season is the main period of pollution in this reservoir basin. Hydrodynamics is very important for understanding these spatial differences [4,17,23]. The nutrient spatial distributions in reservoir sediments would be thought to have significant differences. Calibration of the total nonpoint source pollution load should comprehensively consider the use of modeling approaches, laboratory simulation experiments, and other research methods [19,24]. The objective of this study was to (1) investigate the distribution characteristics of the TOC, TN, and TP in the sediments of the Danjiangkou Reservoir in flood and nonflood seasons, (2) assess the sediments pollution of the reservoir, and (3) estimate the pollution load of nitrogen and phosphorus in the Danjiangkou Reservoir sediments.

2. Materials and Methods

2.1. Sample Collection

Danjiangkou Reservoir (32°36′–33°48′ N, 110°59′–111°49′ E) is located in the middle and upper reaches of Han River, the largest tributary of the Yangtze River. This area lies at the intersection of Henan and Hubei provinces. The whole project covers 43 counties in 8 cities in Shanxi, Hubei, and Henan provinces, with a total land area of 89,300 km^2. The annual storage water level is between 157 and 170 m. The surface water area of this reservoir is 1050 km^2, with a total storage capacity of 29.05 km^3 when it is filled to the normal 170 m level. In addition, the average annual precipitation amounts to 800–1400 mm, 80–90% of which falls from May to October [25]. As the water source of the middle route of the South-to-North Water Diversion Project, the Danjiangkou Reservoir is an important part of the strategic pattern of water resources in China. The water quality of this deepwater reservoir is related to thousands of households, affecting the people's livelihood.

Danjiangkou Reservoir has usually been divided geographically into the Han River Reservoir and Dan River Reservoir, according to the tributaries. The corresponding main tributaries are the Han River and the Danjiang River. This study investigated and analyzed the current situation of carbon, nitrogen, and phosphorus pollution in the surface sediment of the reservoir. We set six sampling points in Han River Reservoir and eight sampling points in Dan River Reservoir, combined with the topographic characteristics. These sampling sites were consistent with the routine water quality monitoring sites in the reservoir, as shown in Figure 1. Sediment samples were collected from 0–10 cm surface layer of the reservoir area during the nonflooding period at the end of October 2020 and the flooding period at the beginning of August 2021, respectively, using a grab bucket-type mud collector. All the sediment samples were stored in sterile and sealable plastic bags and placed in a refrigerator (4 °C) at the laboratory. Before the experiment, the samples were freeze-dried, ground, and homogenized through a 100-mesh screen.

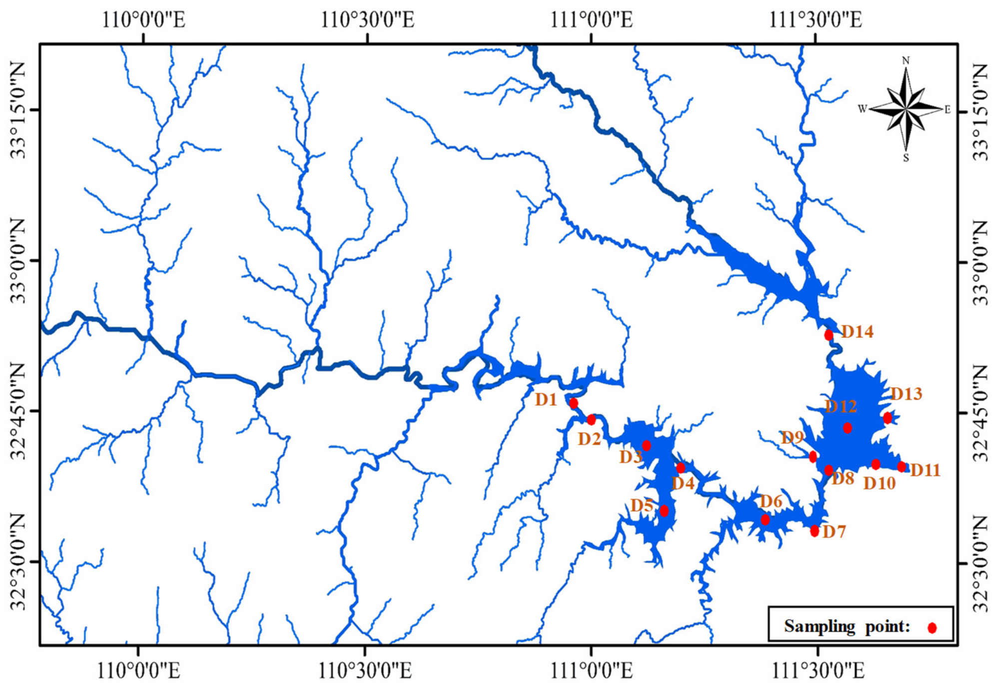

Figure 1. Sampling sites of the sediments in the Danjiangkou Reservoir.

