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Distribution and risk assessment of nutrients and heavy metals from sediments in the world-class water transfer projects

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Abstract

South-to-North Water Diversion Project, a globally renowned engineering feat, aims to address water supply issues. The sediments within reservoirs play a pivotal role in natural ecosystems, not only as habitats for diverse biota but also as repositories of heavy metals, organic matter, and other contaminants. These sediments serve as a critical interface between sediment and water bodies. This comprehensive analysis focused on the spatial patterns of nutrients, organic matter, and heavy metals in the surface layer and profiles of reservoirs, exploring their interconnectedness. Leveraging the integrated pollution index, organic pollution index, potential ecological risk index, and geo-accumulation index, an ecological risk assessment was performed. The key findings are as follows: (i) Along the Middle Route of the South-to-North Diversion Project, the nutrient and organic matter contents in sediments tends to rise with distance from the Danjiangkou Reservoir, with the TN and TC contents increasing by 2.35- and 3.05-fold, respectively. (ii) As the sediment depth increases, the carbon, nitrogen, phosphorus, and organic matter contents exhibit varying degrees of decline, with average decreases of 62.38%, 67.47%, 17.56%, and 41.83% for TN, TC, TP, and OM, respectively. (iii) Among the eight heavy metals, only manganese (Mn) and zinc (Zn) in the Yahekou Reservoir showed moderate pollution levels, according to the geo-accumulation index. The Mn content within the surface sediments of the six reservoirs ranges from 550 to 1837 mg/kg (average, 1019.5 ± 548.3 mg/kg), whereas the Zn content ranges from 89 to 360 mg/kg (average, 156.5 ± 101.6 mg/kg). (vi) Total phosphorus (TP) and total nitrogen (TN) emerged as the primary pollutants in surface sediments. Comprehensive nitrogen and phosphorus pollution assessment revealed that the surface sediment of Danjiangkou Reservoir is mildly polluted, while Baiguishan and Jiangang Reservoirs are moderately polluted, and the rest are heavily contaminated. For the Yahekou and Chaohe Reservoirs, the average pollutant content indicates moderate pollution, while the remaining reservoirs show mild pollution levels.

Highlights

- Characteristics of nutrients in the profile of sediments were investigated.
- Complex relationship between organic matter and heavy metal was revealed.

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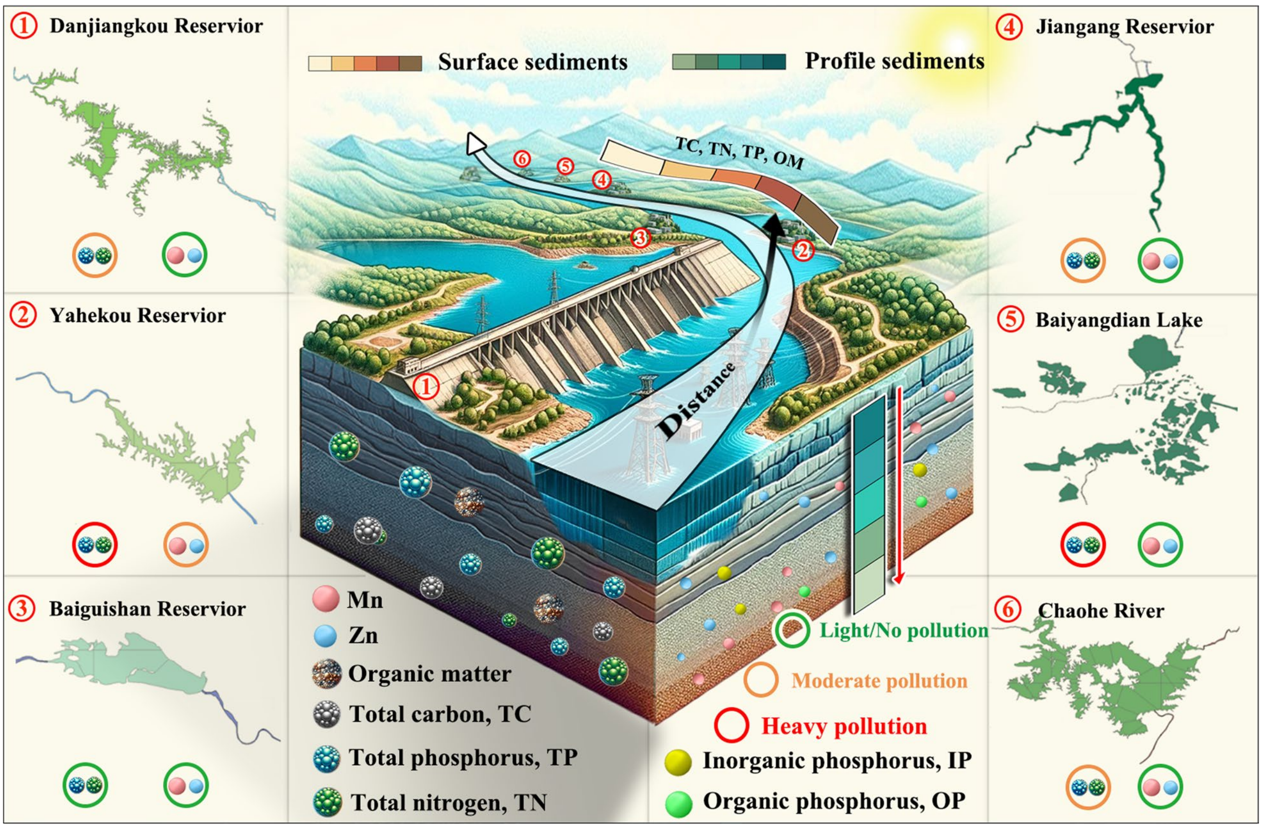
- Water quality of part reservoirs has ecological risk by the multiple methods.

Keywords Sediments, Nutrients, Heavy metals, Profiles, Pollution

Graphical Abstract



Introduction

Sediment is an important part of water ecosystem, which usually contains soil, sand, organic matter or minerals that are toxic or hazardous to human or environmental health [1]. Nutrients in sediments are recycled through the migration of organisms and water flows, which can greatly affect the process of water eutrophication [2]. Heavy metal is a kind of persistent pollutant with strong biotoxicity, easy to accumulate and difficult to degrade [3]. Most of the heavy metals entering the reservoir enter the sediment through flocculation and precipitation, which is the "sink" of heavy metals [4]. At the same time, heavy metals will be released from the sediment and enter the water under certain conditions. Metals remain in the aquatic ecological environment and may accumulate in microorganisms, aquatic animals and plants, and then may enter the human food chain and pose a threat to human health [5–7]. Organic matter is considered to be the main carrier of heavy metals due to its strong affinity for metals through adsorption or complexation [8]. Therefore, the study of sediment pollution status is of great significance for water ecosystem protection.

Interactions between sediments and water bodies are essential for understanding the environmental health of aquatic ecosystems [9–11]. A series of case studies highlight the application of various methodologies, including the potential ecological risk index and geo-accumulation index, to ascertain pollution levels. Previous research has investigated the distribution patterns of nutrient and heavy metals in the sediments of the Huangbai River cascade reservoir [12]. Using methodologies such as the potential ecological risk index and geo-accumulation index, assessed the pollution levels of six distinct heavy metals within the sediment [12]. Previous research has also investigated the distribution characteristics and evaluation of nitrogen, phosphorus, and organic matter in the middle reaches of the Chaobai River and inferred the source through a Pearson correlation analysis of the total phosphorus (TP), total nitrogen (TN), organic matter (OM), and total organic carbon (TOC) characterization [13]. Other scholars have examined the distribution of nutrients and pollution in surface sediments of the Qinglinjing Reservoir, determining organic matter sources by calculating the TN and TOC correlations and the TOC/TN ratio, thus assessing pollution status [14]. Another study examined the nutrient distribution, pollution, and phosphorus evolution in the columnar sediments of the Xiaoshangpao Lake [15]. Through an integrated analysis of OM, TN, grain size, and sedimentary age, they assessed the contamination in sedimentary cores and identified significant correlations driving nitrogen and phosphorus accumulation across various sediment forms since 1940 [15]. Additional studies in the Yitong River and Hengshui Lake have employed different indices and chemical extraction methods to assess the nutrient salt distribution and pollution risk [16, 17]. Their findings highlighted the significant impact of TOC on TN release, the correlation between higher TOC content and elevated pollution risk from potential nitrogen sources, and variations in the release risk of different forms of nitrogen and phosphorus, substantiated by C/N, C/P, and N/P ratios for source characterization. Characterization studies following an assessment of the current pollution status facilitate pollution source identification, while traceability analysis provides guidance for subsequent remediation strategies [18, 19]. Concurrently, robust research can verify the efficacy of management interventions, assess the effectiveness of governance measures, and offer insights into potential improvements [20, 21]. However, these studies often face limitations, such as the difficulty in pinpointing the exact pollution sources and the variability of pollutant behavior under different environmental conditions. Furthermore, most research has focused on specific rivers, lakes, and reservoirs, with relatively few studies examining the cumulative impact and complex interactions of pollutants along the routes of world-class water transfer projects. This gap in research highlights the need for more comprehensive analyses in these large-scale engineering contexts to better understand and manage ecological risks.

