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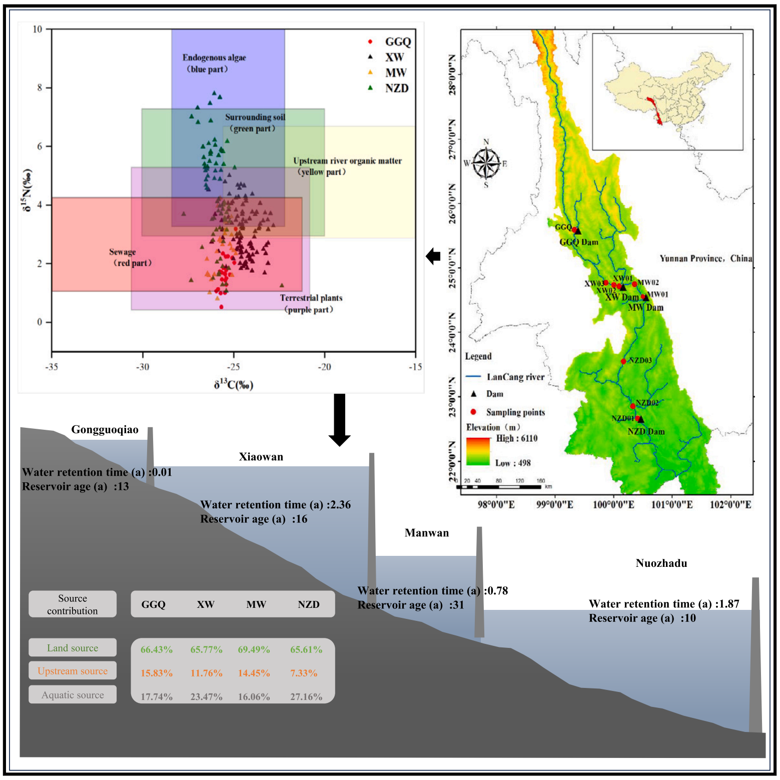
Impact of cascade reservoir on the sources of organic matter in sediments of Lancang river

Graphical abstract



Highlights

- TOC and TN concentrations exhibit significant spatial variations
- TOC is primarily supplemented by terrestrial organic matter
- The endogenous organic matter increases in large reservoirs

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In brief

Earth sciences; Earth-surface processes; Earth surface sediment transport; Hydrology; Soil hydrology

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Impact of cascade reservoir on the sources of organic matter in sediments of Lancang river

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SUMMARY

The construction of dams to intercept natural rivers constitutes the most severe human activity influencing the underlying surface. This study focuses on four cascade reservoirs of the Lancang River and explores their impact on the migration of organic matter in sediments. The research reveals significant spatial variations in total organic carbon (TOC) and total nitrogen concentrations in the sediments of the four reservoirs. The carbon and nitrogen isotopes indicate that terrigenous organic matter is the main source of TOC in the sediments, contributing an average of 66.80%. Endogenous algal-derived organic matter is the second significant source, contributing between 14.30% and 32.91%. The sources contributed from upstream organic matter are the lowest, ranging from 6.36% to 15.33%. Our study demonstrates that the construction of cascade reservoirs may significantly alter the processes of material sources in the river basin ecosystem, particularly in the large reservoir which increased more endogenous algal-derived organic matter.

INTRODUCTION

Sediments serve as crucial zones for material cycling in lacustrine ecosystems, recording the processes of basin hydroenvironmental evolution and material migration.[1,2] Carbon is a vital element constituting biological organisms and a core factor in the coupled material cycling of ecosystems. In sediments, carbon primarily exists in the form of organic carbon, which plays a critical role in the storage and transformation of organic matter, reflecting both past environmental conditions and ongoing biological processes.[3,4] Therefore, investigating the sources of organic carbon in aquatic sediments is essential for a deeper understanding of carbon cycling and environmental evolution processes.[5] Total organic carbon (TOC) in sediments originates from a complex interplay of terrestrial vegetation, soil within the basin, upstream inputs, and endogenous contributions from the water body.[6–8] TOC undergoes transportation, sedimentation, and transformation through rivers, thereby influencing the functionality of riverine ecosystems.[9,10]

Currently, approximately half of the world's rivers are directly affected by the dam interception effect, triggering a series of ecological and environmental issues,[11] such as fish migration disruption and material retention. Specifically, the construction of cascade reservoirs in river basins transforms natural rivers into interconnected reservoirs, profoundly altering their natural attributes and processes.[12–14] Reservoir sedimentation significantly enhances the retention of transported materials in rivers, thereby altering the flux and composition of material transport.[15–17] Since the 1970s, studies on the ecological functions of reservoirs in the Colorado and Columbia River basins have shown that "reservoir processes" greatly disrupt the inherent connectivity between river and terrestrial ecosystems.[18] A profound understanding of the changes in the quantity, composition, and flux processes of riverine source materials under the regulation of cascade reservoirs and their driving mechanisms is currently a global focal point in surface science research.[12,19]

The Lancang River, as the upper reaches of the Mekong River, is one of the Asia's important transboundary rivers. With the development of cascade reservoirs on the Lancang River, there has been a significant decline in its ecological integrity,[12,20] leading to increased academic attention. Xu et al.[21] showed that hydropower dams in the Lancang-Mekong River Basin significantly reduced transboundary phosphorus flux by 50–59%, affecting nutrient distribution, especially in downstream regions. Chen et al.[22] found that dam construction increased phosphorus accumulation in sediments and enhanced phosphorus mineralization and bioavailability by elevating the alkaline phosphatase activity of phoD-harboring bacteria. Wang et al.[23] reported that dam operation caused seasonal fluctuations in water temperature in the basin, which potentially impacted the downstream ecosystems. The development of cascade hydropower has affected the water volume and material cycle process of downstream reservoirs through the regulation and storage of upstream reservoirs, forming a special relationship of transport, inheritance and cycle of biological substances.[24,25] Zhang et al.[26] considered that reservoirs with the hydraulic retention time (HRT) greater than 1.0 years are considered as large reservoirs, while those with an HRT of less than 1.0 years are classified as small reservoirs. Further studies by Chen et al.[27] have found that large reservoirs on the Lancang River exhibit higher retention rates of total nitrogen (TN) and total phosphorus (TP) compared to small reservoirs. During the development of reservoir ecosystems, structural and functional changes may occur on a large scale. For example, in newly formed reservoirs, the food chain may primarily be driven and sustained by the bacterial decomposition of exogenous organic matter inputs. As reservoirs mature, levels of aquatic primary productivity increase, with plankton gradually becoming key initiators of material cycling in the food chain and significant sources of sediment material.[12,27,28]

The Lancang River Basin belongs to the long and narrow cascade reservoirs in the southwest of China. Currently, the status of carbon retention and source attributes in the sediments of the reservoirs, as well as their significance to regional carbon cycling and ecosystems, remain unclear. Research has shown that the hydrological characteristics of reservoirs, such as HRT and flow rate, significantly influence the sources and composition of organic carbon.[17,27] In river-type reservoirs, terrigenous organic carbon dominates, while in lake-type reservoirs, the ratio of autochthonous to terrigenous organic carbon is more balanced.[29] Although preliminary studies by Wang et al.[30] have elucidated the sources of TOC in sediment from reservoirs such as Miaowei, Gongguoqiao (GGQ), and Dachaoshan in the middle reaches of the Lancang River, research on the more significant downstream large reservoirs such as Xiaowan (XW) and Nuozhadu (NZD) is scarce. Furthermore, there has been limited comprehensive research on different types of cascade reservoirs. Therefore, this study focuses on various types of cascade reservoirs in the middle and lower reaches of the Lancang River. The aim is to elucidate the impacts of cascade reservoir construction on the sources of sediment TOC, providing a scientific basis for river development and utilization, as well as a reference for improving the ecological environment of this river basin.

RESULTS

Water temperature (WT) and chlorophyll-a variations of the reservoirs

The sampling sites and parameters of four reservoirs in the Lancang River are shown in the Figure 1 and Table 1. Figure 2 shows the variations of water temperature (WT) and chlorophyll-a (Chla) concentrations in different reservoirs. In the GGQ and Manwan (MW) reservoirs, the WT ranges from 16.5°C to 17.0°C and 17.5°C–19.0°C, respectively. The WT slightly decreases with depth. In the XW and NZD reservoirs, the WT ranges from 18.1°C to 24.0°C and 18.0°C–25.2°C, respectively. These show a clear temperature gradient range and significant thermal stratification phenomenon in the reservoirs where the upper water layer is heated by strong solar radiation, while the lower water layer cools rapidly due to limited sunlight.[31]

The Chla concentrations in all reservoirs show a decreasing trend with depth. Phytoplankton biomass is abundant in the surface layer. The Chla concentrations in the GGQ and MW reservoirs are low, indicating low phytoplankton productivity of the water body. In contrast, the Chla concentrations in the XW and NZD reservoirs are higher.

Total organic carbon, total nitrogen, and carbon-nitrogen ratio variations in the sediments of Lancang river reservoirs

Figure 3 shows the variations of TOC and TN concentrations in the sediment samples. In GGQ, XW, MW, and NZD Reservoirs, they range from 0.24% to 0.76%, 0.34%–1.48%, 0.30%–1.48%, and 0.49%–1.90%, with averages of 0.53%, 0.77%, 0.63%, and 1.15%, respectively. The GGQ Reservoir exhibits the lowest average TOC concentration, while the highest TOC concentration is found in the sediment of NZD02. Generally, the TOC concentrations increase gradually downstream along the river.