2.2. Sample Analysis

The sediment TN content was measured by the alkaline potassium persulfate oxidation analysis method [26]. A total of 0.1 g of sediment sample was weighed in a 25 mL colorimetric tube, after which 10 mL of potassium persulfate solution was added, and then it was shaken well. It was dissolved in an autoclave at 125 °C for 1 h. After the sample cooled down, it was transferred to a 500 mL beaker and diluted to 500 mL with ammonia-free water. The filtrate was filtered at atmospheric pressure, the pH was adjusted to 7.0, and the TN content of the filtrate was detected as the same method as the water samples; refer to ultraviolet spectrophotometry method HJ/T346-2007 [27]. In turn, the sediment TN was determined.

The sediment TP content was analyzed as SRP [28]. The samples were cauterized at a high temperature (450 °C) in a porcelain crucible. After cooling, the samples in the crucible were rinsed with 20 mL of 3.5 mol/L hydrochloric acid solution. All the rinsing solution was transferred to a centrifuge tube and centrifuged after 16 h of shaking at a chilled temperature. Then, a certain volume of supernatant was taken and filtered through a 0.45 µm aqueous filter head in a 25 mL colorimetric tube to fix the volume. A wet colorant was added. The concentration of TP was determined by the molybdenum–antimony anticolorimetric method.

The content of the sediment total organic matter (TOM) was determined using the $K_2Cr_2O_7$-H_2SO_4 wet oxidation method [29]. The sample was oxidized with 10 mL of 0.075 mol/L 1/6($K_2Cr_2O_7$)-H_2SO_4 and boiled in a paraffin oil bath at 185~190 °C for 5 min. Phenanthroline was used as an indicator, and the remaining potassium dichromate was titrated with ferrous sulfate to calculate the organic carbon content from the amount of potassium dichromate consumed.

All the instruments used in the sediment sample analysis passed the national measurement examination. Reference materials (GSD-9) and standard reagents were used for quality control.

2.3. Pollution Assessment Standards

The standard evaluation values of the integrated pollution index for TN and TP used for the current status of sediment nitrogen and phosphorus pollution in Danjiangkou Reservoir were 0.55 and 0.60 g/kg, respectively, which are consistent with the TN and TP contents in sediment that can cause the lowest level of ecological risk effects given by the Environment and Energy Ministry of Ontario, Canada (as shown in Table 1) [30]. The single pollution index was calculated by the formula:

$$S_i = C_i/C_s \tag{1}$$

$$FF = \sqrt{\frac{F^2 + F_{\max}^2}{2}} \tag{2}$$

where S_i was a single evaluation index or standard index; if $S_i > 1$, this indicated that the contaminant concentrations exceeded the standard evaluation value. C_i was the measured concentration of contaminant i (g/kg). C_s was the standard evaluation value of contaminant i (g/kg). C_s of TN was 0.55 g/kg, and C_s of TP was 0.60 g/kg. FF was the comprehensive pollution index. F was the average of all the pollution indices (standard index S_{TN} of TN and standard index S_{TP} of TP). $F_{\max}$ was the maximum single pollution index (the maximum value of S_{TN} and S_{TP}). The evaluation of nitrogen and phosphorus pollution in the surface sediment of the Danjiangkou Reservoir and the grading basis of pollution degree are shown in Table 2.

Table 1. Sediment nutrient quality benchmarks for Ontario, Canada.

Indicator	Security Level	Lowest	Severe Level
TN	<550 mg/kg	550~4800 mg/kg	>4800 mg/kg
TP	<600 mg/kg	600~2000 mg/kg	>2000 mg/kg
Organic matter	<1 (%)	1–10 (%)	>10 (%)

Table 2. Classification of comprehensive pollution degree of surface sediments.

