https://doi.org/10.5194/egusphere-2026-3912
Preprint. Discussion started: 21 July 2026

Spatiotemporal Shifts in Organic Carbon Sources in Cascade Reservoirs - a case study in the Lancang River

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https://doi.org/10.5194/egusphere-2026-3912
Preprint. Discussion started: 21 July 2026

ABSTRACT

Dam construction profoundly alters sediment organic matter regimes in large rivers. Yet, the underlying mechanisms and how cascade reservoirs jointly shape organic matter sources remain insufficiently understood. Here, we quantified organic matter sources across five cascade reservoirs in the middle–lower Lancang River using stable isotopes with a Bayesian mixing model. We found that algal-derived organic matter dominated during the dry season and in reservoirs with longer retention, whereas terrestrial organic matter prevailed during the wet season and intensified downstream with increasing watershed inputs. The structural equation model analyses demonstrated that reservoir regulation and seasonality influenced organic matter sources indirectly through nutrient dynamics rather than through direct hydrological forcing. Hydrodynamic conditions, represented by a composite index derived from hydraulic retention time and backwater length, were positively associated with nutrient enrichment in both water and sediments, whereas temperature showed a negative relationship with sediment nutrients; these nutrient variations were further linked to increased contributions of terrestrial, algal, and sewage-derived organic matter. Complementary boosted regression tree analyses further identified the key environmental predictors shaping organic matter partitioning. Water temperature together with sediment nutrients formed the core controls on the balance between terrestrial and algal organic matter (>48% cumulative influence). Hydrodynamic factors were crucial for sewage-derived organic matter, with water depth and retention time jointly contributing 35.2% of its variability. Together, these results reveal that organic matter provenance in cascade systems emerges from the coupled effects of reservoir-

https://doi.org/10.5194/egusphere-2026-3912
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induced nutrient regulation and temperature–hydrology interactions, producing source dynamics distinct from single-reservoir systems. This study provides mechanistic insights needed to improve reservoir ecosystem management and underscores the importance of integrating cascade-scale nutrient regulation into future assessments of human impacts on riverine carbon cycling.

Keywords: Sediment organic matter, isotope, biogeochemical cycling, the Lancang River, cascade reservoirs

Introduction

Large river systems are central to the global carbon cycle, functioning as both longitudinal conduits for organic matter (OM) and active biogeochemical reactors that determine its ultimate fate (Cole et al. 2007, Maavara et al. 2017, Chen et al. 2024). Central to these dynamics are riverine sediments, which function as dual sinks and sources of organic carbon (OC) through complex processes of deposition, sequestration, transformation, and emission (Aufdenkampe et al. 2011, Mendonça et al. 2017). The composition and provenance of sedimentary organic matter (SOM) ultimately dictate carbon burial efficiency and carbon emission fluxes. Therefore, fingerprinting OC sources is fundamental to understanding ecosystem-scale carbon turnover and evaluating the ecological ramifications of hydropower development on the global carbon cycle (Tranvik et al. 2009, Raymond et al. 2013, Gao et al. 2021).

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The proliferation of dams has fundamentally restructured riverine carbon cycling (Maavara et al. 2017, Maavara et al. 2020, Dethier et al. 2022). By reducing flow velocities and extending hydraulic residence time (HRT), dam construction enhances particle settling, thereby altering the transport and burial patterns of land-derived organic matter. Concurrently, increased water depth triggers thermal stratification and alters light availability, which in turn shifts the balance between allochthonous organic matter inputs and in-reservoir primary production (Mendonça et al. 2017, Tranvik et al. 2018, Schulz-Zunkel et al. 2022). In cascade reservoir systems, these impacts are not merely localized but accumulate along the river continuum, where sequential reservoirs synergistically reshape hydrodynamics, sediment trapping efficiency, and nutrient stoichiometry (Li et al. 2020, Maavara et al. 2020, Wang et al. 2024). Collectively, these dam-induced modifications are expected to exert profound controls on both the magnitude and proportional contributions of organic matter inputs to the benthos.