For TN concentrations in sediments, In GGQ, XW, MW, and NZD Reservoirs, they range from 0.06% to 0.12%, 0.05%–0.19%, 0.05%–0.10%, and 0.05%–0.29%, with averages of 0.09%, 0.11%, 0.07% and 0.13%, respectively. The variation trends of TN concentrations with depth at different sampling points are shown in Figure 3B. The vertical variation trend of TN is similar to that of TOC, but the fluctuation of TN concentration is smaller generally. The variation trend of the C/N ratio at different sampling points with depth is shown in Figure 3C. The C/N ratio of the samples mainly ranges from 4.1 to 10.2, indicating a mixture of phytoplankton and terrestrial plants.

Characteristics of sediment $\delta^{13}C$ and $\delta^{15}N$ variations

The variations in organic carbon isotopes ($\delta^{13}C$) and nitrogen isotopes ($\delta^{15}N$) in the sediment samples along the Lancang River are shown in Figure 4. In GGQ、XW、MW and NZD Reservoirs, sediment $\delta^{13}C$ values range from −25.97‰ to −24.90‰, −26.40‰ to −22.83‰, −26.49‰ to −24.89‰ and −27.76‰ to −22.36‰, with averages of −25.49‰, −24.50‰, −25.72‰ and −25.97‰, respectively. The vertical variations of $\delta^{13}C$ values shows fluctuations within a certain range with increasing depth for most sampling points. The $\delta^{15}N$ values at different sampling points is illustrated in Figure 4B. In GGQ, XW, MW, and NZD Reservoirs, the values range from 0.52‰ to 3.19‰, 1.69‰–5.01‰, 0.81‰–4.25‰, and 1.08‰–7.81‰, with averages of −1.69‰, 3.13‰, 2.53‰ and 4.38‰, respectively. The highest $\delta^{15}N$ value is found at NZD02 and the lowest is at GGQ.

The sources of total organic carbon in sediments

To illustrate the sources of TOC in sediments of cascade reservoirs, we cited the nitrogen isotope metadata from the article[30] which divided the sources of TOC into five parts: Upstream River Organic Matter, Terrestrial plants, Endogenous Algae, Surrounding Soil, and Sewage (in the supplementary materials).

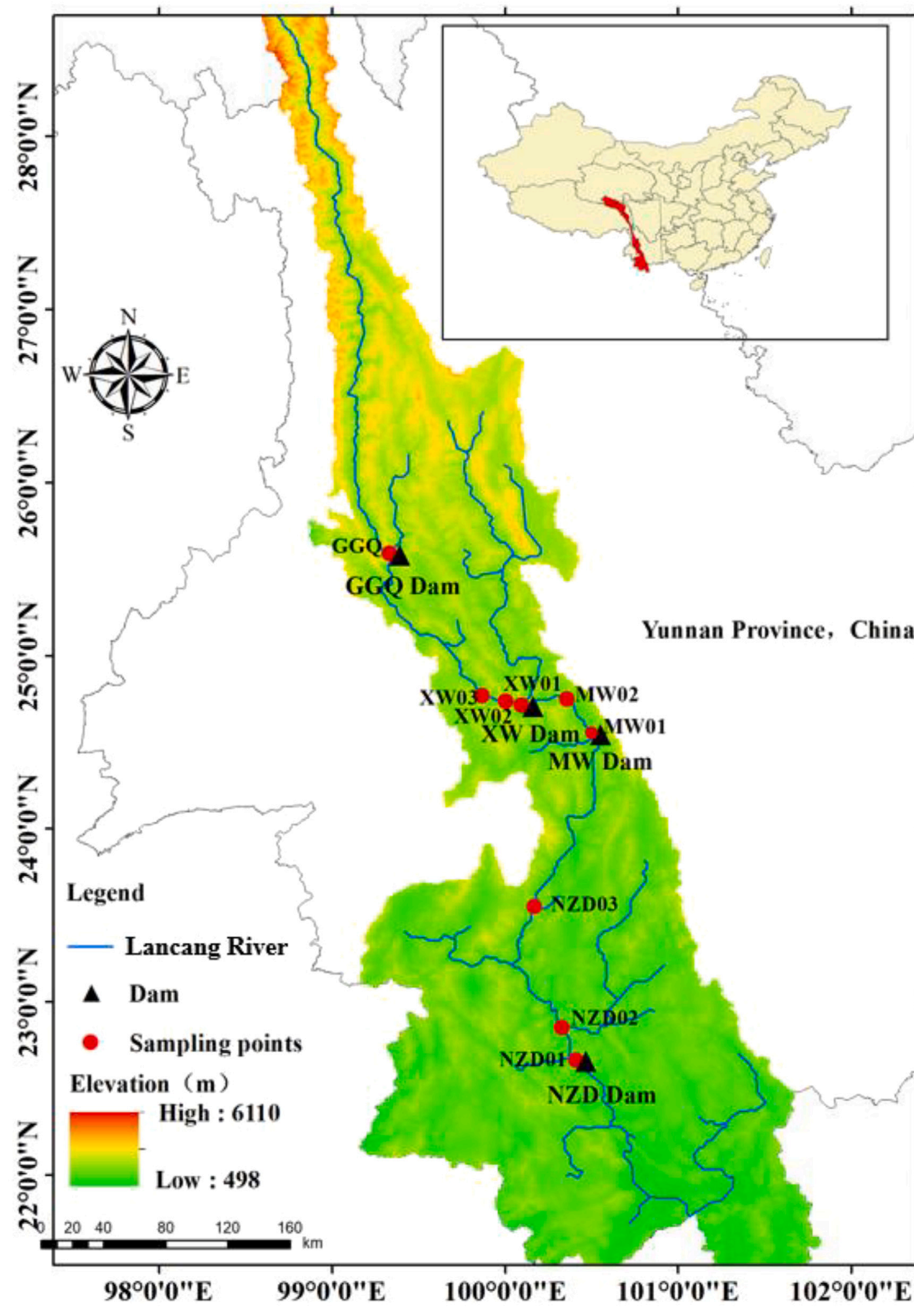

Figure 1. Distribution Map of Sediment Core Sampling Points in the Basin

NZD is the abbreviation for Nuozhadu Reservoir, MW is the abbreviation for Manwan Reservoir, XW is the abbreviation for Xiaowan Reservoir, GGQ is the abbreviation for Gongguoqiao Reservoir. The same abbreviations for the following figures.

Table 1. Detailed parameters of the four reservoirs and information on sampling points

Reservoir name	Total storage capacity ($\times 10^8 m^3$)	Annual average flow (m^3/s)	Average water retention time (year)	Sampling point information
Gongguoqiao (GGQ)	510	1010	0.01	GGQ
Xiaowan (XW)	14560	1220	2.36	XW01, XW02, XW03
Manwan (MW)	920	1230	0.78	MW01, MW02
Nuozhadu (NZD)	22400	1730	1.87	NZD01, NZD02, NZD03

It is worth noting that upstream river organic matter refers to the organic matter it carries in the upstream, which includes multiple sources of organic matter from the upstream river system (Qinghai Tibet Plateau region). According to the Bayesian stable isotope mixing model, in GGQ Reservoir, sediment TOC mainly originates from terrestrial plants and soil inputs. The average contributions of terrestrial plants and soil to sediment TOC are 24.72% and 21.49%, respectively. The average contribution of sewage to sediment TOC is 20.59%. Contributions from endogenous algae and upstream river organic matter are lower, averaging 17.74% and 15.83%, respectively. In XW Reservoir, sediment TOC is primarily sourced from terrestrial plants and endogenous algae, with their contributions exceeding 45%. This indicates a higher abundance of planktonic organisms in large reservoirs, while the contribution of upstream river organic matter decreases compared to GGQ, with an average contribution of 11.76%.

In MW Reservoir, sediment TOC at the sampling point is dominated by terrestrial plants and soil inputs, with their contributions exceeding 47%. Contributions from endogenous algae and upstream river organic matter are lower, with average contributions ranging from 14.29% to 17.83% and 13.57%–15.33%, respectively. The average contribution of sewage to sediment TOC is 21.25%. Notably, MW Reservoir, being the oldest among the studied reservoirs, intercepted a significant amount of upstream river organic matter before GGQ and XW Reservoirs were built,