Grade	S_{TN}	S_{TP}	FF	Pollution Level
1	$S_{TN} < 1.0$	$S_{TP} < 0.5$	$FF < 1.0$	Clean
2	$1.0 \leq S_{TN} \leq 1.5$	$0.5 \leq S_{TP} \leq 1.0$	$1.0 \leq FF \leq 1.5$	Mild pollution
3	$1.5 < S_{TN} \leq 2.0$	$1.0 < S_{TP} \leq 1.5$	$1.5 < FF \leq 2.0$	Moderate pollution
4	$S_{TN} > 2.0$	$S_{TP} > 1.5$	$FF > 2.0$	Heavy pollution

2.4. Pollution Load Estimation

Based on the field research of the Danjiangkou Reservoir, nitrogen and phosphorus pollution release in its sediments was studied under different temperatures. The simulation experiments were carried out in an incubator controlled by temperature, light, and humidity. A glass measuring cylinder with a lid with good tightness was used to construct the simulation experiment device. The volume of the measuring cylinder was 2 L, and the inner diameter was 10 cm. Then, we added a certain thickness of surface sediments of the Danjiangkou Reservoir and injected reservoir raw water corresponding to the bottom mud into the simulation experiment device with a siphon according to the actual mud-water ratio of the Danjiangkou Reservoir.

In this study, three different temperatures (15 °C, 20 °C, 25 °C) were set under a static state for nitrogen and phosphorus release simulation test treatment in the incubator. Each group was treated with two replicates. The TN and TP concentrations of water were determined by taking supernatant at different time points. TP was determined by molybdenum–antimony resistance spectrophotometry and TN by ultraviolet spectrophotometry. The release rate of nitrogen and phosphorus in sediments of the Danjiangkou Reservoir was obtained according to the results of those simulation experiments. The annual release fluxes of endogenous nitrogen and phosphorus in sediments of the Danjiangkou Reservoir were calculated by the following formula [31,32]:

$$W = (r_1 \times t_1 + r_2 \times t_2 + r_3 \times t_3) \times A \tag{3}$$

where W was the annual release flux of sediment nitrogen and phosphorus (kg). A was the reservoir area (m^2). r_1, r_2, and r_3 corresponded to the release rates of sediment nitrogen and phosphorus at three different temperatures, respectively ($mg/(m^2 \cdot d)$). t was the duration of different temperatures (d).

2.5. Data Processing and Analysis

The raw data were processed using Microsoft Excel 2010 (Microsoft, Redmond, Washington, WA, USA). One-way ANOVA (SPASS v19.0) was used to test the significance of the differences in carbon, nitrogen, and phosphorus contents of sediments at different sites, and the relevant graphs were prepared in Origin 8.0 (Origin Lab Corporation, Northampton, MA, USA) and Excel 2010 software.

3. Results and Discussion

3.1. Carbon, Nitrogen, and Phosphorus Distribution Characteristics

The surface sediment nitrogen content of the Danjiangkou Reservoir was low in the nonflood season. As shown in Figure 2, the TN concentration was detected between 571.8 and 1144.9 mg/kg, among which the average concentration of the Han River Reservoir was 737.0 mg/kg, and the Dan River Reservoir was 852.5 mg/kg. The results of the survey of the flood season showed an increase in the TN content in the reservoir surface sediment. The detected TN concentrations ranged from 549.6 to 1752 mg/kg, with an average concentration of 1061.2 mg/kg, including 986.2 mg/kg in the Han River Reservoir and 1136.2 mg/kg in the Dan River Reservoir. They were much less than the eutrophic reservoirs in other studies, such as the Upper Peirce Reservoir, Singapore (5530 mg/kg), and the Carlyle Reservoir, USA (3680 mg/kg) [33,34]. Compared with the monitoring results from 2011 to 2016 reported by Li et al. [21], of which the concentrations ranged from 720 to 1910 mg/kg, the TN content in the Dan River Reservoir sediments decreased slightly.