However, the interplay between dam-induced alterations and natural hydrological seasonality creates a complex spatiotemporal mosaic of carbon processing (Chen et al. 2015, Xu et al. 2023). In large monsoonal rivers like the Lancang River, pronounced seasonal shifts in discharge and sediment loads further complicate these dynamics. While the impacts of individual impoundments are well-documented, the collective influence of multi-reservoir cascades, where sequential reservoirs may either amplify or attenuate watershed signals, remains an area of significant uncertainty. Specifically, how these "serial discontinuities" mediate the balance between allochthonous inputs and autochthonous production under contrasting hydrological regimes is yet to be mechanistically elucidated. Addressing this gap

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is critical for moving beyond site-specific observations toward a basin-scale understanding of carbon cycling in heavily regulated river networks (Raymond et al. 2013, Regnier et al. 2013, Fang et al. 2023).

The objectives of this study were to: (1) quantify the relative contributions of multiple sedimentary organic carbon (SOC) sources in cascade reservoirs using a stable isotope-based mixing model, (2) identify the environmental drivers (e.g., HRT, nutrient availability, and monsoonal discharge) underlying spatial and seasonal variability of SOC sources, and (3) evaluate the implications of cascade hydropower development for longitudinal carbon connectivity. By integrating hydrological and operational context, this study provides new insights into how cascade dams modulate SOC dynamics in river systems.

2. Materials and Methods

2.1 Study Area

The Lancang River, the upper reach of the Mekong, traverses the Tibetan Plateau and Yunnan Province in China before cascading into Southeast Asia. Its steep topographic relief has made it one of the world's most concentrated regions for hydropower development, with the middle and lower reaches hosting a series of intensive damming projects. This study focuses on a representative cascade segment spanning from the Miaowei (MIW) to the Dachaoshan (DCS) reservoirs (Fig.1). These impoundments exhibit distinctive hydrodynamic regimes and HRT, with their specific morphometric and operational characteristics summarized in Table S1.

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The basin is governed by a pronounced monsoonal climate, with 80%–85% of annual precipitation occurring during the wet season (May–October). This hydrological seasonality triggers pulsed fluctuations in river discharge and sediment transport (Shi et al. 2020, Zhou et al. 2024). Land-use patterns vary along the cascade continuum; generally, vegetation richness increases progressively from upstream to downstream reaches, following the descending altitudinal gradient (Lang et al. 2024, Zhang et al. 2025). Furthermore, localized anthropogenic and natural stressors differentiate these reservoirs: the Manwan (MW) reservoir is heavily impacted by intensive aquaculture and fishing activities, while the Gongguoqiao (GGQ) reservoir receives perennial input from a turbid tributary characterized by severe upstream soil erosion. Collectively, these diverse conditions provide a unique natural gradient to investigate the impact of cascade damming on the sources and dynamics of SOC.

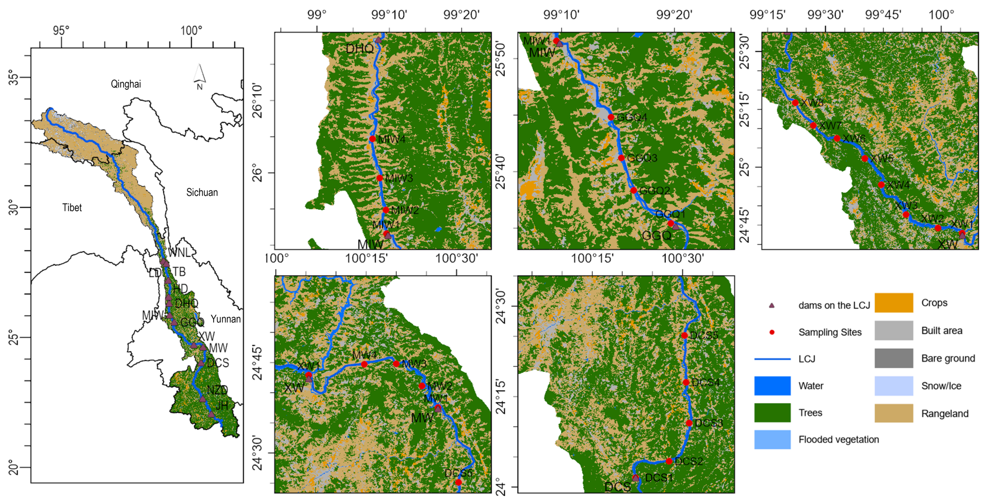

Fig.1 Sampling locations in Lancang River including five major reservoirs (Miaowei (MIW), Gongguoqiao (GGQ), Xiaowan (XW), Manwan (MW), Dachaoshan (DCS))