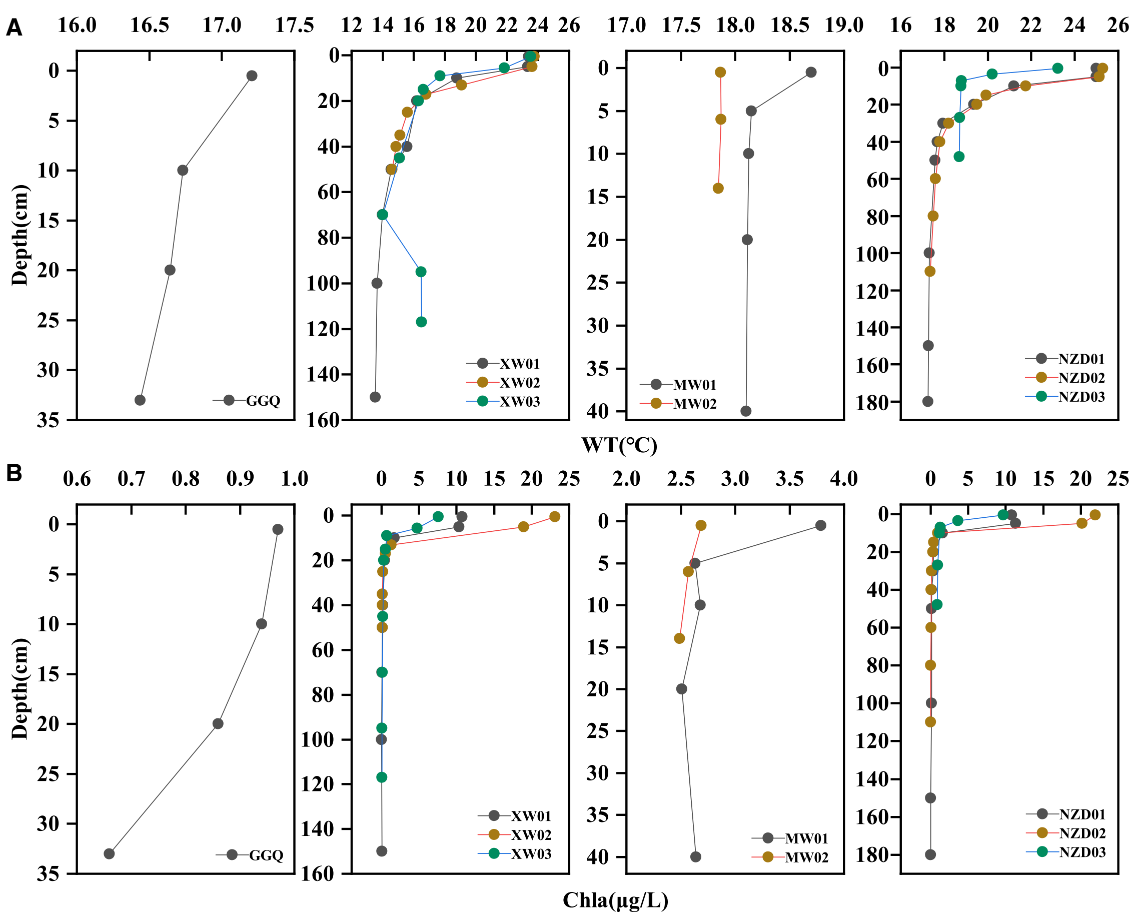

Figure 2. Water temperature (WT) and Chloropgyll-a (Chla) in the profile of water column
(A) Vertial profiles of WT in the water column of sampling sites.
(B) Vertial profiles of Chla in the water column of sampling sites.

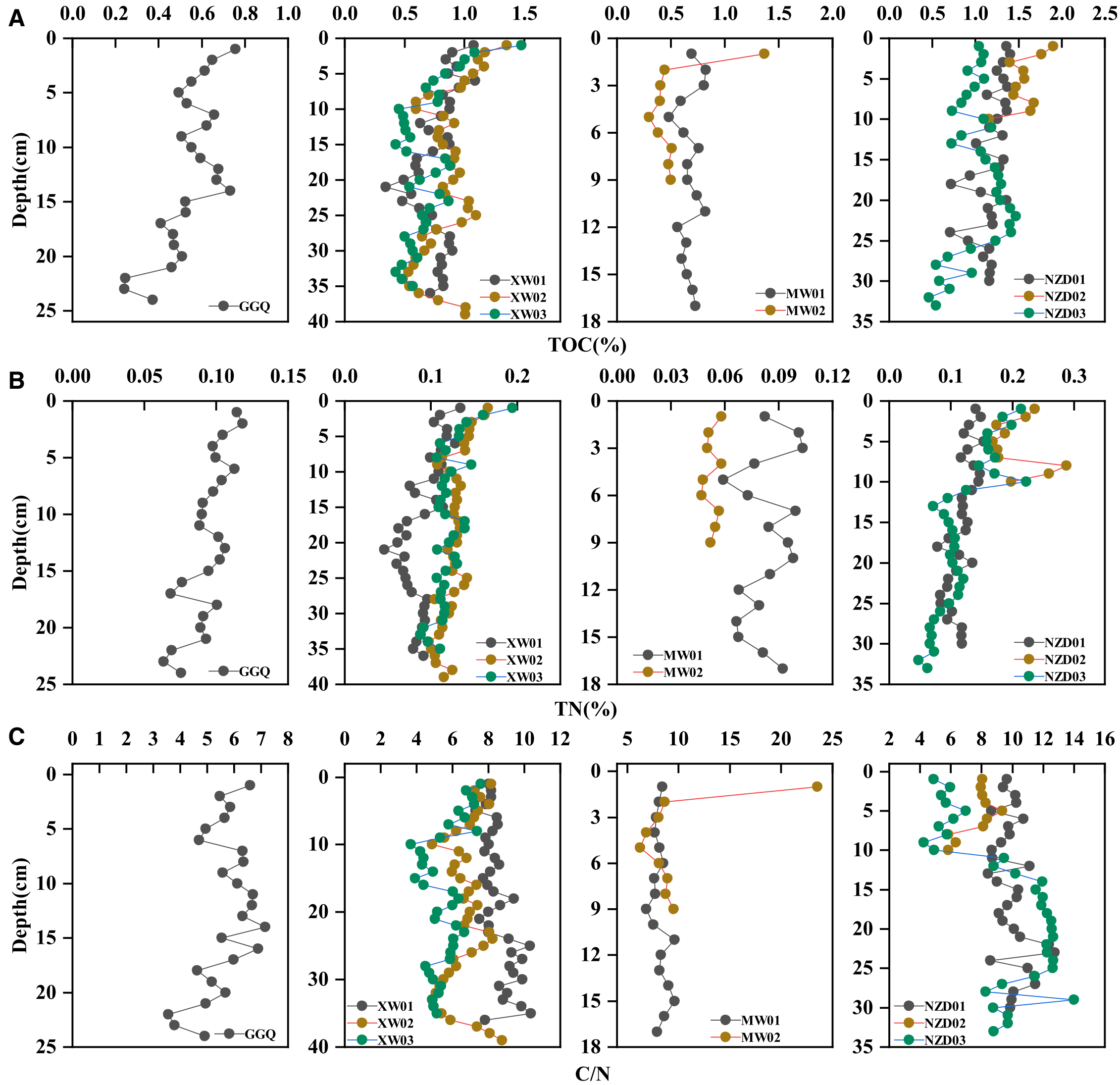

Figure 3. The concentrations of Total organic carbon (TOC), Total nitrogen (TN) and TOC toTN ratio (C/N) in the sediment cores of the sampling sites

(A) Vertial profiles of TOC concentrations in sediment cores.

(B) Vertial profiles of TN concentrations in sediment cores.

(C) Vertial profiles of C/N in sediment cores.

resulting in higher contributions of upstream river organic matter in MW Reservoir compared to XW Reservoir upstream. The sources of sediment TOC in NZD significantly differ from the other reservoirs. Except for the NZD03 sampling point at the end of the reservoir, heavily affected by watershed erosion and predominantly sourced from terrestrial plants (26.28%), sediment TOC at the other two points (NZD01 and NZD02) is primarily sourced from endogenous algae, with average contributions of 27.84% and 35.41%, respectively. This is mainly due to the high abundance of planktonic plants. Additionally, influenced by interception from upstream cascade reservoirs, the contribution of upstream river organic matter to sediment TOC in NZD Reservoir is significantly lower than in other reservoirs, ranging from 6.36% to 8.16%.

DISCUSSION

The spatial variations and relationship of sediment total organic carbon and total nitrogen

The content of TOC in sediments depends on the input of organic matter and the preservation capacity of the sedimentary environment for organic matter.[32] Across the sampling points along the Lancang River, TOC concentrations range from 0.24% to 1.90%, with average concentrations showing GGQ < MW < XW < NZD. The concentration of sediment TOC is related to the basin environment and the presence of aquatic phytoplankton and zooplankton, which fix organic matter through photosynthesis using chlorophyll within their bodies.[33] Therefore, phytoplankton and zooplankton can reflect the level

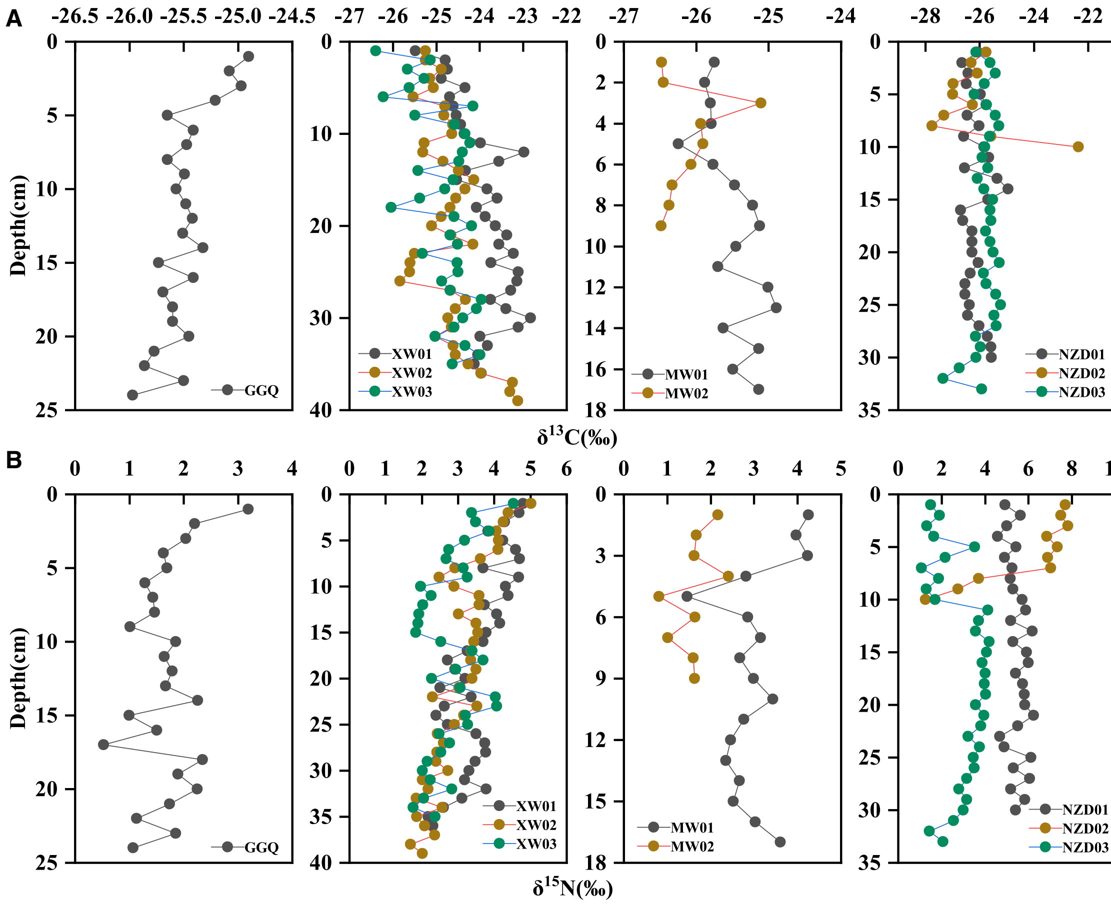

Figure 4. Carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope signatures in the sediment cores.