The South-to-North Water Diversion Project (SNWDP) is a world-class water transfer projects. The middle route project focuses on solving the problem of water resources shortage in Beijing, Tianjin, Henan and Hebei provinces and cities in China. It is an important strategic project of drinking water supply guarantee in the north of China, and its water quality is closely related to the safety of water supply. This study focused on the Danjiangkou Reservoir, Yahekou Reservoir, Baiguishan Reservoir, Jiangang Reservoir, Baiyangdian Lake, and the Chaohe Reservoir, which are parts of SNWDP central route of China. The present study investigated the spatial distribution of TN, TC, TP, OM, and heavy metals in the surface and profile sediments of these reservoirs. TN, TC, TP, and OM are essential for understanding nutrient cycling and potential eutrophication processes, while heavy metals (e.g., Mn, Zn, As, Cr, Cd, Hg, Ni, and Pb) pose significant pollution risks due to their toxicity and persistence in the environment. Manganese (Mn) is a common metal element and water pollutant; it is easily dissolved and concentrated in water bodies in various states, such as the ionic, colloidal, complex, and suspended states, in reservoirs, causing the pollution of water ecosystems. Zinc (Zn) is toxic to aquatic organisms and affects the stability of water ecosystems. Therefore, the present study focused on Mn and Zn, and examined the spatial distribution of nutrients, OM, and heavy metals in the surface and sediment profiles and the relationship between these components.

By examining the relationships between these components, our study provides insights into the environmental health and potential contamination risks affecting the SNWDP. The analysis of nutrient, OM, and heavy metal contents in sediments at different depths offers valuable data for risk assessment and highlights the importance of maintaining water quality in such a vital water transfer project. Understanding these risks is essential for developing effective management strategies to ensure the long-term sustainability and safety of the SNWDP, thereby securing reliable water supply for northern China. Furthermore, the findings and methodologies from the present study will serve as a valuable reference for other large-scale water transfer projects globally, providing a basis for assessing and managing water quality and ecological health in similar initiatives.

Materials and methods

Overview of the study area

The SNWDP, a strategic initiative in China, encompasses three routes—east, central, and west—to address water scarcity, particularly in the northern regions, notably in the Huanghai Basin, and to optimize water resource allocation. For this project, we sourced water from the Danjiangkou Reservoir in the Han River Basin and conveyed it to Henan, Hebei, Tianjin, and Beijing, ultimately reaching Tuancheng Lake in the Summer Palace, Beijing. Spanning 1,277 km, the main canal of the project encounters multifaceted environmental factors that affect water quality, posing a significant challenge to water pollution prevention and control.

Danjiangkou Reservoir (32°36’ ~ 33°48’N, 110°49’ ~ 110°59’E) is located in Hubei Province, and the reservoir area by the Hanjiang River, Danjiang River, two major reservoirs and a narrow river channel, is the largest artificial freshwater reservoir in Asia. For the SNWDP water source, located in the river and Danjiang reservoir area at the confluence of the dam height to 176.6 m, the total storage capacity was 29.05 billion m^3, and the water area expanded to 1050 km^2 [22]. Yahekou Reservoir, situated north of Nanyang City in Henan Province, is a significant reservoir in the upper Baihe River, a tributary of the Han River in the Yangtze River Basin. Encompassing an expansive area of 120 km^2, the reservoir has a total capacity of 1,339 million m^3. It is an integral part of the largest natural-flow irrigation system in Henan Province, spanning a controlled watershed area of 3,030 km^2. Baiguishan Reservoir (33°40’ ~ 33°50’N, 112°50’ ~ 113°15’E) is located in the southern part of Xincheng District, Pingdingshan City, the reservoir occupies an area of nearly 70 km^2, with a capacity of 649 million m^3, and a total controlled watershed area of 1310 km^2 [23]. Jiangang Reservoir, situated within Zhengzhou City, encompasses a control basin area of 113 km^2. With a total capacity of 68.2 million m^3, the reservoir holds a cumulative water resource of 424 million m^3 and experiences an average annual flow rate of 11.1 m^3/s [24]. Baiyangdian Lake are located in Baoding City and Cangzhou City, at the junction of 143 interconnected sizes of the precipitation of the general term, and are the largest freshwater reservoir and wetland in North China. They have a total area of 366 km^2 and an average annual water storage capacity of 1.32 billion m^3 [25]. The Chaohe Reservoir is located in the northern part of Miyun District, Beijing, and is the only surface water source in Beijing, with a reservoir area of 188 km^2, watershed area of 15,788 km^2, and reservoir capacity of 4 billion m^3[26]. The sampling locations are shown in Fig. 1.

Sample collection and pretreatment

Surface and profile sediment samples were collected from July 30 to September 1, 2020 from reservoirs along the South-to-North Water Diversion Central Route Project, and sediment samples were collected by using a self-gravity profile sediment collector, and one sediment profile core was collected from each sampling point to be protected from light and cryopreserved to be brought back to the laboratory. The sampling points were located at the center of the reservoirs to avoid interference from