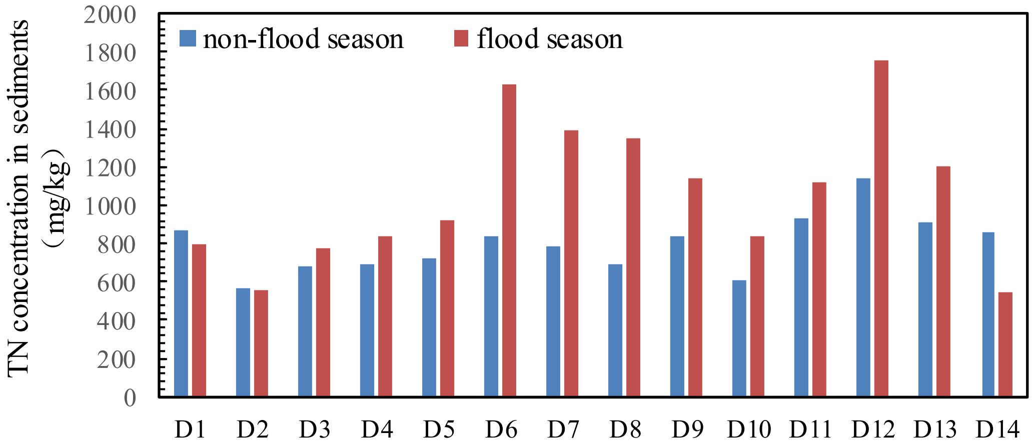

Figure 2. Distribution characteristics of TN content in surface sediments of the Danjiangkou Reservoir in different water periods.

The TN content of the reservoir sediments was significantly different in space. On the whole, the inlet was higher than other areas of the reservoir, and the TN content of sediments in the wide area of reservoir water tended to be higher. By comparing the sediment TN content in different water periods, we found that the TN content in most sampling points, especially the core reservoir area, increased significantly during the flood season. The reason might be that the increase in rainfall in the flood season had led to a significant increase in exogenous pollution and sediment input in the inflow river and surrounding reservoir area. Zhai et al. [35] statistically divided the monthly TN and TP inflow fluxes and runoff in the main tributaries of the Danjiangkou Reservoir, and the results showed that the two changes were consistent and showed a very significant positive correlation. The most nonpoint source pollutants were imported in flood season. According to the reference value of nutrient salt background TN (640 mg/kg) in the Background Value of Soil Elements in China, TN was enriched in the surface sediments of the Danjiangkou Reservoir [36]. Similar to the results of this study, Sun et al. [1] pointed out the TN content of Panjiakou sediments, a seasonally stratified deepwater reservoir, increased gradually from spring to autumn and then decreased in winter. However, the TN levels in the active sediments of the shallow lakes have consistently shown little temporal change. Zhang et al. [37] and Wu et al. [4] both found that seasonal variations in nitrogen in the surface sediment of Lake Taihu were not significant.

The TP concentrations in the surface sediment of the Danjiangkou Reservoir during the nonflood season ranged from 360.9 to 1379.6 mg/kg, with an average concentration of 807.2 mg/kg (Seen in Figure 3). This showed that the overall phosphorus content in the reservoir was low at present. Geographically, the average TP concentration of the Han River Reservoir was 1020.0 mg/kg, and the Dan River Reservoir was 594.0 mg/kg, while the results of the flood season showed that the overall phosphorus content in the surface sediment of the Danjiangkou Reservoir decreased. During the flood season, the TP content ranged from 395.0–867.0 mg/kg, and the average content was 559.5 mg/kg, among which the average concentration of the Han River Reservoir was 514.6 mg/kg, and the average concentration of the Dan River Reservoir was 604.6 mg/kg. Before 2016, the maximum reported TP content in the Danjiangkou Reservoir sediments was 821.4 mg/kg [20,21]. It indicated the enrichment of phosphorus in reservoir sediments. In our study, it was also found that the TP content of reservoir sediments had some spatial and temporal differences, and those differences were more significant than the TN content distribution in reservoir sediments. Firstly, the TP content in reservoir sediments showed a trend higher than that in other areas of the reservoir, whether in flood season or nonflood season. Secondly, the TP content in front of the dam sediments was significantly higher than that in the surrounding sediments during the nonflood season and decreased during the flood season. The water velocity in front of the dam was slowed down in the nonflood season. It might cause an increase in sediment TP content by the sedimentation of adsorbed particle phosphorus in the suspended sediment [38]. After the flood season, the frequency of water change in the reservoir would be accelerated, coupled with multiple flood discharges. Although there was more phosphorus pollution entering the reservoir at this time, more phosphorous sediment in front of the dam was washed away at the same time. In addition, as the sediment–water interface flowed faster, more phosphorus was released into the water. Neto et al. [17] reported that reservoir stratification and hypolimnetic hypoxia of tropical reservoirs with high seasonal water level changes were more notable during the flood season. It resulted in higher phosphorus concentration in the water column due to the combined effects of internal and external loadings. It might also be the reason for the decreased TP content in sediments in the flood season. Finally, the overall TP content of the Han River Reservoir sediments in the nonflood season was higher than that of the Dan River Reservoir, while the overall TP content of the Han River Reservoir sediments in the flood season was lower than that of the Dan River Reservoir. The TP in the Dan River Reservoir sediments did not fluctuate significantly in different water periods as a whole. It was probably caused by as many as 12 tributaries around the Han River Reservoir, accounting for 75% of the total rivers in the Danjiangkou Reservoir, which had provided most of the incoming water to the reservoir. In addition, the topography of the Han River Reservoir area is long and narrow. The hydrological characteristics varied greatly during different water periods. Therefore, the TP content of sediments fluctuated. According to the reference value of nutrient salt background TP (520 mg/kg) in the Background Value of Soil Elements in China, TP in the surface sediment of the reservoir was not significantly enriched [36]. The results are consistent with those reported in other studies. Sun et al. [1] found the sediment TP content in the Panjiakou Reservoir was lower during the stratified period than during the unstratified period, and water temperature stratification in reservoirs usually occurred during the summer flood season. Yin et al. [39] also pointed out the rank of water seasons in terms of the proportion and load of inflowing TP retained to the reservoir was the low-water season (LWS) > normal-water season (NWS) > high-water season (HWS), which might be due to the high phosphorus concentration and long hydraulic retention time during the LWS.