(A) Vertical profiles of $\delta^{13}C$ in sediment cores.

(B) Vertical profiles of $\delta^{15}N$ in sediment cores.

of primary productivity in water bodies to a certain extent. Chen et al.[12] found that large reservoirs such as NZD and XW have higher phytoplankton abundance, which may explain the higher TOC concentrations and higher contribution of endogenous algae in the sediment of NZD and XW reservoirs. Additionally, existing studies indicate that temperature significantly affects TOC content.[34,35] Generally, higher temperatures promote net primary productivity in watershed ecosystems. Chla is the primary pigment for photosynthesis, and its concentration can reflect the biomass of phytoplankton in the water, serving as an indirect indicator of primary productivity in the water body. In this study, the XW and NZD reservoirs exhibited relatively higher water temperatures and Chla concentrations, leading to higher primary productivity, and consequently higher TOC concentrations compared to other reservoirs. Regionally, sediment TOC concentrations in Lancang River reservoirs overall remain relatively low compared to regions such as the Yangtze River, Dianchi Lake, and Taihu Lake.[32,36–38]

The vertical distribution of TOC in sediments at various sampling points is primarily influenced by organic matter mineralization.[30] In general, the TOC concentration in sediments shows a decreasing trend from top to bottom. This trend is attributed to the decomposition of organic matter in the sediment's redox environment.[39] As the sediment depth increases, the impact of the redox environment on the sediment becomes more significant, resulting in more pronounced mineralization and decomposition, which in turn leads to lower TOC concentrations. Figure 5 demonstrates the linear relationship between TOC and TN contents in sediments from four reservoirs. The sample was treated with hydrochloric acid before analysis and the TN content was approximately equal to the organic nitrogen (ON) content. Therefore, it shows good linear relationships between the TOC content and TN content of the sediment column at the most sampling sites.

As for the C/N ratios (Figure 3C), for the GGQ, the uppermost of these reservoirs, shows a decreasing C/N ratio with the depth increases, which indicates that the organic matter in the sediment undergoes degradation in the deeper layers. This is likely because GGQ Reservoir receives more fresh external terrestrial organic matter, leading to a higher C/N ratio in the surface layer, but as carbon is gradually decomposed in the sediment, the C/N ratio decreases in the deeper layers. As the oldest reservoir, MW Reservoir shows little change in the C/N ratio with depth, suggesting that the source and degradation of organic matter

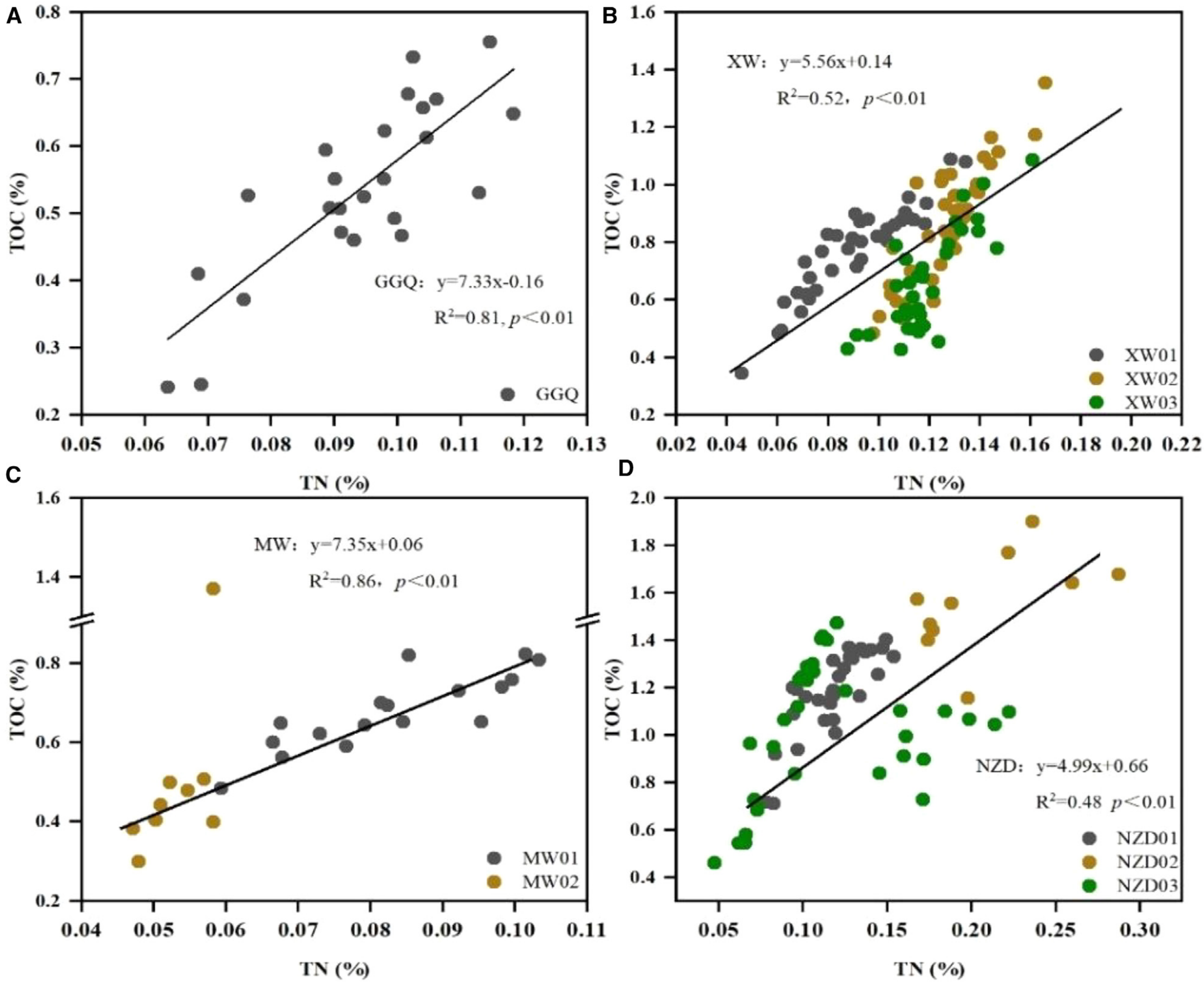

Figure 5. Relationship between sediment TN and TOC at various sampling points

(A) A linear relationship ($R^2 = 0.81$; $p < 0.01$) between sediment TN and TOC in GGQ.

(B) A linear relationship ($R^2 = 0.52$; $p < 0.01$) between sediment TN and TOC in XW.

(C) A linear relationship ($R^2 = 0.86$; $p < 0.01$) between sediment TN and TOC in MW.

(D) A linear relationship ($R^2 = 0.48$; $p < 0.01$) between sediment TN and TOC in NZD.

are relatively consistent across different depth layers in the sediment. The long-term sedimentation and stable input of organic matter may result in relatively uniform organic matter sources in this reservoir. In the NZD and XW Reservoirs, the C/N ratios show an increasing trend with depth, indicating that the surface layer may have accumulated more organic matter with a low C/N ratio (such as algal organic matter).[40]

The C/N ratios of terrestrial soils in this area ranged from 6 to 16 with a mean value of 9.6.[40] Particulate organic carbon (POC, mainly algae organic matter) values ranged from 2.3 to 8.6 with a mean value of 4.7.[41,42] From Figure 5, it can be seen that the slopes of the regression lines of TOC and TN are 7.33, 5.56, 7.35, and 4.99 for GGQ, XW, MW, and NZD, which reflects that the carbon source of sediment TOC in GGQ and MW are mainly from the terrestrial organic matter. For the large reservoirs (XW and NZD), it is more likely contributed from the endogenous algal organic matter qualitatively.