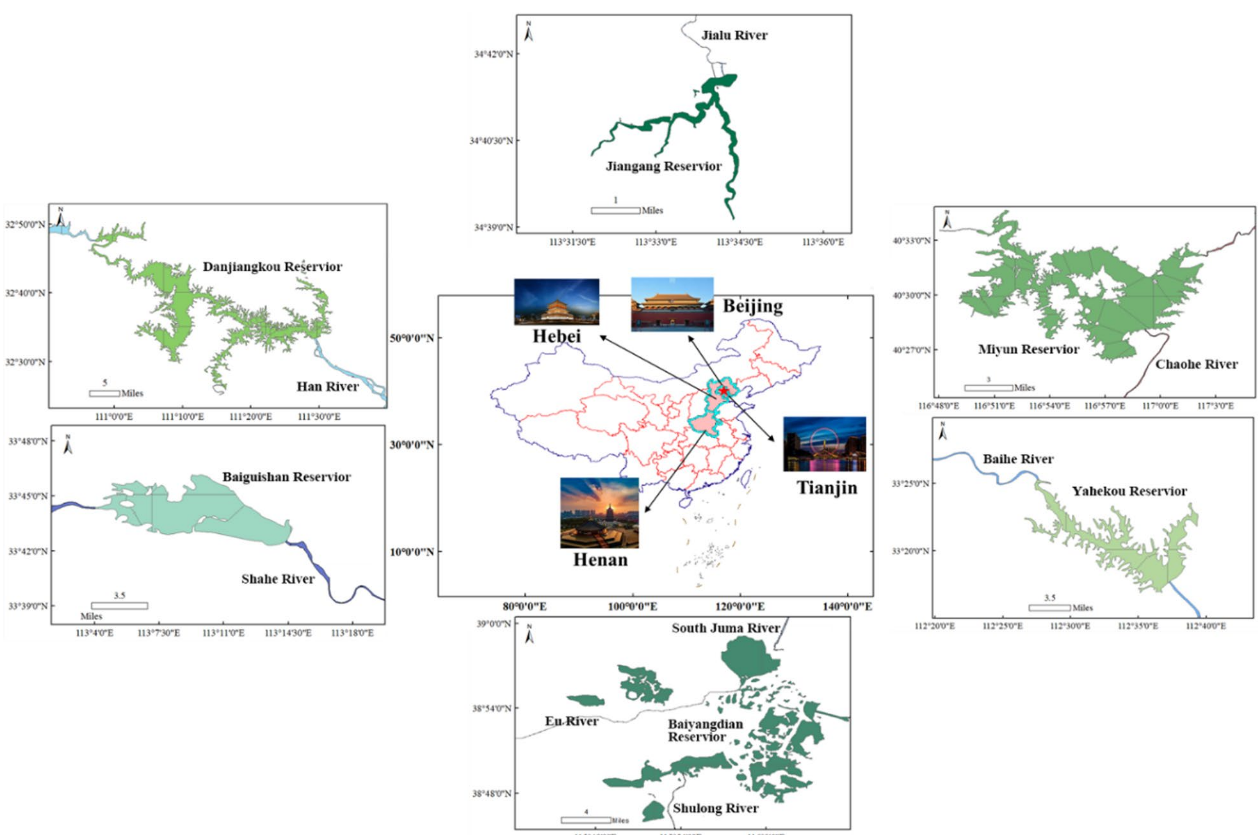


Fig. 1 Study area

external sources, ensuring that we focused on the sediment profiles. We sampled the sediments of the Danjiangkou Reservoir, Yahekou Reservoir, Baiguishan Reservoir, Jiangang Reservoir, Baiyangdian Lake, and the Chaohe Reservoir in layers (one layer per 1 cm). The detailed sampling points are listed in Table 1. At each sampling point, three parallel, surface, and profile sediments, totaling 360 samples, were collected to detect various pollution indicators in the sediments and analyze the data to obtain the distribution characteristics of pollutants and conduct a risk assessment. The Danjiangkou Reservoir has 6 layers, numbered DJ1-DJ6. The Yahekou Reservoir has 30 layers, numbered YH1-YH30. The Baiguishan Reservoir consists of 18 layers, labeled BG1–BG18. The Jiangang Reservoir has 17 layers, numbered JG1–JG17. The Baiyangdian Lake comprises 14 layers, labeled BY1–BY14. The Chaohe Reservoir includes 35 layers, numbered CH1–CH35. The depths of these layers were determined based on the depths of their respective reservoirs. DJ1, YH1, BG1, JG1, BY1, and CH1 are the surface samples of the six reservoirs, and the rest are profile samples of individual reservoirs. The obtained sediment samples were dried using a freeze dryer to remove impurities such as plant debris and large stone particles, ground through a 100-mesh sieve, and stored at −20 °C for subsequent experiments.

Analytical methods

Elemental determination of total carbon and nitrogen was carried out using an elemental analyzer (Elementar Vario macro EL, Germany). The determination of each form of phosphorus in the sediments was carried out by molybdenum-antimony spectrophotometry, which is mainly divided into total phosphorus (TP), inorganic phosphorus (IP), and organic phosphorus (OP), obtained by differential subtraction [27, 28]. Determination of OM in sediments was carried out using the standard method in "Solid waste—Determination of organic matter—Ignition loss method" (HJ761-2015) [29], the specific test method is reflected in the supporting information (SI. Text 1). The dissolution of heavy metals (Mn, Zn, As, Cd, Cr, Hg, Ni, Pb) in the sediment was conducted following the standard procedure outlined in "Soil and sediment-determination of aqua regia extracts of 12 metal elements- inductively coupled plasma mass spectrometry" (HJ 803–2016) [30], and concentrations were determined using an inductively coupled plasma optical emission spectrometry (ICP-OES). The limit of detection (LOD) was 0.000055–0.081500 mg/L, and the limit of quantitation (LOQ) was 0.0002–0.2446 mg/L (SI. Text 2).

Here, the authors used comprehensive quality control procedures in the pilot study, including standard operating procedures and reagent blank analyses. To ensure the quality of the analyzed data, three replicates were used for all analyses, and the results are presented as mean values.

Data processing methods

The pollution risk assessment of nutrients, organic matter, and heavy metals was conducted using single-factor and comprehensive pollution index evaluation methods [31–33], organic pollution index evaluation methods [32], potential ecological risk index assessment methods [34–36], and geo-accumulation index evaluation method [33, 34, 36] (SI. Text 3). The Partial Least Squares Structural Equation Modeling (PLS-SEM) software Smart PLS was employed for the analysis, while the data processing and statistical analyses were conducted using Microsoft Excel 2016. The mapping and graphical illustrations were created utilizing QGIS and Origin version 8.5 software. Statistical analyses included normality tests, variance analyses, and correlation analyses, with Pearson correlation coefficients (R) indicating the strength and direction of relationships.

Results and discussion

Distribution of nutrient

Characterization of nutrient

The vertical distribution characteristics of total nitrogen (TN) and total carbon (TC) in the sediments of the reservoirs along the Middle Route of the SNWDP are shown in Figure S1. The reservoirs, arranged from south to north along the SNWDP line, include the Danjiangkou Reservoir, Yahekou Reservoir, Baiguishan

Table 1 Reservoir characteristics and overview of sampling points [22–26]

Reservoir	Capacity (million m^3)	Area (km^2)	Samples	Longitude	Latitude
Danjiangkou	29050	1050	DJ1–DJ6	111.58866876	32.74175185
Yahekou	1339	120	YH1–YH30	112.56340319	33.35284577
Baiguishan	649	70	BG1–BG18	113.18637711	33.73273893
Jiangang	68	113	JG1–JG17	113.56801316	34.69151422
Baiyangdian	1320	366	BY1–BY14	116.03078018	38.86231676
Chaohe	4000	188	CH1–CH35	116.98616692	40.48225268

Reservoir, Jiangang Reservoir, Baiyangdian Lake, and Chaohe Reservoir. Throughout this study, "each reservoir" refers to this sequential arrangement, unless otherwise stated. Strong correlations were observed between TN and TC in the sediments of each reservoir (R = 0.989, 0.981, 0.960, 0.896, 0.997, and 0.977, respectively). This suggests a common source or a similar formation or enrichment mechanism for nitrogen and carbon. The ratio of the TC to TN is an important index of self-purification ability. A lower C/N ratio is often associated with a higher rate of degradation for materials such as algae and aquatic macrophytes, indicating their propensity for more rapid decomposition [32]. The regulation of carbon source and nitrogen source can promote the material circulation of water ecosystem and the decomposition of organic matter, better maintain the stability of water quality, and provide a good living environment for drinking water safety and aquatic organism health [33]. In addition to external inputs, carbon in aquatic ecosystem mainly comes from photosynthesis of phytoplankton, absorption of fixed carbon dioxide, Nitrogen mainly comes from the dead remains of aquatic organisms. The C: N ratio varied among different reservoirs, which could be attributed to variations in geographical environments, microbial communities, or inputs from external pollutants. The TN and TC contents in the sediments showed a decreasing trend with increasing depth (Figure S1). This trend is influenced by the gravitational settling of various pollutants, and the aquatic biomass remains in the surface layer where benthic communities are more active. In contrast, sediments in deeper layers underwent longer periods of pollutant degradation due to the reduced microbial population, resulting in lower TN and TC contents compared to the surface layers [37, 38]. Variations in the vertical changes in TN and TC contents exhibited distinct differences among the different reservoirs (Figure S1).

In the Baiguishan Reservoir and Baiyangdian Lake, the TN and TC contents decreased gradually with increasing depth. The rate of decrease slowed as depth increased, and below a depth of 10 cm, the content remained relatively stable. Conversely, in the Danjiangkou Reservoir and Chaohe Reservoir, the TN and TC exhibited an initial decreasing trend, followed by an increase. An increase was observed in the Danjiangkou Reservoir after a depth of 4 cm, and in the Chaohe Reservoir after a depth of 30 cm. For the Jiangang and Yahekou reservoir, the TN and TC contents displayed significant fluctuations within the depth ranges of 0–7 cm and 0–14 cm, respectively, while the overall trend continued to decrease. These fluctuations could be attributed to specific biological activities.