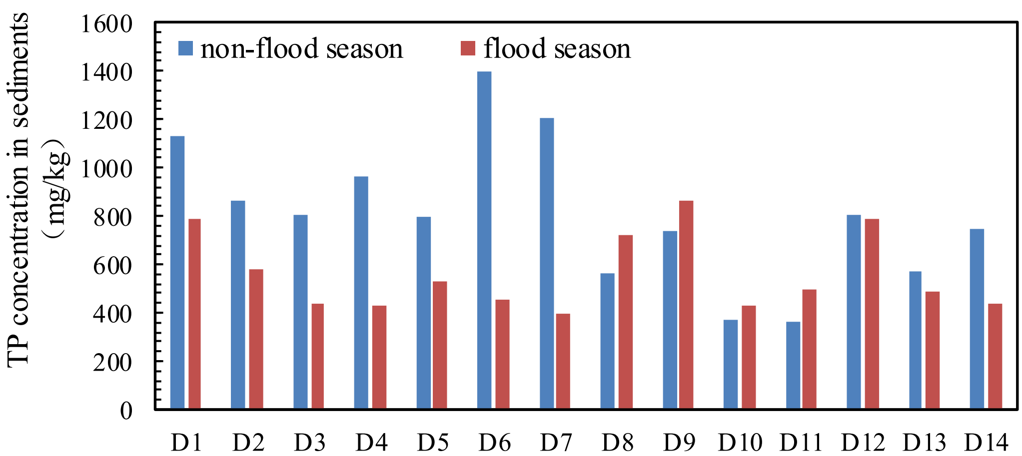

Figure 3. Distribution characteristics of TP content in surface sediments of Danjiangkou Reservoir in different water periods.

The mass fraction of total organic matter (TOM) detected in the Danjiangkou Reservoir surface sediments during the nonflood season ranged from 4.3% to 11.7% (seen in Figure 4), with an average content of 8.70%. The average TOM content in sediments of the Han River Reservoir was slightly higher than the Dan River Reservoir. They were 9.07% and

8.34%, respectively. In addition, the TOM of reservoir surface sediments in the flood season decreased significantly compared with that in the nonflood season, in which the content ranged from 3.80–8.60%, with an average content of 6.30%. The average TOM contents of the Han River Reservoir and the Dan River Reservoir were 5.80% and 6.90%, respectively. The former one was also slightly lower than that of the latter in the flood season. Water exchange in the Danjiangkou Reservoir accelerated significantly during the flood season, and the flow velocity at the sediment–overlying water interface also increased significantly, which resulted in organic matter entering the overlying water [40]. Due to the large inflow of water in the Han River Reservoir, the water exchange would be more frequent. It might cause the TOM content in the Han River Reservoir sediment to decrease more significantly than that in the Dan River Reservoir. In addition, the degradation characteristics of organic matter in reservoirs were affected by the regulation and storage of reservoirs [5]. It was another important reason for the decrease in TOM content in the Han River Reservoir sediments during the flood season.