Quantitative analysis of total organic carbon sources in sediments

According to the isotopic end-member diagram (Figure 6), each sampling point falls within the intersection of multiple end-members, indicating that sediment TOC is influenced by multiple sources. There is a wide range of $\delta^{15}N$ values among sampling points, with $\delta^{15}N$ values serving as an important indicator for analyzing the sources of TOC. The changes of $\delta^{15}N$ values with depth often indicate nitrogen cycling processes in the sediment such as the origin of organic matter, the degree of organic matter decomposition, and environmental changes.[31,43,44] Higher $\delta^{15}N$ values typically indicate that TOC originates from aquatic

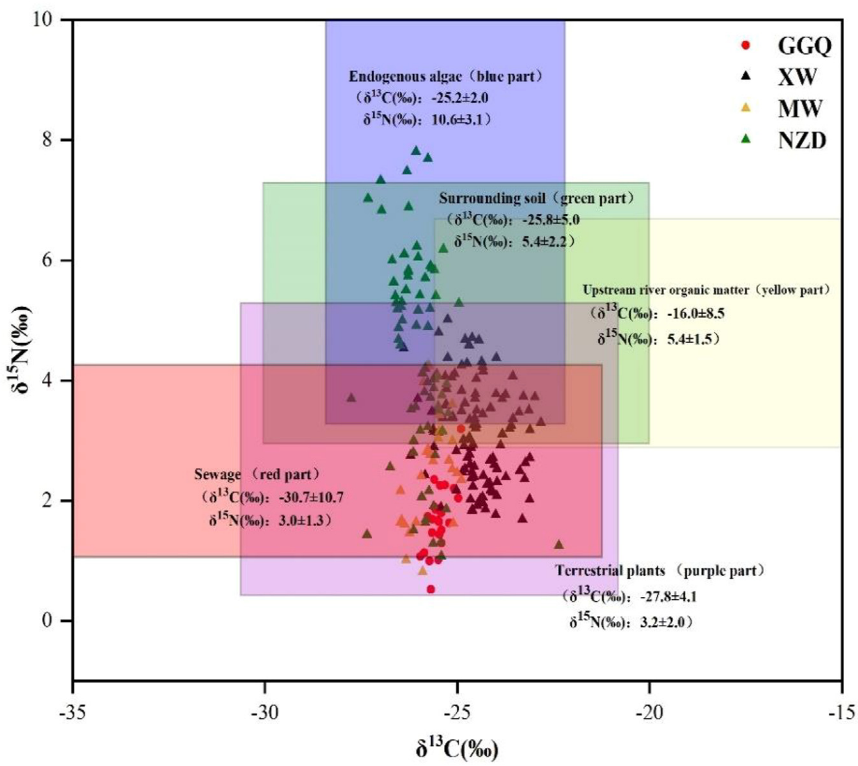

Figure 6. End-member diagram of carbon and nitrogen isotopes in sediments from cascade reservoirs in the middle and lower reaches of the Lancang River

organisms. Aquatic organisms in rivers often exhibit higher $\delta^{15}N$ values because they may occupy higher trophic levels in the food web or utilize sediment organic matter enriched in ^{15}N.[31] Those with lower $\delta^{15}N$ values may originate from vegetation along the riverbank.[31] Organic residues such as plant debris and leaves from these plants enter the river, and due to their low $\delta^{15}N$ values, the sediment in the water body also exhibits low $\delta^{15}N$ values. In this study, the relatively high $\delta^{15}N$ values in NZD Reservoir suggest a transition in the sources of sediment TOC from terrestrial organic matter to endogenous organic matter. The significant fluctuations in isotope values within the samples (especially in MW02 and NZD02) indicate substantial changes in the depositional environment. These variations may be related to shifts in sedimentation rates, redox conditions, or fluctuations in organic matter input.[30]

The trend of sediment TOC sources with depth at each sampling point is shown in Figure 7. The four reservoirs are divided into two types: small through-flow reservoirs (GGQ, MW) and large impounding reservoirs (XW, NZD). The main difference between these types lies in their operational characteristics. Through-flow reservoirs typically lack prolonged stagnation periods. Continuous water flow promotes sediment mixing and resuspension, thereby reducing the distinct stratification of sediment layers. Consequently, sediments formed in these reservoirs are often more evenly distributed vertically. These reservoirs do not have extensive and long-term stagnant water areas, which helps maintain dynamic sediment equilibrium.[27] Therefore, the sediment sources in GGQ and MW appear relatively homogeneous vertically. In contrast to through-flow reservoirs, large impounding reservoirs (XW, NZD) have larger water storage capacities and longer HRT which enrich nutrients in the water, promoting the growth of aquatic plants and plankton, thereby enhancing primary productivity.[27] This results in more biomass being converted into organic matter, leading to the increased accumulation of endogenous organic matter in sediments.[12] Organic matter sourcing from endogenous algae is generally more bioavailable and active. The algal-derived organic matter at the bottom undergoes metabolism, decomposition, and cycling, contributing to the higher proportion of endogenous organic matter observed in the surface layers of NZD and XW reservoirs vertically (as shown in Figure 7). Besides, it is worth noting that the contributions of sewage to the sediment TOC in the four reservoirs account about 22%, which is consistent with the phenomenon that many immigrants are living around the reservoirs between the canyons in the middle and lower reaches of the Lancang River. Our other research in the Lancang River was also found that the contribution of manure and sewage to the nitrogen is 24.0%–31.3% due to the increasing human activities in the downstream.[45]

Impact of cascade damming on the sources and transport of organic matter

The Figure 8A presents the variation of the contributions from different sources to TOC in sediments along four reservoirs in the Lancang River. The results indicate that regional terrestrial organic matter inputs (Terrestrial plants, Surrounding Soil, and Sewage) play a dominant role. The Lancang River is a typical valley-type watershed, where soil, riparian vegetation, and sewage from both banks are more easily transported into the reservoir ecosystem through rainfall erosion, which is consistent with the basic geographical and environmental characteristics of the watershed.[45] The overall proportion of terrestrial organic matter at each sampling point shows a slight downward trend along the watershed direction (Figure 8B), while the contribution rate of endogenous organic matter gradually increases in the large reservoirs in the downstream, which is mainly related to the temperature of the watershed and the reservoir environment. The increasing temperature from upstream to downstream is more conducive to the growth and metabolism of algae and environmental microorganisms.[26] Besides, the Chla concentration of large reservoirs (XW and NZD) in the surface water is higher than the other two reservoirs (Figure 2B). The sedimentation of algae death leads to the increasing contributions of endogenous organic matter in the sediment TOC of downstream reservoirs.

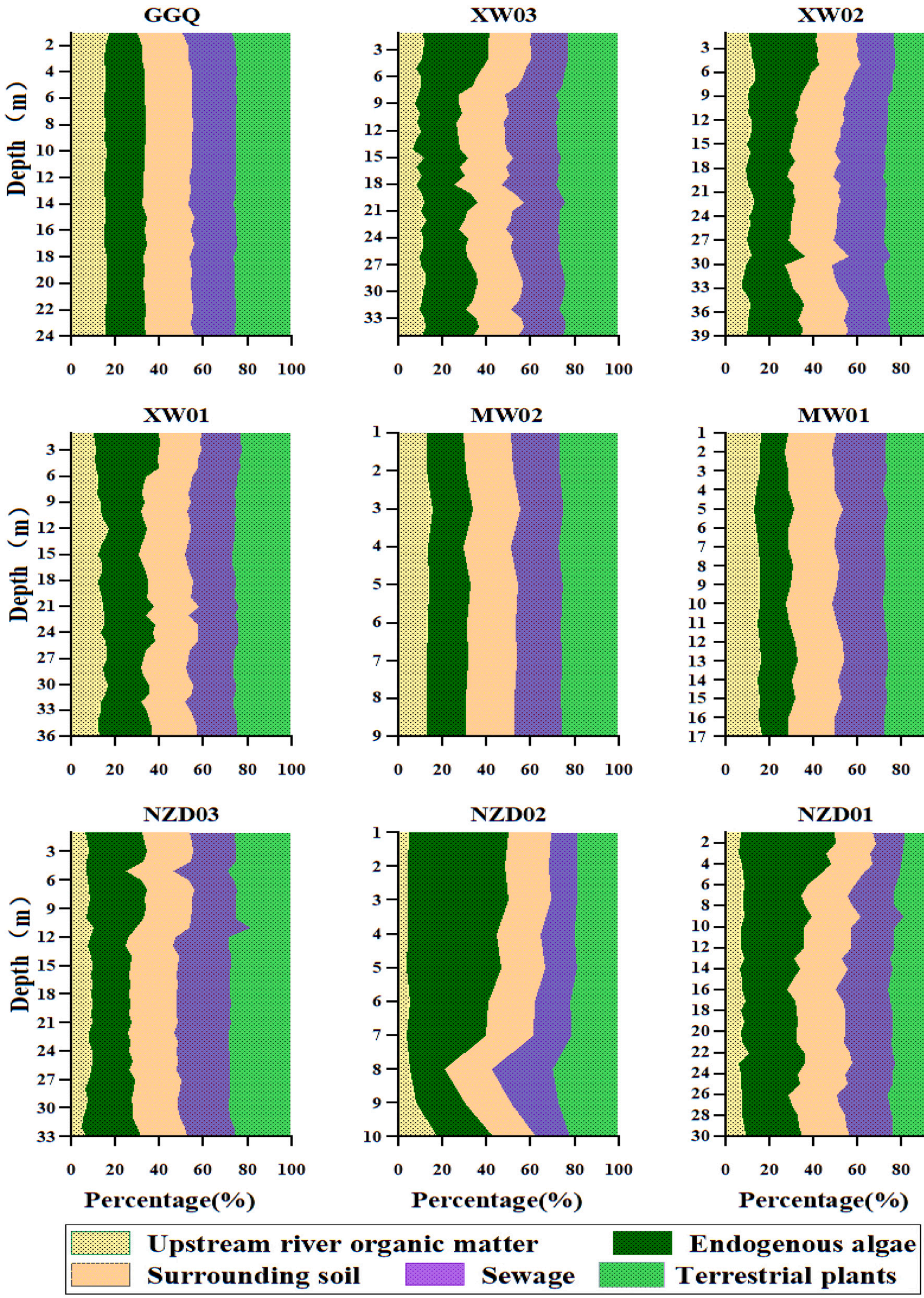

Figure 7. Vertical contribution of different sources to TOC in sediments from cascade reservoirs in the middle and lower reaches of the Lancang River