Comparing TN contents with those of surface sediments, a reduction of 36.00%, 47.67%, 79.29%, 69.65%, 78.43%, and 63.22% was observed in Baiguishan Reservoir, Baiyangdian Lake, Danjiangkou Reservoir, Chaohe Reservoir, Jiangang Reservoir, and Yahekou Reservoir, respectively, with an average decrease of 62.38%. Similarly, comparing the TC contents with those of the surface sediments, reductions of 55.90%, 54.24%, 92.99%, 44.59%, 88.18%, and 68.90% were recorded in the reservoirs, respectively, yielding an average decrease of 67.47%.

As illustrated in Fig. 2a, the surface sediment TN content across reservoir spans from 1287.21 to 4310.62 mg/kg, with a mean value of 2534.13 ± 1046.04 mg/kg. The maximum TN content was observed in the Chaohe Reservoir, whereas the lowest was observed in the Danjiangkou Reservoir. Generally, the TN content in surface sediments exhibited a progressive increase northward along the route, with the Yahekou Reservoir demonstrating slightly elevated TN levels compared to its adjacent

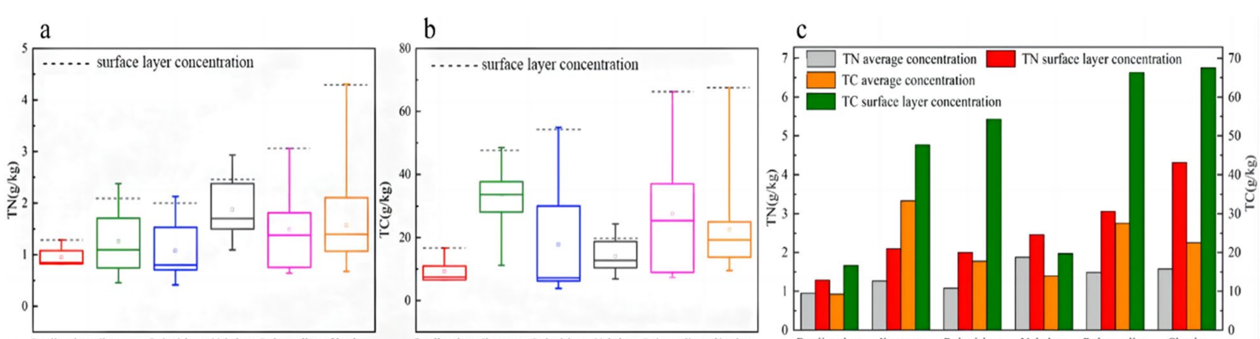


Fig. 2 Differences in the mass concentrations of TN and TC in reservoirs along the middle route of the SNWDP. (**a** comparison of TN concentrations in reservoirs; **b** comparison of TC concentrations in reservoirs; **c** comparison of TN and TC concentrations and mean TN and TC concentrations in the surface sediments)

reservoirs. The TN content of the surface layers along the route increased by 2.35-fold.

As depicted in Figure S2, the mean TN contents of the six reservoirs (i.e., the average vertical TN content of an individual reservoir) were 951.03, 1879.03, 1077.07, 1260.06, 1487.00, and 1575.37 mg/kg, respectively. The overall average across all sites was calculated as 1371.59 ± 343.0 mg/kg. Yahekou Reservoir had the highest TN content, whereas the lowest TN concentration was recorded in Danjiangkou Reservoir. In general, except for the notably elevated TN content in the Yahekou Reservoir, the average TN content of the sediments gradually increased in a northward direction along the route, closely resembling the pattern observed in the surface sediments.

As shown in Fig. 2b, the difference in TC content in sediments of all reservoirs ranged from 16.66 to 67.52 g/kg, with an average of 45.34 ± 22.32 g/kg in surface sediments of the six reservoirs. The highest TC content was found in the Chaohe Reservoir, and the lowest in the Danjiangkou Reservoir. In general, the TC content on the sediment surface gradually increased along the line and the concentration increased sharply between the Yahekou and Baiguishan reservoirs. The total TC content of the surface layer along the line increased by 3.05 times. The average TC content of the six reservoirs (i.e. the average vertical TC content of a single reservoir) was 9.25, 13.96, 17.76, 33.32, 27.54, 22.55 g/kg, respectively, and the overall average was 20.73 ± 21.47 g/kg, with the highest content in Jiangang Reservoir and the lowest content in Danjiangkou Reservoir. In general, the average TC content first increased and then decreased along this line.

As shown in Fig. 2c, the surface TN and TC of reservoir showed an increasing trend with the distance from the Danjiangkou Reservoir to other reservoirs along the line. This is because in the process of one-way water transport, pollutants in the surrounding environment continue to enter the water body through rainfall and surface runoff, resulting in an increase in TN and TC content in sediments. Among them, the average TC of Baiyangdian Lake and the Chaohe Reservoir was lower than that of the upstream reservoir due to the deep sediment being less affected by the water body and reflected the pollution status of the reservoir before the middle route of the South-to-North Water Diversion project.

The vertical distributions of TN and TC in the sediments of reservoir had a strong correlation (R of reservoir was 0.989, 0.981, 0.960, 0.896, 0.997, and 0.977, respectively) and showed a decreasing trend with increasing profile depth. The TN content of reservoir decreased by 36.00%, 47.67%, 79.29%, 69.65%, 78.43% and 63.22%, respectively, with an average decrease of 62.38%. The TC content in reservoir decreased by 55.90%, 54.24%, 92.99%, 44.59%, 88.18%, and 68.90%, with an average decrease of 67.47%.

Distribution of phosphorus

The vertical distribution characteristics of the TP, IP, and OP contents in the sediments of reservoir are shown in Figure S2. TP and IP in the sediments of reservoir were strongly correlated ($p < 0.05$), suggesting that TP and IP have the same source or were formed for similar reasons. The TP and OP contents in reservoir showed a decreasing trend with increasing profile depth. This is because various pollutants and residues of aquatic organisms in the water body were deposited on the surface under the action of gravity, and some microorganisms participated in the transformation of the phosphorus form, causing the IP content to fluctuate horizontally with increasing profile depth. The variations in TP, IP, and OP contents in the vertical direction of reservoir are different, which may be caused by different historical factors, geographical environments, microbial populations, or exogenous pollution inputs.

The TP, IP, and OP contents in Baiyangdian Lake decreased steadily with increasing depth. The contents of TP and OP in Danjiangkou Reservoir first decreased slightly with increasing depth, then increased slightly, and finally decreased sharply at 5 ~ 6 cm, while the IP content increased steadily with increasing depth. The contents of TP, IP, and OP in Jiangang Reservoir fluctuated within a relatively stable range, and the contents of TP and OP dropped sharply at 5 cm, even though the measured value of TP was lower than the measured value of IP, which may indicate strong biological activity. The contents of TP and IP in Baiguishan Reservoir showed regular and gentle fluctuations with depth. The “peak” appeared at 3 cm, 10 cm and 18 cm, respectively, while the IP content was relatively stable, and there was a corresponding “valley” at the peak of TP and IP content. The TP and IP contents of Yahekou Reservoir showed a strong correlation and a decreasing trend in general, rising and falling rapidly at 7, 14, and 27 cm, while the OP content fluctuated back and forth in a relatively stable range. The TP and OP contents in the Chaohe Reservoir generally showed a decreasing trend with many drastic fluctuations, whereas the IP content of the Chaohe Reservoir fluctuated back and forth in a relatively stable range, and its fluctuations were strongly correlated with the fluctuations in TP content.

The vertical TP contents of Danjiangkou Reservoir, Yahekou Reservoir, Baiyangdian Lake, and Chaohe Reservoir decreased by 12.13%, 27.84%, 44.13%, and 28.85%, respectively, whereas the TP contents of Baiguishan Reservoir and Jiangang Reservoir increased by 6.69% and 0.88%, respectively, with an average decrease of 17.56%.

The IP content in the Yahekou, Baiyangdian, and Chaohe reservoirs decreased by 32.56%, 26.65%, and 8.28%, respectively. The IP contents of the Danjiangkou, Baiguishan, and Jiangang reservoirs increased by 11.32%, 21.69% and 6.14%, respectively. The OP content in six reservoirs decreased by 78.90%, 17.05%, 30.40%, 23.10%, 100%, and 57.55%, respectively, with an average decrease of 51.17%.