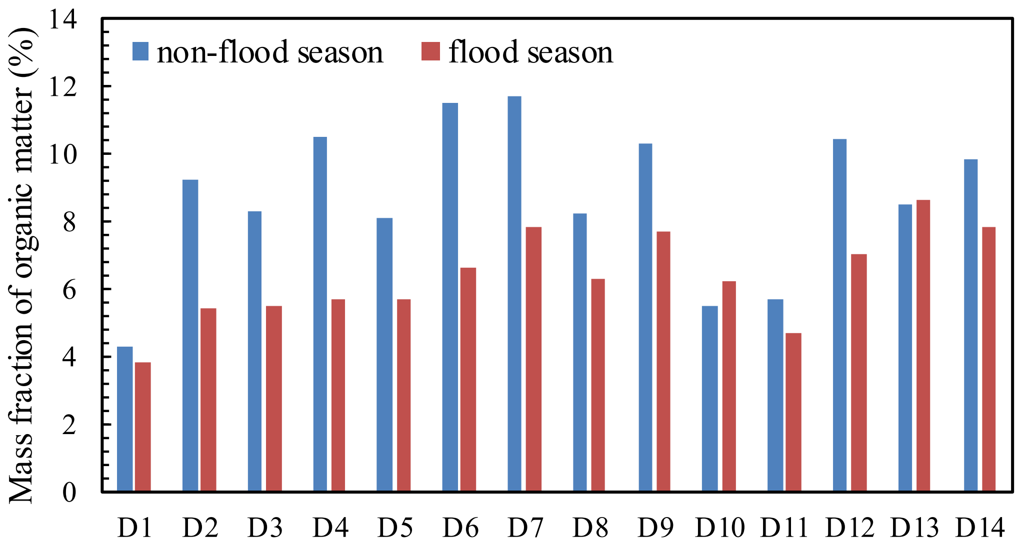

Figure 4. Distribution characteristics of organic matter content in surface sediments of Danjiangkou Reservoir in different water periods.

3.2. Nitrogen and Phosphorus Pollution Assessment

The nitrogen and phosphorus pollution status of 0–10 cm surface sediments of the Danjiangkou Reservoir in different water periods were evaluated according to the nutrient quality standards released by the Ontario Ministry of Environment and Energy, Canada, and the results are shown in Table 3. In the nonflood season, *FF* of D6 surface sediments in all samples was more than 2, indicating severe pollution. *FF* of D1, D5, D7, and D12 were between 1.5 and 2, indicating moderate pollution. The D10 sediment was clean, with an *FF* value of less than 1. The other eight sampling sites were mildly polluted, accounting for 57.1% of all. There was severe nitrogen pollution at sampling point D12, in which the nitrogen single evaluation index (S_{TN}) was greater than 2. The phosphorus single evaluation index (S_{TP}) of D6 was also greater than 2, which also meant severe pollution. During the flood season, the number of sampling sites where *FF* over 2 had increased. In addition, the D6, D7, D8, and D12 sites were heavily polluted. The nitrogen pollution discharged from the surrounding water-leveling zone into the reservoir would always increase during the flood season. It might be a very important reason. In addition, the *FF* values of D9, D11, and D13 were between 1.5 and 2, indicating moderate pollution. The *FF* values of D2 and D14 did not exceed 1, and the sediments here were clean. The others were lightly polluted.

Table 3. Results of integrated pollution rating of surface sediments in Danjiangkou Reservoir.

Name	Sampling Point	S_{TN}		S_{TP}		*FF*	
		Nonflood Season	Flood Season	Nonflood Season	Flood Season	Nonflood Season	Flood Season
Han River Reservoir	D1	1.58	1.45	1.89	1.31	1.81	1.42
	D2	1.04	1.01	1.44	0.96	1.34	1.00
	D3	1.24	1.40	1.34	0.73	1.32	1.24
	D4	1.25	1.53	1.61	0.71	1.52	1.34
	D5	1.31	1.67	1.33	0.88	1.32	1.49
	D6	1.53	2.96	2.30	0.76	2.12	2.47
	D7	1.42	2.53	2.01	0.66	1.87	2.11
	Average value	1.34	1.79	1.70	0.86	1.61	1.58
Dan River Reservoir	D8	1.26	2.45	0.93	1.20	1.18	2.16
	D9	1.52	2.08	1.23	1.45	1.45	1.93
	D10	1.10	1.53	0.62	0.72	0.99	1.34
	D11	1.69	2.04	0.60	0.82	1.44	1.76
	D12	2.08	3.19	1.34	1.32	1.90	2.76
	D13	1.65	2.18	0.96	0.82	1.49	1.87
	D14	1.57	1.00	1.24	0.73	1.49	0.93
	Average value	1.55	2.07	0.99	1.01	1.42	1.82