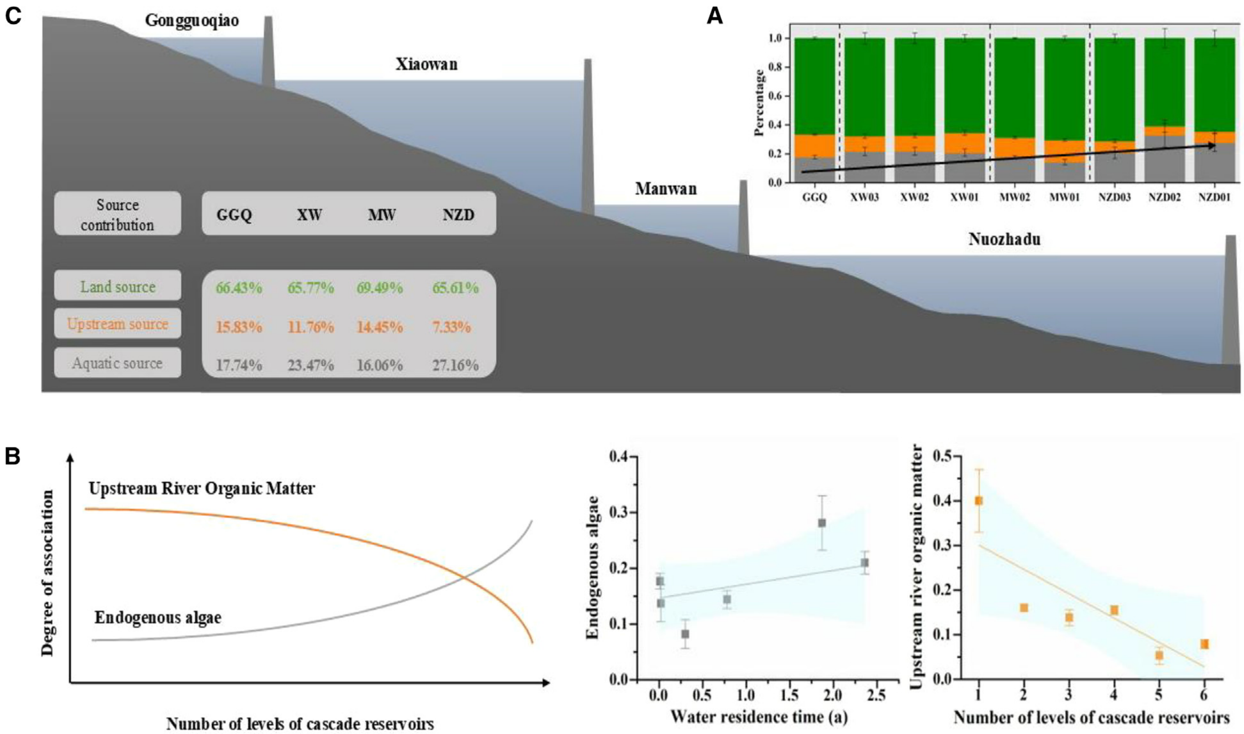

Figure 8. Conceptual diagram of the sources and impacts of TOC sediments in the cascade reservoirs in the middle and lower reaches of Lancang River

(A) The bar chart of the different sources contribution of the sampling sites.

(B) The relationships of the TOC contribution of endogenous algae and water residence time; The relationships of the TOC contribution of upstream river organic matter and number of levels of cascade reservoirs.

(C) The Conceptual diagram of the sources and TOC sediments in the cascade reservoirs.

More importantly, damming significantly increases the retention time of water bodies, disrupting the original ecological balance of the river.[46,47] As the biological communities undergo natural selection and succession in response to habitat changes, a lake-type autotrophic system dominated by plankton gradually becomes the dominant process, enhancing aquatic primary productivity.[30,48] Zhang et al. (2023) have found that phytoplankton biomass was highest in the XW and NZD reservoirs.[26] They also discovered a highly significant correlation between biomass and hydraulic retention time ($p < 0.01$), further indicating that the higher the hydraulic retention time in large reservoirs, the higher the primary productivity of the reservoir.

Algal-derived organic matter forms particulate organic carbon through attachment and settles into the sediment. Due to the more active metabolic processes of algal-derived organic matter, the reservoir ecosystem (mainly manifested in changes in primary productivity levels and succession of plankton communities) might significantly alter the absorption, consumption, multi-level utilization, and sediment cycling of biogenic substances, thereby significantly changing the migration and transformation of related elements in the river water environment and their associated environmental effects.[45–47] Besides, TOC from upstream channels is intercepted by cascade reservoirs layer by layer, with the contribution rate of upstream sources to sediment TOC decreasing by approximately half from GGQ to NZD.

Figure 8C summarizes the conceptual model of TOC sources in sediments of the four cascade reservoirs in the middle and lower reaches of the Lancang River. On the one hand, at the geographical spatial scale, carbon inputs from terrestrial sources dominate within the basin, while the construction of cascade reservoirs continuously intercepts carbon from upstream inflows. On the other hand, in terms of reservoir effects, the input of algal-derived organic matter in large reservoirs increases gradually over time. Considering the higher biological availability and activity of algal-derived organic matter compared to the relatively inert carbon from upstream inputs, the manner and intensity of these changes vary with reservoir operation and environmental evolution, thereby posing different environmental risks. As observed in the study of the Wujiang Reservoir,[49] the reservoir system exhibits a rapid cycling feedback mechanism of algal-derived nutrients (source materials) between the upper water layer and benthic sediment layer, enhancing the environmental activity of source materials significantly. Therefore, the environmental evolution effects of cascade reservoir systems in river basins, especially large reservoirs, should be given particular attention.

Conclusion

(1) The concentrations of TOC and TN in the middle and lower reaches of the Lancang River cascade reservoirs

exhibit significant spatial variations. Specifically, the TOC concentration is lowest in the GGQ reservoir, averaging at 0.53%, and highest in the NZD reservoir, averaging at 1.15%. TN concentration shows a similar trend, with an average of 0.09% in the GGQ reservoir and 0.13% in the NZD reservoir.

(2) Analysis of carbon and nitrogen isotopes in reservoir sediments indicates that the source of carbon in the reservoirs is primarily supplemented by terrestrial organic matter inputs. Spatially, an overall decreasing trend is observed. Due to the interception effect of the dams, the carbon source contributing from upstream also exhibits a decreasing trend. Conversely, the proportion of endogenous algal-derived organic matter sources gradually increases, particularly in the case of the large-scale NZD Reservoir and XW Reservoir.

(3) The analysis shows that the source of organic matter in the sediments of NZD has changed and the algal-derived organic matter is the biggest contributor. Notably, considering the significantly higher bioavailability and activity of endogenous algae-derived organic matter compared to the relatively inert carbon input from upstream, the diverse environmental risks posed by this transition warrant further attention and research.

Limitations of the study

It should be noted that our analyses of the impact of cascade reservoir on the sources and transport of organic matter in sediments of the LCR were based on the sampling and monitoring data in the LCR in May 2021, they may be potentially uncertainties due to 1) the lack of long-term measurements in the study areas; 2) the randomness of sampling sites.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Dr Yuchun Wang (wangyciwhr@163.com).

Materials availability

This study did not generate any new materials.

Data and code availability

- Data: All data reported in this study will be shared by the lead contact upon reasonable request.
- Code: This article does not report the original code.
- All other requests: Any additional information required to reanalyze the data reported in this article is available from the lead contact on request.

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AUTHOR CONTRIBUTIONS

Writing – review and editing, investigation, data curation, and conceptualizationY.B., M. S.; funding acquisition, writing – review and editing, and supervision Y. W., J. L.; methodology and investigation Y. W., H. C., S. L., and Y. Q.; data curation and conceptualization Z.W., J. W., X. W., and Z. W. All authors have read and agreed to the published version of the article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

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REFERENCES

1. Yang, C., Li, Z., Wang, S., Ran, F., Nie, X., Liu, Y., and Xiao, T. (2023). Anthropogenic activities control the source dynamics of sediment organic carbon in the lower reach of an inland river. Water Res. *233*, 119779. https://doi.org/10.1016/j.watres.2023.119779.
2. Zhang, Y., Shen, J., Feng, J.M., Li, X.Y., Liu, H.J., and Wang, X.Z. (2023). Composition, distribution, and source of organic carbon in surface sediments of Erhai Lake. Sci. Total Environ. *858*, 159983. https://doi.org/10.1016/j.scitotenv.2022.159983.
3. Gu, Y.G., Ouyang, J., Ning, J.J., and Wang, Z.H. (2017). Distribution and sources of organic carbon, nitrogen, and their isotopes in surface sediments from the largest mariculture zone of the eastern Guangdong coast, South China. Mar. Pollut. Bull. *120*, 286–291. https://doi.org/10.1016/j.marpolbul.2017.05.013.
4. Liu, T., Bao, K., Chen, M., Neupane, B., Gao, C., and Zaccone, C. (2024). Human activity has increasingly affected recent carbon accumulation in Zhanjiang mangrove wetland, South China. iScience *27*, 109038. https://doi.org/10.1016/j.isci.2024.109038.
5. Kubo, A., and Kanda, J. (2017). Seasonal variations and sources of sedimentary organic carbon in Tokyo Bay. Mar. Pollut. Bull. *114*, 637–643. https://doi.org/10.1016/j.marpolbul.2016.10.030.
6. Li, T., Zhang, G., Wang, S., Mao, C., Tang, Z., and Rao, W. (2022). The isotopic composition of organic carbon, nitrogen, and provenance of organic matter in surface sediment from the Jiangsu tidal flat, southwestern Yellow Sea. Mar. Pollut. Bull. *182*, 114010. https://doi.org/10.1016/j.marpolbul.2022.114010.
7. Yu, K., Zhang, Y., He, X., Zhao, Z., Zhang, M., Chen, Y., Lang, X., and Wang, Y. (2022). Characteristics and environmental significance of organic carbon in sediments from Taihu Lake, China. Ecol. Indic. *138*, 108796. https://doi.org/10.1016/j.marpolbul.2022.114010.
8. Du, J., Zhang, F., Du, J., Wang, Z., Ren, X., and Yao, Z. (2023). Source and sequestration of sediment organic carbon from different elevation zones in estuarine wetland. Sci. Total Environ. *859*, 160253. https://doi.org/10.1016/j.scitotenv.2022.160253.