As depicted in Fig. 3a, the TP content of surface sediments within the six reservoirs ranged from 476.30 to 912.06 mg/kg, with an average of 633.27 ± 162.84 mg/kg. The highest content was observed in the Chaohe Reservoir, whereas the lowest was found in the Danjiangkou Reservoir. Generally, the TP content of the surface sediments exhibited a gradual increase in the northern direction, except for the Yahekou Reservoir, which displayed significantly higher levels than the adjacent reservoirs. Furthermore, the Chaohe Reservoir exhibited a substantially elevated surface TP content compared to other reservoirs, reflecting a 47.78% increase. The average vertical TP content within the dataset of each reservoir was 464.01, 630.18, 562.66, 538.01, 470.01, and 633.54 mg/kg, respectively, with an overall mean of 549.78 ± 67.76 mg/kg. Generally, the Chaohe Reservoir exhibits the highest TP content, whereas the Danjiangkou Reservoir exhibits the lowest. Along the route from Yahekou Reservoir to Baiyangdian Lake, the average TP content gradually decreased. It is worth mentioning that Baiyangdian Lake, has been seriously polluted in the past few decades [39]. The damage to the ecological environment of Baiyangdian Lake is mainly caused by the construction of a large number of water conservancy projects upstream, which cut off the water source, resulting in the reduction of the river water volume [40]. A large number of industrial wastewater and domestic sewage flowed into Baiyangdian Lake. In 2018, The State Council issued the Plan for Ecological Environment Governance and Protection of Baiyangdian Lake (2018–2035), which comprehensively managed point source and non-point source pollution sources in the upper reaches of Baiyangdian Lake. By 2021, the water environmental quality will reach or exceed Class IV of environmental assessment of water quality in China [41]. According to a recent study on Baiyangdian Lake, the average TP was 696.73 mg/kg for samples collected during the precipitation period (July to September) in 2020. The sampling site was located at the Baiyangdian Lake, which is the lower reaches of the Fuhe River, and phosphorus may settle and accumulate in the sediment during the flow of the river [42]. At the

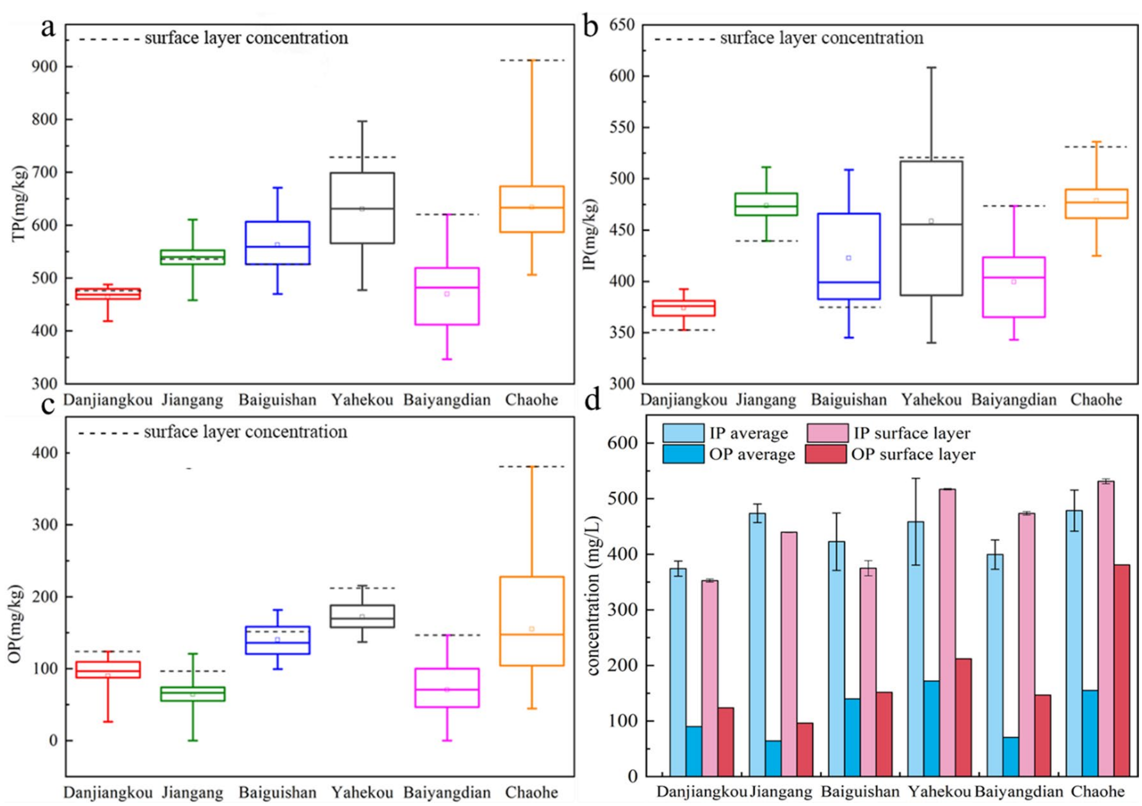


Fig. 3 Differences in the mass concentrations of TP, IP, and OP in reservoir sediments along the middle route of the SNWDP (**a** comparison of TP contents; **b** comparison of IP contents; **c** comparison of OP contents; **d** comparison of OP and IP contents in the sediments)

same time, the temperature in the precipitation period is higher than that in the water transfer period and non-water transfer period, which could decrease the solubility of oxygen in water [43]. The physical, chemical and biological reaction rate in the sediment is faster, and the microbial activity is increased, which promotes the release of phosphorus from the sediment [44].

As illustrated in Fig. 3b, the IP content of surface sediments within the six reservoirs ranged from 352.51 to 531.19 mg/kg, with an average of 448.07 ± 73.32 mg/kg. Similar to TP, the Chaohe Reservoir exhibited the highest IP content, whereas the Danjiangkou Reservoir had the lowest. With the exception of Yahekou Reservoir, which presented notably higher levels than the adjacent reservoirs, a general increasing trend in IP content along the northern direction was observed. The cumulative IP content within the surface layer along this route increased by 33.64%. The mean IP content (representing the average vertical TP content of a single reservoir dataset) was 374.04, 458.52, 422.62, 473.60, 399.52, and 478.50 mg/kg, respectively, resulting in an overall mean value of 434.47 ± 42.57 mg/kg. The highest content was found in the tidal river, whereas the lowest content was found in the Danjiangkou Reservoir.

As shown in Fig. 3c, the OP content of surface sediments within the six reservoirs ranged from 96.40 to 380.87 mg/kg, with an average of 185.20 ± 103.22 mg/kg. The highest content was recorded in the Chaohe Reservoir, significantly surpassing the other reservoirs, whereas Jiangang Reservoir exhibited the lowest content. Generally, the OP content exhibited an initial increase, followed by a decrease, and a subsequent increase towards the north. Overall, the surface OP content increased by 67.50%. The average OP content within each reservoir dataset (representing the average vertical OP content of a single reservoir) was 89.97, 171.96, 140.04, 64.41, 70.48, and 155.03 mg/kg, respectively, resulting in an overall average of 115.31 ± 46.13 mg/kg. The highest content was observed in the Yahekou Reservoir, whereas the lowest was found in the Jiangang Reservoir. Generally, the trend in the surface OP content was similar, with the average OP content in the Chaohe Reservoir being marginally lower than that in the Jiangang Reservoir.

A comparative analysis of the surface and average concentrations of TP, IP, and OP in each reservoir is presented in Fig. 3d. Apart from Yahekou Reservoir, which displayed elevated surface and average concentrations of TP, IP, and OP compared to other reservoirs, the surface sediments of the remaining reservoirs demonstrated an ascending pattern from Danjiangkou Reservoir to other reservoirs along the spatial continuum. This distributional trend intensified with increasing distance from Danjiangkou Reservoir. The average concentrations of TP, IP, and OP were notably influenced by the historical characteristics of reservoir, exhibiting a sequence of initial increases, followed by decreases and subsequent increases.