It was noteworthy that the average S_{TN} value of all sampling points in the Han River Reservoir was lower than S_{TP}, and the average S_{TN} value of all sampling points in the Dan River Reservoir was higher than S_{TP} during the nonflood season. The average S_{TN} values of these two river reservoirs were higher than S_{TP} in the flood season. It indicated that phosphorus pollution in the Han River Reservoir was more prominent in the nonflood season, while nitrogen pollution in the Dan River Reservoir was more prominent. After the flood season, the nitrogen pollutions in these two river reservoirs' sediments were both more serious. The results indicated that flood season was the main period of nitrogen pollution input in the Danjiangkou Reservoir. The surrounding tributaries of the Han River Reservoir area were the main inflow rivers of the Danjiangkou Reservoir. Sediment in the upstream water would be silted along the way after entering. Moreover, the adsorption of phosphorus particles in the water column during sediment deposition in the nonflood season might play a key role in the high TP in the Han River Reservoir. The comprehensive pollution index of surface sediments showed that the Han River Reservoir was moderately polluted (*FF* = 1.61) and the Dan River Reservoir was mildly polluted (*FF* = 1.42).

3.3. Nitrogen and Phosphorus Pollution Load Estimation

The nitrogen and phosphorus nutrients in the Han River Reservoir and the Dan River Reservoir sediments were released slowly to a certain extent under static conditions, as shown in Figure 5. Both of the nutrient concentrations in the simulated release device showed a fluctuating upward trend. Among them, the release rates of nitrogen were 1.06, 2.23, and 1.95 mg/(m^2·d) in the Han River Reservoir under different temperature conditions (15, 20, and 25 °C), respectively. The Dan River Reservoir had a higher nitrogen release rate, with corresponding rates of 1.97, 1.89, and 3.97 mg/(m^2·d), respectively. The release rates of phosphorus were 0.14, 0.22, and 0.34 mg/(m^2·d) in the Han River Reservoir at 15, 20, and 25 °C, respectively. The Dan River Reservoir could release more phosphorus at the same time, and the corresponding rates were 0.07, 0.74, and 0.94 mg/(m^2·d), respectively. It was estimated that the average temperature of the Danjiangkou Reservoir lasts for 4 months at 15, 20, and 25 °C, respectively. The average area of the reservoir over the years was nearly 600 km^2 [41,42]. The annual release flux of endogenous polluted nitrogen and phosphorus were calculated as 470.44 t and 87.89 t. In 2019, 33,100 t of nitrogen and 2400 t of phosphorus were imported from nonpoint sources in the Danjiangkou Reservoir [35]. It illustrated that the internal pollution of the Danjiangkou Reservoir was light, and the release amount was small, so it was not the main pollution source of the reservoir at present.