2.2 Sampling Design

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Field campaigns were conducted in September 2023 and April 2024, capturing the peak of the wet season (high water level) and the dry season (low water level), respectively. Samples were taken in both the lacustrine zones (from boats) and the fluvial zones (from bridges or riverbanks). At each site, in situ physicochemical parameters, including pH, water temperature (WT), dissolved oxygen (DO) and electrical conductivity, were measured using a calibrated multiparameter probe (YSI, Yellow Springs, OH, USA). Surface water samples (250 mL) were collected in pre-cleaned polyethylene bottles, stored in the dark, frozen, and transported to the laboratory. Water samples were analyzed for total phosphorus (wTP), total nitrogen (wTN), water nitrate (wNO_3^--N), water nitrite (wNO_2^--N), and water ammonium (wNH_4^+-N) using a spectrophotometer (DR6000, Hach, USA) following the National Standards of China (2002). The water total carbon (wTC) concentrations in water samples were measured using a TOC analyzer (Multi N/C 3100, Analytik Jena GmbH, Germany).

Surface sediments (0–20 cm) were collected using an Ekman grab sampler (ZG0204, Shanghai ZiGui Instrument Co., Ltd.). After removal of coarse debris (e.g., rocks, branches), samples were homogenized and immediately frozen with liquid nitrogen. In the laboratory, sediments were freeze-dried and analyzed for total carbon (TC) content using an elemental analyzer (Vario MACRO cube, Elementar Inc., Germany). Sediment total phosphorus (sTP), sediment total nitrogen (sTN), sediment nitrate (sNO_3^--N), sediment nitrite (sNO_2^--N), and sediment ammonium (sNH_4^+-N) concentrations were determined spectrophotometrically (DR6000, Hach, USA).

2.3 Stable isotope analysis and three-end-member mixing model (TEMM)

$\delta^{13}C$ and $\delta^{15}N$ of sediment organic matter were measured using an isotope ratio mass spectrometer (IRMS) coupled to an elemental analyzer. Isotopic ratios were expressed in δ notation relative to Vienna Pee Dee Belemnite (V-PDB) for carbon and atmospheric N_2 for nitrogen:

$$\delta X(‰) = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \quad (1)$$

where X is ^{13}C or ^{15}N, and R is the corresponding heavy-to-light isotope ratio ($^{13}C/^{12}C$ or $^{15}N/^{14}N$) (Middelburg and Nieuwenhuize 1998, Torres et al. 2012).

To quantify the sources of SOM in the Lancang River cascade, we employed a Bayesian three-end-member mixing model using the MixSIAR package in R (Stock and Semmens 2016, Stock et al. 2018, Choi et al. 2025). Based on the hydro-ecological setting of the basin and previous in situ data from regional field surveys (Wang et al. 2019, Bao et al. 2025), three primary potential sources were defined: (1) Terrestrial organic matter (T-OM): Derived from upstream riverine inputs, riparian vegetation, and soil erosion from the Tibetan Plateau and adjacent catchments; (2) Autochthonous Algae organic matter (A-OM): Generated via in-reservoir phytoplankton and periphyton primary production; (3) Sewage-derived organic matter (Sew-OM): Representing anthropogenic inputs, including domestic wastewater and agricultural runoff.