9. Cifuentes, L.A., and Eldridge, P.M. (1998). A mass-and isotope-balance model of DOC mixing in estuaries. Limnol. Oceanogr. *43*, 1872–1882. https://doi.org/10.4319/lo.1998.43.8.1872.

10. Harmelin-Vivien, M., Loizeau, V., Mellon, C., Beker, B., Arlhac, D., Bodiguel, X., Ferraton, F., Hermand, R., Philippon, X., and Salen-Picard, C. (2008). Comparison of C and N stable isotope ratios between surface particulate organic matter and microphytoplankton in the Gulf of Lions (NW Mediterranean). Cont. Shelf Res. *28*, 1911–1919. https://doi.org/10.1016/j.csr.2008.03.002.

11. Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., et al. (2019). Author Correction: Mapping the world's free-flowing rivers. Nature *569*, 215–221. https://doi.org/10.1038/s41586-019-1111-9.

12. Chen, Q.W., Shi, W.Q., Jef, H., Maberly, S.C., Zhang, J.Y., Yu, J.H., Chen, Y.C., Daniele, T., and Yi, Q.T. (2020). Hydropower reservoirs on the upper Mekong River modify nutrient bioavailability downstream. Nat. Sci. Rev. *7*, 1449–1457. https://doi.org/10.1093/nsr/nwaa026.

13. Wang, Y., Long, D., and Li, X. (2023). High-temporal-resolution monitoring of reservoir water storage of the Lancang-Mekong River. Remote Sens. Environ. *292*, 113575. https://doi.org/10.1016/j.rse.2023.113575.

14. Zhao, W., Li, D., Wang, Y., Jiang, E., Liu, Y., Li, J., and Wang, Q. (2024). A multifunctional synergy development evaluation model of the impact of the cascade reservoir construction sequence on basins. Ecol. Indic. *158*, 111547. https://doi.org/10.1016/j.ecolind.2024.111547.

15. Liu, D., Li, X., Emeis, K.C., Wang, Y., and Richard, P. (2015). Distribution and sources of organic matter in surface sediments of Bohai Sea near the Yellow River Estuary, China. Estuar. Coast Shelf Sci. *165*, 128–136. https://doi.org/10.1016/j.ecss.2015.09.007.

16. Lyu, J., Shi, Y., Zhang, S., Liu, S., Liu, T., Xu, X., Yang, G., and Gao, J. (2023). The reservoirs gradually changed the distribution, source, and flux of particulate organic carbon within the Changjiang River catchment. J. Hydrol. X. *623*, 129808–129815. https://doi.org/10.1016/j.jhydrol.2023.129808.

17. Zhang, G., Deng, A., Chen, J., Wang, D., Yin, Y., and Wang, H. (2024). Impacts of climate change and human activities on sediment load in Longchuan River Basin, China. J. Hydrol. Reg stud. *51*, 101613. https://doi.org/10.1016/j.ejrh.2023.101613.

18. Kelly, V.J. (2001). Influence of reservoirs on solute transport: a regional-scale approach. Hydrol. Process. *15*, 1227–1249. https://doi.org/10.1002/hyp.211.

19. Sabo, J.L., Sinha, T., Bowling, L.C., Schoups, G.H.W., Wallender, W.W., Campana, M.E., Cherkauer, K.A., Fuller, P.L., Graf, W.L., Hopmans, J.W., et al. (2010). Reclaiming freshwater sustainability in the Cadillac Desert. Proc. Natl. Acad. Sci. USA *107*, 21263–21270. https://doi.org/10.1073/pnas.1009734108.

20. Shi, W., Chen, Q., Yi, Q., Yu, J., Ji, Y., Hu, L., and Chen, Y. (2017). Carbon Emission from Cascade Reservoirs: Spatial Heterogeneity and Mechanisms. Environ. Sci. Technol. *51*, 12175–12181. https://doi.org/10.1021/acs.est.7b03590.

21. Xu, B., Li, Y., Han, F., Zheng, Y., Ding, W., Zhang, C., Wallington, K., and Zhang, Z. (2020). The transborder flux of phosphorus in the Lancang-Mekong River Basin: Magnitude, patterns, and impacts from the cascade hydropower dams in China. J Hydrol *590*, 125201. https://doi.org/10.1016/j.jhydrol.2020.125201.

22. Chen, J., Wang, P., Wang, C., Wang, X., Gao, H., Cui, G., Liu, S., and Yuan, Q. (2022). How dam construction affects the activity of alkaline phosphatases in reservoir sediments: A study of two highly regulated rivers. Environ. Res. *207*, 112236. https://doi.org/10.1016/j.envres.2021.112236.

23. Wang, J., Yuan, X., Lu, Y., Yan, C., Zhang, K., Li, Y., Guo, Z., and Duan, Q. (2024). Cross-border impacts of cascade reservoirs on the temperature of the Lancang-Mekong River. Ecol. Indicat. *160*, 111918. https://doi.org/10.1016/j.ecolind.2024.111918.

24. Zhai, H., Rubin, E.S., and Versteeg, P.L. (2011). Water use at pulverized coal power plants with postcombustion carbon capture and storage. Environ. Sci. Technol. *45*, 2479–2485. https://doi.org/10.1021/es1034443.

25. Shi, W., Chen, Q., Zhang, J., Liu, D., Yi, Q., Chen, Y., Ma, H., and Hu, L. (2020). Nitrous oxide emissions from cascade hydropower reservoirs in the upper Mekong River. Water Res. *173*, 115582. https://doi.org/10.1016/j.watres.2020.115582.

26. Zhang, Q., Chen, Y., Lin, Y., Chen, Q., Zhang, J., Ding, J., and Ma, H. (2023). Characteristic of phytoplankton community structure and its driving factors along the cascade reservoirs in the Lancang River. J. Lake Sci. *35*, 530–535. https://doi.org/10.18307/2023.0211.

27. Chen, Q., Chen, Y., Lin, Y., Zhang, J., Ni, J., Xia, J., Xiao, L., Feng, T., and Ma, H. (2024). Does a hydropower reservoir cascade really harm downstream nutrient regimes. Sci. Bull. *69*, 661–670. https://doi.org/10.1016/j.scib.2024.01.007.

28. Zeng, L., Mcgowan, S., Swann, G.E., Leng, M.J., and Chen, X. (2022). Eutrophication has a greater influence on floodplain lake carbon cycling than dam installation across the middle Yangtze Region. J Hydrol *614*, 128510. https://doi.org/10.1016/j.jhydrol.2022.128510.

29. Park, H.K., Byeon, M.S., Shin, Y.N., and Jung, D.I. (2009). Sources and spatial and temporal characteristics of organic carbon in two large reservoirs with contrasting hydrologic characteristics. Water Resour. Res. *45*, 2471–2481. https://doi.org/10.1029/2009WR008043.

30. Wang, C.F., Hu, Z.L., Yang, Z.J., Dan, Y., Zhao, P., Hao, W.C., Nie, X.F., Nie, R., Xu, L.d., and Liu, D.F. (2019). Analysis of Total Organic Carbon Source Differences Between New and Old Cascade Reservoirs using Carbon and Nitrogen Isotopes. Envir. Sci. *40*, 3039–3048. https://doi.org/10.13227/j.hjkx.201811243.

31. Bao, Y., Zhang, D., Wang, Y., Yang, Z., Hu, P., Chen, H., Nie, B., Liu, X., Huang, W., Li, J., et al. (2024). Analysis of nitrogen migration and transformation in the typical deep and large reservoir of the Lancang River — Evidence from nitrogen and oxygen isotopes. J. Hydrol. X. *640*, 131701. https://doi.org/10.1016/j.jhydrol.2024.131701.

32. Li, G., Wang, X.T., Yang, Z., Mao, C., West, A.J., and Ji, J. (2015). Dam-triggered organic carbon sequestration makes the Changjiang (Yangtze) river basin (China) a significant carbon sink. JGR. Biogeosciences *120*, 39–53. https://doi.org/10.1002/2014JG002646.

33. Fang, X., Yang, Z., Ji, D., Yao, X., and Liu, D. (2013). Responses of spring phytoplankton communities to their habitats in the Xiangxi Bay of Three Gorges Reservoir, China. Acta Ecol. Sinica. *33*, 308–316. https://doi.org/10.1016/j.chnaes.2013.09.002.

34. Melillo, J.M., Steudler, P.A., Aber, J.D., Newkirk, K., Lux, H., Bowles, F.P., Catricala, C., Magill, A., Ahrens, T., and Morrisseau, S. (2002). Soil warming and carbon-cycle feedbacks to the climate system. Science *298*, 2173–2176. https://doi.org/10.1126/science.1074153.

35. Deng, C., Zhang, H., and Hamilton, D.P. (2024). Sensitivity of streamflow and nutrient loads to changes in leaf area index and soil organic carbon in a sub-tropical catchment subject to climate change. J. Hydrol. Reg stud. *52*, 101682. https://doi.org/10.1016/j.ejrh.2024.101682.