There was a strong correlation between the vertical distribution of TP and IP in the sediments (R was −0.514, 0.974, 0.881, 0.503, 0.981, 0.249, respectively). The TP and OP contents of bank showed a decreasing trend with increasing profile depth. The IP content fluctuated horizontally with increasing profile depth. The TP content of the Danjiangkou Reservoir, Yahekou Reservoir, Baiyangdian Lake, and Chaohe Reservoir decreased by 12.13%, 27.84%, 44.13%, and 28.85%, respectively; the TP content of the Baiguishan Reservoir and Jiangang Reservoir increased by 6.69% and 0.88%, respectively, and the average decrease in the six reservoirs was 17.56%. The OP contents in the Danjiangkou, Jiangang, Baiguishan, Yahekou, Baiyangdian, and Chaohe Reservoir decreased by 78.90%, 17.05%, 30.40%, 23.10%, 100%, and 57.55%, respectively, with an average decrease of 51.17%.

Distribution of organic matter

The vertical distribution characteristics of OM content in the sediments of reservoir are shown in Figure S3. The OM content within the sediments of reservoir exhibited a similar decreasing trend as the total nitrogen (TN) and total carbon (TC) contents, yet distinct distribution characteristics still had some differences. For instance, in the Danjiangkou Reservoir, the OM content demonstrated a consistent decline, with a significant decrease observed between the depths of 1 and 2 cm. While the distribution trends of TN and TC contents were relatively stable, the OM content within the Jiangang and Yahekou reservoirs fluctuated considerably across the 0–7 cm and 0–14 cm depth ranges, respectively. In contrast, the TN and TC contents within the 8–17 cm and 14–30 cm depth ranges displayed more gradual and consistent trends.

Comparing these trends, the OM content in Baiguishan Reservoir and Baiyangdian Lake exhibited strong consistency. However, Baiguishan Reservoir maintained a rapid rate of decrease at depths of less than 10 cm. In the Chaohe Reservoir, the OM content experienced an initial decrease, followed by an increase, with two substantial fluctuations evident within the 15–17 and 17–25 cm depth ranges.

The individual OM content reductions in reservoir were 34.70% (Danjiangkou Reservoir), 39.36% (Jiangang Reservoir), 62.09% (Yahekou Reservoir), 15.55% (Baiguishan Reservoir), 63.69% (Baiyangdian Lake), and 35.60% (Chaohe Reservoir). The combined average decrease across all reservoirs was 41.83%.

Figure 4 illustrates the disparities in organic matter (OM) content within the sediments of various

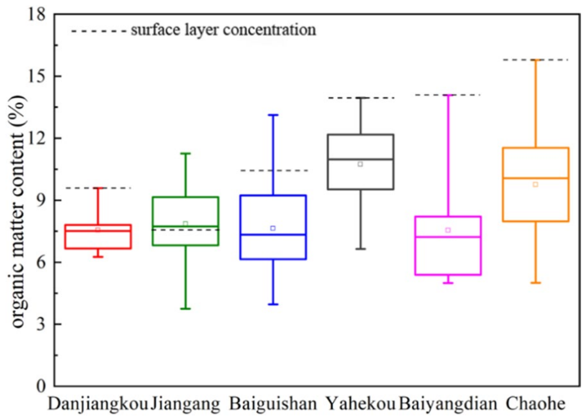


Fig. 4 Differences in the OM contents in the reservoirs along the middle route of the SNWDP

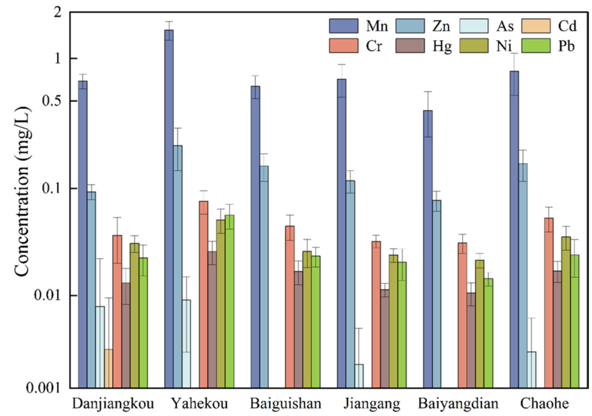


Fig. 5 Concentrations of heavy metals in the sediments of reservoirs along the middle route of the SNWD

reservoirs. The OM content within the surface sediments of the six reservoirs spans a range of 9.59% to 15.79%, with an average value of 11.90 ± 3.18%. The highest content was observed in the Chaohe Reservoir, whereas the lowest content was found in Jiangang Reservoir. Broadly, the OM content of the surface sediments displayed a sequence of initial increase, followed by a decrease, and subsequent increase. The surface OM content increased by 39.27%. The mean OM content within each reservoir dataset (representing the average vertical OM content of a single reservoir) is 7.56%, 10.74%, 7.64%, 7.85%, 7.55%, and 9.75%, respectively, resulting in an overall mean value of 8.51 ± 1.38%. The highest OM content was found in the Yahekou Reservoir, whereas the lowest was found in Baiyangdian Lake. Generally, the OM content in the Yahekou Reservoir and Chaohe Reservoir is relatively higher, whereas the OM content within the other reservoirs falls within the range of 7.5% to 7.9%, demonstrating a relatively stable pattern.

The OM content in the sediments of reservoir showed a decreasing trend similar to that of TN and TC; the OM content of reservoir decreased by 34.70%, 39.36%, 62.09%, 15.55%, 63.69%, and 35.60%, respectively, with an average decrease of 41.83%. The sediment along the middle route of the SNWDP is transferred from a water source (Danjiangkou Reservoir) to other reservoirs along the route. Except for Yahekou Reservoir, the concentration of pollutants was higher, and the sediment nutrient concentration and OM content of the other reservoirs increased with distance from Danjiangkou Reservoir. Total carbon, total nitrogen and total phosphorus increased 3.05 times, 2.35 times and 47.78%, respectively, IP and OP increased 33.64% and 67.50%, and OM increased 39.27% on average. The average vertical nutrient and OM contents along the reservoir first increased, then decreased, and then increased.

Distribution of heavy metals

The average concentration of eight heavy metals in the sediment is shown in Fig. 5. The concentration of Mn ranges from 0.425 mg/L to 1.544 mg/L, with the highest concentration measured in the Yahekou Reservoir and the lowest in the Baiyangdian Lake. That of Zn ranges from 0.079 mg/L to 0.227 mg/L, with the highest in Yahekou and lowest in Baiyangdian. The concentration of As ranges from 0 mg/L to 0.009 mg/L, with the highest in Yahekou. The Cd concentration ranges from 0.000 mg/L to 0.003 mg/L, with the highest in Danjiangkou. The Cr concentration ranges from 0.032 mg/L to 0.077 mg/L, with the highest in Yahekou and lowest in Baiyangdian. The concentration of Hg ranges from 0.011 mg/L to 0.038 mg/L, with the highest in Danjiangkou and lowest in Baiyangdian. The concentration of Ni ranges from 0.022 mg/L to 0.053 mg/L, with the highest in Yahekou and lowest in Baiyangdian. The concentration of Pb ranges from 0.015 mg/L to 0.058 mg/L, with the highest in Yahekou and lowest in Baiyangdian (Fig. 5). Among these heavy metals, the levels of Mn and Zn were significantly higher in the Yahekou Reservoir, indicating a higher potential risk of pollution. This study focuses on the distribution and potential ecological risk of Mn and Zn.

The vertical distribution characteristics of manganese (Mn) and zinc (Zn) contents within the sediments of reservoir are illustrated in Fig. 5. The content of Zn fluctuated at different depths, whereas the content of Mn exhibited a descending trend as depth increased, marked by substantial fluctuations. Within the Danjiangkou Reservoir, both Mn and Zn generally exhibited an ascending trend with depth, characterized by relatively sharp fluctuations. The content of Zn in reservoirs remains relatively stable overall, it decreases in deeper layers compared to surface layers. In contrast, the content of Mn in reservoirs experiences significant drops at depths of 5 cm and 17 cm, while showcasing an overall increasing pattern. The contents of Mn and Zn are lower in the shallow and bottom layers, and higher within the middle depths, also displaying considerable fluctuations in Baiguishan Reservoir. Both contents of Mn and Zn generally exhibit a decreasing trend, with a sharp drop in content of Zn observed at a depth of 8 cm. The content of Mn displays more pronounced fluctuations within the 0 ~ 8 cm range than at other depths. For the Baiyangdian Lake, the contents of Mn and Zn exhibit an initial decrease followed by an increase, with both elements experiencing an increase at depths of 12 ~ 14 cm. Within the Chaohe River, the contents of Mn and Zn remained relatively stable. Notably, there are two distinct "valleys" with markedly decreased content observed at depths of 24 ~ 31 cm. Additionally, the content of Mn within the surface layer is significantly higher than at other depths.