The end-member isotopic signatures were determined using an integrated approach that combines published literature ranges with constraints derived from the measured isotopic compositions of sediment samples in this study (Table S2). This strategy was adopted to better represent the specific hydro-biogeochemical conditions of the Lancang River cascade, which

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differ from those of typical river–lake systems. T-OM was characterized by relatively depleted $\delta^{13}C$ values (–27.8 ± 2.0‰) and moderate $\delta^{15}N$ values (5.4 ± 1.5‰), consistent with inputs from C_3-dominated upstream soils, vegetation debris, and riverine particulate matter. A-OM exhibited comparatively enriched $\delta^{13}C$ values (–16.0 ± 2.5‰) and intermediate $\delta^{15}N$ values (6.0 ± 1.5‰), reflecting in-reservoir primary production under HRT. The relatively enriched $\delta^{13}C$ signature of A-OM is consistent with the influence of a $\delta^{13}C$-enriched dissolved inorganic carbon pool in the carbonate-rich Lancang River basin. Sew-OM showed markedly enriched $\delta^{13}C$ (–4.5 ± 2.5‰) and elevated $\delta^{15}N$ values (8.5 ± 2.0‰), indicative of anthropogenic inputs associated with wastewater discharge and intensified nitrogen cycling. The enriched carbon signature may also be related to contributions from C_4-based agricultural runoff (e.g., sugarcane and maize) in the midstream catchment (Yang et al. 2025, Yin et al. 2025).

Notably, these end-member values deviate from commonly reported ranges, particularly for algal and sewage sources. Such deviations likely reflect the distinctive environmental setting of the Lancang River cascade, characterized by strong hydrological regulation, high-altitude catchment inputs, and altered carbon and nitrogen cycling processes. The selected signatures are constrained by the observed isotopic distribution of sediment samples, ensuring that the mixing space adequately encompasses the empirical data. Sensitivity analyses further demonstrated that the end-member configuration yields stable and robust estimates of organic matter contributions across both seasons and reservoirs.

In the MixSIAR framework, "Reservoir" was treated as a fixed effect to capture spatial patterns across the cascade while accounting for internal variability. The model was run using

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a "long" MCMC chain (300,000 iterations) to ensure convergence, which was verified using Gelman-Rubin and Geweke diagnostics. Posterior means and 95% credible intervals are reported for each source at the reservoir scale (Gelman and Shalizi 2013). Additionally, site-specific contributions were evaluated independently to capture localized heterogeneity, considering process error (Parnell et al. 2010). Due to differences in model structure, reservoir-level estimates may not equal the arithmetic mean of site-level estimates (Gelman and Hill 2007). We acknowledge that these estimates are relative and reflect inherent uncertainties in end-member characterization; thus, results are interpreted as indicative of broad ecological trends (Link and Barker 2009a, b).

2.4 Statistical Analyses

All statistical calculations were performed using R software. Seasonal and spatial differences among reservoirs were assessed using two-way ANOVA followed by Tukey's HSD post hoc tests, with a significance threshold of $p < 0.05$. Data visualization was conducted using Origin 2024. The correlation analysis between SOC sources and hydro-environmental parameters was based on simple linear regression after data normalization. The Bayesian mixing approach (using the MixSIAR package) was performed in R 4.1. Composite indices were derived from variables of the same type (e.g., hydro-index, water and sediment nutrient variables) using principal component analysis (PCA) to reduce dimensionality and mitigate multicollinearity. Based on these indices, a structural equation model (SEM) was constructed using the R plspm package to assess the direct and indirect effects of environmental factors on water and sediment nutrients and the proportion of allochthonous organic matter. Model

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evaluation included bootstrap significance of path coefficients, as well as latent variable average variance extracted (AVE) and overall goodness-of-fit (GoF).

3. Results

3.1 Environmental conditions along the cascade

Monitoring of five cascade reservoirs from the wet season (Autumn 2023) to the dry season (Spring 2024) revealed significant spatiotemporal variations in key environmental parameters (Fig.2). WT peaked in the wet season (maximum 26.57°C in XW Reservoir), exhibiting a significant negative correlation with DO concentrations, which were highest in the dry season. pH values were consistently higher in the wet season than in the dry season.