36. Dean, W.E., and Gorham, E. (1998). Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geol. *26*, 535–538. https://doi.org/10.1130/0091-7613(1998)026<0535:MASOCB>2.3.CO;2.

37. Kunz, M.J., Anselmetti, F.S., Wüest, A., Wehrli, B., Vollenweider, A., Thüring, S., and Senn, D.B. (2011). Sediment accumulation and carbon, nitrogen, and phosphorus deposition in the large tropical reservoir Lake Kariba (Zambia/Zimbabwe). J Geophys Res-Biogeo *116*, 1–13. https://doi.org/10.1029/2010jg001538.

38. Ittekkot, V. (1988). Global trends in the nature of organic matter in river suspensions. Nature *332*, 436–438. https://doi.org/10.1038/332436a0.

39. Mu, Z., Wang, Y., Wu, J., Cheng, Y., Lu, J., Chen, C., Zhao, F., Li, Y., Hu, M., and Bao, Y. (2020). The influence of cascade reservoir construction on

sediment biogenic substance cycle in Lancang River from the perspective of phosphorus fractions. Ecol. Eng. *158*, 106051. https://doi.org/10.1016/j.ecoleng.2020.106051.

40. Zhao, C., Dong, S., Liu, S., An, N., Sylvie, I., Zhao, H., Liu, Q., and Wu, X. (2017). Preliminary study on the effect of cascade dams on organic matter sources of sediments in the middle Lancang–Mekong River. J Soil Sediment *18*, 297–308. https://doi.org/10.1007/s11368-017-1790-5.
41. Fox, J.F., and Papanicolaou, A.N. (2008). Application of the spatial distribution of nitrogen stable isotopes for sediment tracing at the watershed scale. J Hydrol *358*, 46–55. https://doi.org/10.1016/j.jhydrol.2008.05.032.
42. Machiwa, J.F. (2010). Stable carbon and nitrogen isotopic signatures of organic matter sources in near-shore areas of Lake Victoria, East Africa. J. Great Lakes Res. *36*, 1–8. https://doi.org/10.1016/j.jglr.2009.11.005.
43. Xiao, H., Mao, C., Wang, S., Jia, Z., and Rao, W. (2023). Seasonal variation and provenance of organic matter in the surface sediments of the Three Gorges Reservoir: Stable isotope analysis and implications for agricultural management. Sci. Total Environ. *870*, 161886. https://doi.org/10.1016/j.scitotenv.2023.161886.
44. Zhang, Y., Gao, X., Sun, B., and Liu, X. (2024). Oxygen evolution and its drivers in a stratified reservoir: A supply-side perspective for informing hypoxia alleviation strategies. Water Res. *257*, 121694. https://doi.org/10.1016/j.watres.2024.121694.
45. Bao, Y., Wang, Y., Hu, M., Hu, P., Wu, N., Qu, X., Liu, X., Huang, W., Wen, J., Li, S., et al. (2025). Deciphering the impact of cascade reservoirs on nitrogen transport and nitrate transformation: Insights from multiple isotope analysis and machine learning. Water Res. *268*, 122638. https://doi.org/10.1016/j.watres.2024.122638.
46. Maavara, T., Chen, Q., Meter, K.V., Brown, L.E., Zhang, J., Ni, J., and Zarfl, C. (2020). River dam impacts on biogeochemical cycling. Nat Rev Earth Env *1*, 103–116. https://doi.org/10.1016/j.jseaes.2023.105654.
47. Wang, W., Li, S.L., Zhong, J., Yi, Y., Yue, F., Han, Z., Wu, Q., He, D., and Liu, C.Q. (2024). Unraveling the factors influencing CO_2 emissions from hydroelectric reservoirs in karst and non-karst regions: A comparative analysis. Water Res. *248*, 120893. https://doi.org/10.1016/j.watres.2023.120893.
48. Yang, M., Li, X.D., Huang, J., Ding, S., Cui, G., Liu, C.Q., Li, Q., Lv, H., and Yi, Y. (2020). Damming effects on river sulfur cycle in karst area: A case study of the Wujiang cascade reservoirs. Agric. Ecosyst. Environ. *294*, 106857. https://doi.org/10.1016/j.agee.2020.106857.
49. Wang, W.F., Li, S.L., Zhong, J., Maberly, S.C., Li, C., Wang, F.S., Xiao, H.Y., and Liu, C.Q. (2020). Climatic and anthropogenic regulation of carbon transport and transformation in a karst river-reservoir system. Sci. Total Environ. *707*, 135628. https://doi.org/10.1016/j.scitotenv.2019.135628.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
The parameters of the four reservoirs	China National Committee on Large Dams	http://www.chincold.org.cn/chincold/index.htm
Software and algorithms		
R-software (V3.6.3)	The R Foundation	https://www.r-project.org/
TOC sources	Wang et al.[30]	https://www.hjkx.ac.cn/hjkx/ch/index.aspx

METHOD DETAILS

Study area overview

The Lancang-Mekong River, originating from the Tanggula Mountains on the Qinghai-Tibet Plateau, flows through six countries, and empties into the South China Sea near Ho Chi Minh City, Vietnam. The river basin harbors over ten thousand species of biological resources with a total length of 4,400 km and a basin area of 795,000 km^2. In China, it is referred to as the Lancang River, with a mainstream length of approximately 2,160 km and a basin area of 195,000 km^2. Currently, 11 hydropower stations have been completed in the Yunnan section of the river, forming a cascade development pattern in the basin. The sequential ''high dam with deep reservoir'' configuration has become a key node in regulating river hydrological processes. This study selected four cascade reservoirs in the middle and lower reaches of the Lancang River as research objects, including Gongguoqiao (GGQ) Reservoir, Xiaowan (XW) Reservoir, Manwan (MW) Reservoir, and Nuozhadu (NZD) Reservoir. The first three reservoirs belong to the subtropical climate, while the NZD reservoir belongs to tropical climate. This study utilized isotopic techniques combined with Bayesian isotope mixing models to investigate the distribution and sources of TOC in the sediments of these cascade reservoirs. The sampling locations and detailed parameters of the four reservoirs are provided in Figure 1 and Table 1.

Sample collection and testing

The study was conducted in May 2021 at GGQ, XW, MW, and NZD. Since the XW and NZD reservoirs have a storage capacity exceeding 10 billion cubic meters and a depth greater than 150 m, three sampling points were selected: the reservoir head, mid-reservoir, and reservoir tail. For the MW reservoir, two sampling points were selected: the reservoir head and reservoir tail. As the first reservoir in this study, GGQ had one sampling point at the reservoir head for some sampling reasons. A total of nine sediment core profiles were sampled for analysis, including one from GGQ, namely GGQ1, three from XW, namely XW01, XW02, and XW03, two from MW, namely MW01 and MW02, and three from NZD, namely NZD01, NZD02, and NZD03. Sediment core samples were collected using a custom-made sediment corer (60 × 1000 mm). The sediment cores were sectioned undisturbed every 1 cm. Each sectioned sediment sample was placed into graduated polyethylene centrifuge tubes, sealed, and stored at 4°C until laboratory analysis.

A water quality multi-parameter analyzer (YSI-EXO2, USA) was used on-site to measure the water temperature (WT) and chlorophyll-a (Chla) concentrations *in situ*. TOC and TN in the sediment were determined using an elemental analyzer (Elementar-vario MACRO cube, USA). During the experiment, about 0.5–1 g of the sample was weighed and added to enough 1 mol/L hydrochloric acid (HCl). The reaction was carried out for 7 h to eliminate carbonates. Subsequently, the sample was washed with ultrapure water for 4–5 times until it reached neutrality. The sample was dried at 50°C, and then placed in a centrifuge tube for determination.

QUANTIFICATION AND STATISTICAL ANALYSIS

The carbon-nitrogen ratio (C/N) was calculated based on the contents of carbon and nitrogen. To ensure the accuracy of experimental analysis, the sediment standard sample B2150 (with a carbon content of 7.17% and a nitrogen content of 0.57%) was inserted, and parallel samples were set up for quality control. The measured values for carbon and nitrogen content of the standard sample were 7.04% ± 0.34% and 0.59% ± 0.04%, respectively. Sediment organic carbon isotopes ($\delta^{13}C$) and nitrogen isotopes ($\delta^{15}N$) were measured using a stable isotope mass spectrometer (MAT253, USA). The results were calculated using the following formulas:

$$\delta^{13}C \text{ or } \delta^{15}N\ (‰) = [(R_{sample} - R_{standard}) / R_{standard}] \times 1000 \quad \text{(Equation 1)}$$

Where, R_{sample} represents the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ ratio of the sample being tested; $R_{standard}$ represents the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ ratio of the standard sample. The experiments described above were all conducted at the Laboratory of the Institute of Geochemistry, Chinese Academy of Sciences.

The Pearson correlation coefficient was used for two-tailed significance test to analyze the correlation between different parameters. One-way analysis of variance (ANOVA) was used to determine whether indicators had statistical significance at the 95% confidence level in R. The Bayesian stable isotope mixing model in R (MixSIAR) was applied to assess the potential sources contributing to sediment TOC, using δ13C and δ15N as indicators. The contribution proportions of different sources to sediment TOC in the reservoirs were calculated using the following equations:

$$\delta_M = f_A\delta_A + f_B\delta_B + \ldots + f_N\delta_N \quad \text{(Equation 2)}$$

$$1 = f_A + f_B + \ldots + f_N \quad \text{(Equation 3)}$$

Where, δ_A, δ_B, …, δ_N represent the isotopic compositions of various sources. δ_M represents the isotopic composition of organic matter in coastal sediments in this study. f_A, f_B, …, and f_N are the proportional contributions of these various sources.