The contrasting differences in content of Mn within the sediments of reservoir are shown in Fig. 6a. The content of Mn within the surface sediments of the six reservoirs ranges from 550 to 1837 mg/kg, with an average of 1019.5 ± 548.3 mg/kg. The highest content is observed in the Yahekou Reservoir, while the lowest content is found in the Baiyangdian Lake. Overall, the average content of Mn in the sediment of the Yahekou Reservoir (1544.4 mg/kg) is significantly higher than in the other reservoirs, while the content of Mn average (819.5 mg/kg) in the sediment of Chaohe Reservoir is only slightly higher than the other reservoirs. The content of Mn within the surface sediments of the other reservoirs remains relatively stable, fluctuating between 425.3 to 720.1 mg/kg.

The disparities content of Zn within the sediments of reservoir are presented in Fig. 6b. The content of Zn within the surface sediments of the six reservoirs ranges from 89 to 360 mg/kg, with an average of 156.5 ± 101.6 mg/kg. The highest content is observed in the Yahekou Reservoir, while the lowest content is found in the Baiyangdian Lake. Overall, apart from Yahekou Reservoir, the content of Zn in the surface sediments of the other reservoirs remained relatively stable, fluctuating between 89 and 143 mg/kg.

The differences between the contents of Mn and Zn within the surface and the average concentrations in reservoir are shown in Fig. 6c. The contents of Mn and Zn in the Yahekou Reservoir are 1.88 to 3.63 times and 1.40 to 2.42 times higher than those of the other reservoirs, with average values of 1544.4 mg/kg and 226.7 mg/kg. The content of Mn from surface sediment is 2.33 to 3.34 times higher than the other reservoirs, with an average value of 819.5 mg/kg in the Chaohe Reservoir.

Ecological risk assessment of nutrient and heavy metals

Risk assessment of nutrient

Nutrient pollution was assessed by evaluating the average TN and TP contents within the surface sediments, as well as the vertical TN and TP contents within the sediments of reservoir. Pollution evaluation was performed using both the single-factor pollution index method and the comprehensive pollution index method, and the results are summarized in Table 2.

Regarding nitrogen pollution, Danjiangkou Reservoir displayed slight pollution, Baiguishan Reservoir exhibited moderate pollution, and Yahekou Reservoir, Jiangang Reservoir, Baiyangdian Lake, and Chaohe Reservoir were severely polluted. When considering average content, the Danjiangkou Reservoir was categorized as clean, the Baiguishan Reservoir was slightly polluted, and the Yahekou Reservoir, Jiangang Reservoir, Baiyangdian Lake, and Chaohe Reservoir as moderately polluted.

The surface sediments of Danjiangkou Reservoir, Baiguishan Reservoir, Jiangang Reservoir, and Baiyangdian Lake were moderately polluted, whereas Yahekou Reservoir and Chaohe Reservoir were heavily polluted. On average, the Danjiangkou, Baiguishan, Jiangang, and

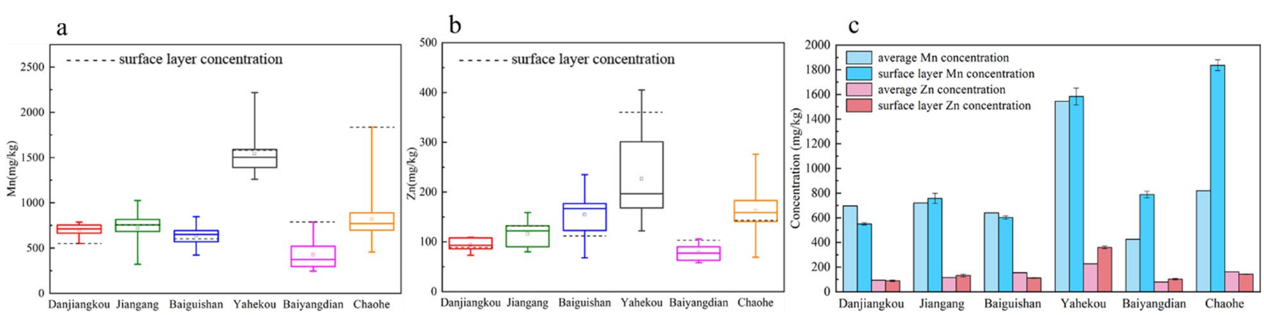


Fig. 6 Comparison of Mn and Zn contents in reservoir sediments along the middle route of the SNWDP (**a** Mn comparison; **b** Zn comparison; **c** sediment Mn and Zn concentration comparison)

Table 2 Evaluation of average surface nutrient content and vertical content of sediments in the reservoirs

Reservoir	Surface layer 0–1 cm			Vertical mean		
	S_{TN}	S_{TP}	FF	S_{TN}	S_{TP}	FF
Danjiangkou	*1.29*	1.13	*1.25*	0.95 ± 0.19	1.10± 0.06	*1.08± 0.10*
Yahekou	**2.46**	**1.74**	**2.28**	1.88± 0.51	**1.50± 0.20**	1.79± 0.42
Baiguishan	2.00	1.25	1.82	*1.08± 0.51*	1.34± 0.14	*1.34± 0.25*
Jiangang	**2.09**	1.28	1.90	*1.26± 0.58*	1.28± 0.07	*1.40± 0.32*
Baiyangdian	**3.06**	1.48	**2.69**	*1.49± 0.72*	1.12± 0.19	*1.43± 0.57*
Chaohe	**4.31**	**2.17**	**3.81**	1.58± 0.75	**1.51± 0.19**	1.65± 0.55

No formatting indicates: $S_{TN} < 1.0$ or $S_{TP} < 0.5$ or FF < 1.0

Bold indicates: $S_{TN} > 2.0$ or $S_{TP} > 1.5$ or FF > 2.0, indicating severe pollution

Underline indicates: S_{TN} between 1.5 and 2.0 or S_{TP} between 1.0 and 1.5 or FF between 1.5 and 2.0, indicating moderate pollution

Italics indicate: S_{TN} between 1.0 and 1.5 or S_{TP} between 0.5 and 1.0 or FF between 1.0 and 1.5, indicating mild pollution

Table 3 Evaluation of surface and vertical mean organic pollution of reservoir sediments along the middle route of the SNWDP

Reservoir	Organic pollution index (OI)			
	Surface layer	Level	Mean	Level
Danjiangkou	0.680	IV	0.405 ± 0.149	III
Yahekou	1.888	IV	1.156 ± 0.482	IV
Baiguishan	1.150	IV	0.510 ± 0.388	IV
Jiangang	0.872	IV	0.583 ± 0.353	IV
Baiyangdian	2.374	IV	0.704 ± 0.597	IV
Chaohe	3.750	IV	0.940 ± 0.722	IV

OI < 0.05 indicates clean water; 0.05 ≤ OI < 0.20, indicating mild pollution; 0.2 ≤ OI < 0.5, indicating moderate pollution; OI ≥ 0.5 indicates severe pollution

Baiyangdian Lake were moderately polluted, whereas the Yahekou and Chaohe Reservoir were severely polluted.

The comprehensive pollution index reflected mild pollution in the Danjiangkou Reservoir, moderate pollution in the Baiguishan and Jiangang Reservoirs, and heavy pollution in the Yahekou Reservoir, Baiyangdian Lake, and Chaohe Reservoir. On average, Danjiangkou, Baiguishan, Jiangang, and Baiyangdian Lake were mildly polluted, whereas Yahekou and Chaohe Reservoir were moderately polluted. TP emerged as the primary nutrient pollutant across all the reservoirs, whereas TN was the main nutrient pollutant in the surface sediments.