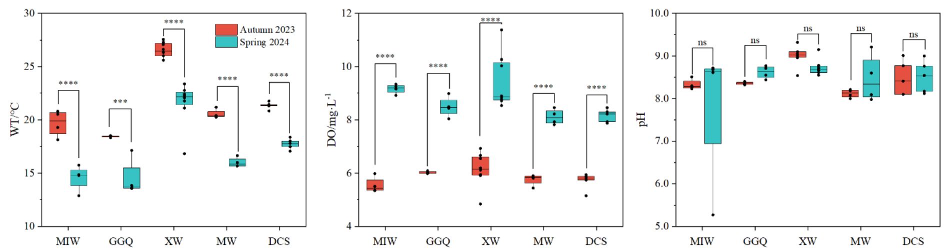

Fig.2 Longitudinal variations in water temperature (WT), dissolved oxygen (DO), and pH of surface waters along the Lancang River, from MIW to DCS (following the flow direction).

Fig.3 illustrates the variations in nutrient concentrations in surface water and sediment samples. The highest average TC contents in both water and sediments were observed in GGQ Reservoir during the dry season. wTN generally showed higher average values in the dry season of 2024 than in the wet season of 2023; both wTN and sTN exhibited significant seasonal differences at the DCS site. In contrast, average concentrations of water and sediment total phosphorus were predominantly higher in wet season of 2023 than in dry season of 2024.

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Regarding nitrogen species, both water and sediment compartments displayed a cumulative effect from upstream to downstream. Additionally, wNO_2^--N and sNO_2^--N demonstrated significant seasonal variations (ANOVA, $p < 0.05$). Notably, the significant accumulation of sNO_2^--N during the dry season indicates intense N transformation activities at the sediment-water interface and a high potential for internal release in the cascade reservoirs during this season.

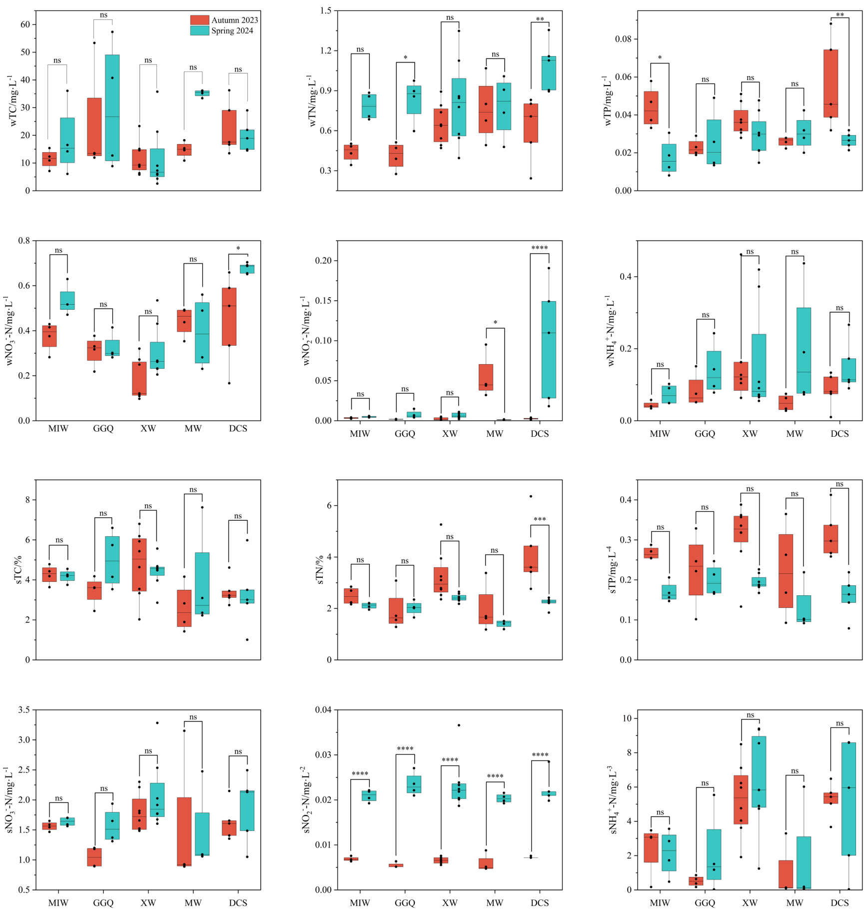

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Fig.3 Longitudinal variations in nutrient concentrations in surface water and sediments along the Lancang River, from MIW to DCS (following the flow direction). Parameters include total carbon (TC), total nitrogen (TN), total phosphorus (TP), nitrate (NO_3^--N), nitrite (NO_2^--N), and ammonium (NH_4^+-N) for both water (w) and sediment (s) compartments.