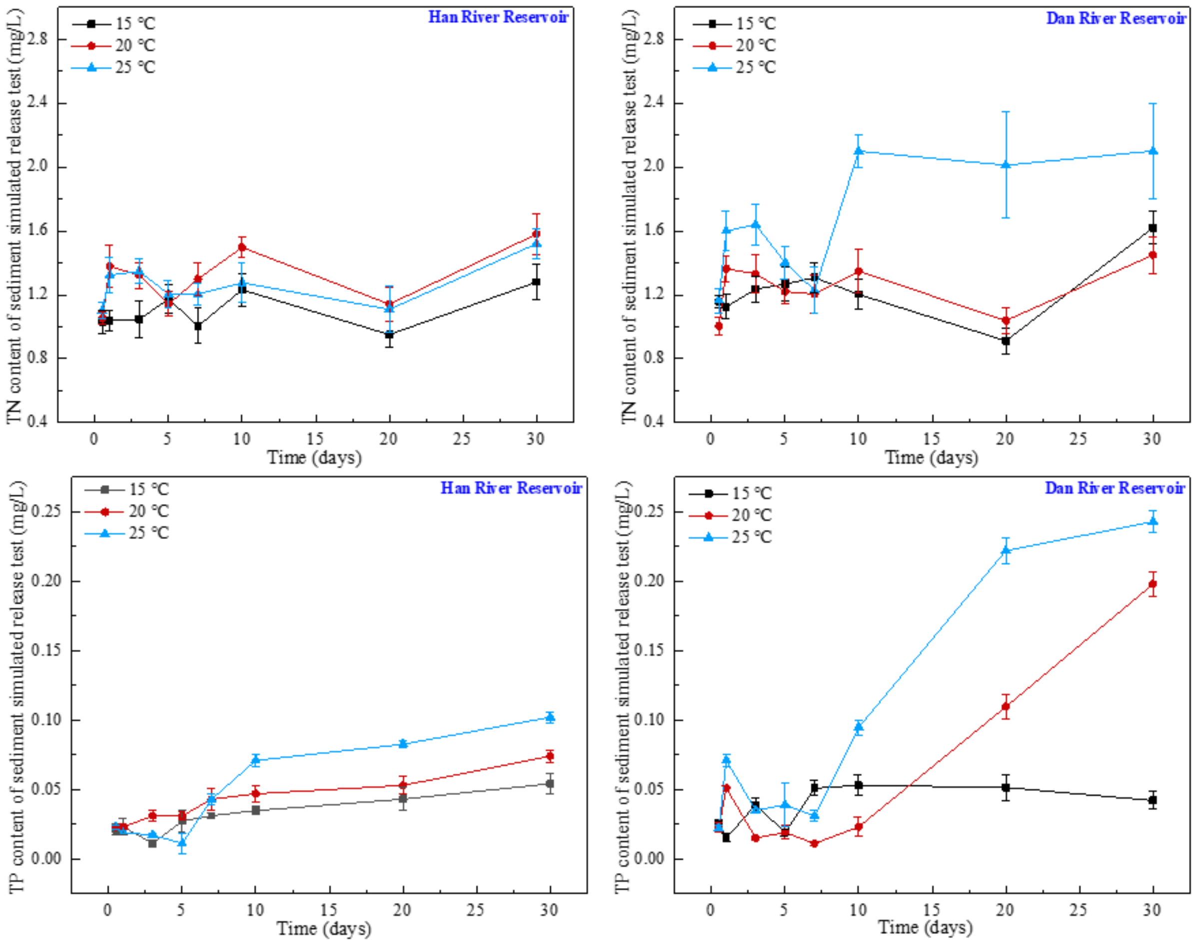

Figure 5. Simulated release of nitrogen and phosphorus from Han River Reservoir and Dan River Reservoir sediments.

4. Conclusions

In this study, we investigated the distribution of carbon, nitrogen, and phosphorus nutrients in sediments of the Danjiangkou Reservoir at different water periods. After a comprehensive analysis and discussion of the results, we found that: (1) Nitrogen pollution in the reservoir was at the lowest level in both the nonflood season and the flood season, which was still acceptable to most habitats. However, there was a certain nitrogen enrichment in the reservoir area, and the flood season was the main period of nitrogen pollution input. (2) Phosphorus pollution in reservoir sediments fluctuated between safe and lowest level pollution at different water stages. As a whole, the TP content of the sediment at the inlet of the inflow river was higher than that in other areas of the reservoir. In addition, there was an obvious enrichment of phosphorus nutrients in front of the dam during the nonflood season, and the content was significantly higher than that in other waters. (3) The organic matter of reservoir sediments was at the lowest level of pollution. The TOM content of the Han River Reservoir sediment was slightly higher than the Dan River Reservoir in the nonflood season but slightly lower than the Dan River Reservoir in the flood season. Water exchange during the flood season might accelerate organic matter degradation. In addition, near the dam, sediment organic matter content increased significantly, reaching severe pollution levels. (4) The nitrogen and phosphorus nutrients in the reservoir would release slowly. Their annual release flux was calculated as 470.44 t and 87.89 t, respectively. The Danjiangkou Reservoir is a multiyear regulating reservoir. Unlike the common lakes and reservoirs, the nutrient contents in this reservoir's sediments fluctuate greatly in different water periods. The reasons for this phenomenon need to be further studied.

In addition, there are some limitations in the laboratory simulated experiment of nitrogen and phosphorus nutrient release in sediments, and in-situ observation of nutrient release in reservoir sediments can be carried out in the future.

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