Risk assessment of organic matter

An organic pollution assessment was carried out by selecting the average TN and OM contents in the surface sediments of reservoir and the vertical TN and OM contents in the sediments. The results obtained using the organic pollution index (OI) evaluation method were presented in Table 3. Danjiangkou Reservoir was considered to be "moderately polluted", while the surface of Danjiangkou Reservoir and the whole of the other reservoirs are "severely polluted".

Risk assessment of heavy metals

The potential ecological risk index of heavy metals was evaluated by selecting the Mn and Zn contents in the surface sediments and the average vertical Mn and Zn contents in the sediments of reservoir. The results obtained using the evaluation method for the potential ecological risk indices are listed in Table 4. The index values of all the profile samples are far below 40, they

Table 4 Evaluation of potential ecological risk indexes of surface and vertical mean values of reservoir sediments along the middle route of the SNWDP

Reservoir	$E^{Mn}{}_{r}$			$E^{Zn}{}_{r}$		
	Surface layer	Mean	Level	Surface layer	Mean	Level
Danjiangkou	0.91	1.15 ± 0.14	I	1.47	1.55 ± 0.23	I
Yahekou	2.62	2.55 ± 0.35	I	5.96	3.95 ± 1.40	I
Baiguishan	0.99	1.06 ± 0.20	I	1.85	2.56 ± 0.66	I
Jiangang	1.25	1.19 ± 0.31	I	2.19	1.92 ± 0.41	I
Baiyangdian	1.29	0.69 ± 0.26	I	1.31	1.01 ± 0.20	I
Chaohe	3.22	1.44 ± 0.47	I	2.49	2.82 ± 0.82	I

are at a slight risk, which is related to the small toxicity response coefficients of Mn and Zn, indicating that the unit concentrations of Mn and Zn are less harmful to the environment.

The surface Mn and Zn contents within the sediments of reservoir, as well as the average vertical Mn and Zn contents within the sediments, were selected to evaluate heavy metal accumulation using the geo-accumulation index (I_{geo}) method, I_{geo} is an indicator used to assess the enrichment of elements in sediments on the surface of Earth. The results obtained using this method are listed in Table 5. For the Mn element, the I_{geo}-Mn values for the surface and average sediment contents of the Danjiangkou Reservoir, Baiguishan Reservoir, Jiangang Reservoir, and Baiyangdian Lake are all less than 0, indicating that the surface sediments and overall sediment of these four reservoirs are in a state of "no pollution". The Yahekou Reservoir exhibits "mild pollution" for both surface sediments and overall sediment. The Chaohe Reservoir is categorized as "moderately polluted" in the surface and profile sediments, but overall falls under the "no pollution". Regarding the Zn element, the surface sediment and overall sediment of the Baiyangdian Lake are classified as "no pollution." The Danjiangkou Reservoir is classified as "no pollution" for some profiles and "mild pollution" overall in the surface sediment. The Baiguishan Reservoir, Jianggang Reservoir, and Chaohe Reservoir are all classified as "mild pollution" for both surface sediment and overall sediment. Surface sediment and overall sediment are classified as "moderately polluted" in the Yahekou Reservoir.

The threshold effect concentration (TEC) of Zn was 121 mg/kg and the probable effect concentration (PEC) was 459 mg/kg according to sediment quality guidelines [45]. Among the six reservoirs, the contents of Baiguishan Reservoir, Yahekou Reservoir and Chaohe Reservoir were between TEC and PEC (154.8 mg/kg, 226.7 mg/kg and 162 mg/kg), Zn metal posed a risk to aquatic life in these three reservoirs [46].

Table 5 Geo-accumulation Index evaluation of surface and average vertical sediment values for reservoirs along the middle route of the SNWDP

Reservoir	I_{geo}-Mn		I_{geo}-Zn	
	Surface layer	Mean	Surface layer	Mean
Danjiangkou	−0.72	−0.39 ± 0.18	−0.03	0.03 ± 0.22
Yahekou	0.80	0.76 ± 0.18	1.99	1.24 ± 0.50
Baiguishan	−0.59	−0.53 ± 0.28	0.31	0.72 ± 0.42
Jiangang	−0.26	−0.39 ± 0.45	0.54	0.33 ± 0.32
Baiyangdian	−0.22	−1.20 ± 0.51	−0.19	−0.60 ± 0.29
Chaohe	1.10	−0.13 ± 0.42	0.73	0.85 ± 0.45

Conclusion

The present study assessed the distribution of and risks associated with nutrients and heavy metals in the sediments of various reservoirs along the SNWDP. The key findings and implications are as follows:

(1) Except for the Yahekou Reservoir, the TC, TN, and TP contents increased with the distance from the Danjiangkou Reservoir. Along the Middle Route of the South-to-North Diversion Project, the TN and TC content increased by 2.35- and 3.05-fold, respectively. The average increase in organic matter content was 39.27%. Nutrient contents decreased with sediment depth across all reservoirs. For instance, the TN content in the Baiguishan and Baiyangdian Lakes decreased by 36.00% and 47.67%, respectively, with increasing depth. Overall, the carbon, nitrogen, phosphorus, and organic matter contents exhibited average decreases of 62.38%, 67.47%, 17.56%, and 41.83% for TN, TC, TP, and OM, respectively.

(2) The Yahekou Reservoir exhibited elevated Mn and Zn contents, indicating moderate pollution. The Mn content within the surface sediments of the six reservoirs ranged from 550 to 1837 mg/kg, with an average of 1019.5 ± 548.3 mg/kg. The Zn content ranged from 89 to 360 mg/kg, with an average of 156.5 ± 101.6 mg/kg. Other reservoirs showed lower or no significant pollution due to these metals. For example, the Mn content in the Chaohe Reservoir was 819.5 mg/kg, while the Zn content was 162 mg/kg.

(3) Phosphorus was identified as the primary pollutant in the reservoirs, with varying degrees of pollution, including heavy pollution. TP and TN emerged as the primary pollutants in surface sediments. The TP content in the surface sediments ranged from 476.30 to 912.06 mg/kg, with the highest content observed in the Chaohe Reservoir. Comprehensive nitrogen and phosphorus pollution assessment revealed that the surface sediment of Danjiangkou Reservoir is mildly polluted, while Baiguishan and Jiangang Reservoirs are moderately polluted, and the rest are heavily contaminated. For the Yahekou and Chaohe Reservoirs, the average pollutant content indicates moderate pollution, while the remaining reservoirs showed mild pollution levels. The organic pollution assessment indicated excessive organic matter across all reservoirs, with the

OM content in the surface sediments ranging from 9.59% to 15.79%.

(4) This study included eight heavy metals. Future studies should focus on more metals to provide a comprehensive view of the pollution status. Sites like the Yahekou Reservoir require detailed ecological risk assessments and continuous environmental monitoring, necessitating immediate restoration strategies.

In summary, while the SNWDP has improved water availability, it has also led to increased nutrient and metal concentrations in certain reservoirs. Effective management and remediation strategies are essential to mitigate these impacts and ensure the long-term sustainability of water resources.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00970-1.

Additional file 1: **Figure S1.** Vertical distribution of the mass concentrations of total nitrogen and total carbon in the lakes and reservoirs along the middle route of the SNWDP. **Figure S2.** Vertical distribution of the mass concentrations of TP, IP, and OP in the lakes and reservoirs along the middle route of the SNWDP. **Figure S3.** Vertical distribution of the mass concentrations of organic matter in the lakes and reservoirs along the middle route of the SNWDP. **Figure S4.** Vertical distribution of the mass concentrations of heavy metals in the sediments of lakes and reservoirs along the middle route of the SNWDP.

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Author contributions
Weiying Feng: Wrote the original draft and funding; Yingru Tao: revised the manuscript and drew graph; Minjie Liu: Experimental operation and data analysis; Fang Yang: revised the manuscript and funding; Haiqing Liao: Sample collection and supervision, Tingting Li: revised the manuscript; Fanhao Song: revised the manuscript; Su Kong Ngien: editing the manuscript.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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