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

The stable carbon and nitrogen isotopic compositions ($\delta^{13}C$ and $\delta^{15}N$) of surface sediments across the five cascade reservoirs exhibited pronounced spatiotemporal heterogeneity (Fig.4). Overall, $\delta^{13}C$ values fluctuated within a wide range of -24.9‰ to -1.7‰, while $\delta^{15}N$ values varied between 1.9‰ and 9.0‰.

Spatially, the most depleted $\delta^{13}C$ signatures were recorded in the downstream DCS reservoir, with values ranging from -24.9‰ to -17.2‰. In contrast, the MW and GGQ reservoirs displayed significantly more enriched $\delta^{13}C$ values (MW: -18.8‰ to -2.5‰; GGQ: -18.9‰ to -3.6‰). Regarding nitrogen isotopes, the GGQ and DCS reservoirs were characterized by relatively elevated $\delta^{15}N$ values, reaching up to 9.0‰ and 8.4‰, respectively. Conversely, the MW reservoir exhibited the lowest $\delta^{15}N$ levels, falling to a minimum of 1.9‰. Two-way ANOVA results further confirmed that both the reservoir factor and the season factor exerted significant influences on the isotopic signatures of both $\delta^{13}C$ and $\delta^{15}N$ ($p < 0.05$).

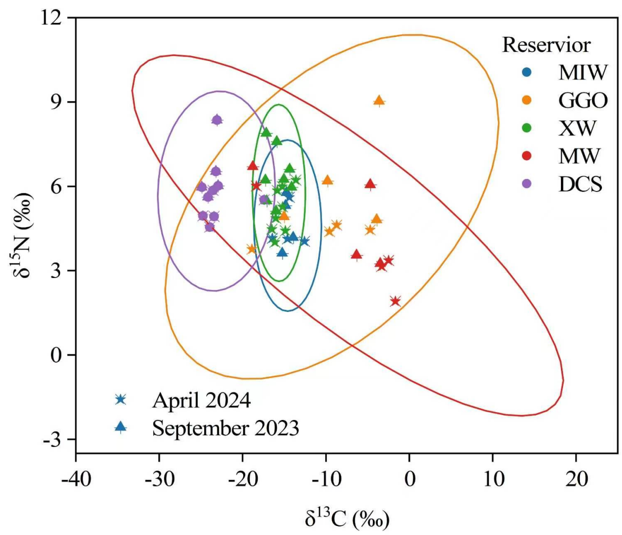

Fig.4 End-member diagram of $\delta^{13}C$ and $\delta^{15}N$ of sedimentary organic matter from cascade reservoirs in the middle and lower reaches of the Lancang River

3.3 Spatial and seasonal variations in SOC source contributions

The three-endmember mixing model revealed pronounced spatiotemporal shifts in the provenance of SOM across the five cascade reservoirs (Fig.5). Overall, the contribution of Sew-OM was relatively minor, accounting for only 4.5%–17.3% of the total SOM.

During the wet season, T-OM constituted a major portion of the SOM across all reservoirs. The highest T-OM contributions were recorded in the GGQ (71.2%), MW (60.3%), DCS (54.9%), and MIW (51.5%) reservoirs. Notably, even in the XW reservoir, where the terrestrial proportion was the lowest (40.2%), T-OM still constituted nearly half of the total SOC.

In stark contrast, a dramatic shift in source composition occurred during the dry season (April 2024), with autochthonous algae becoming the primary contributor, ranging from 61.3% to 87.2%. This algal dominance peaked in the MW reservoir at 87.2%. Concurrently, the

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contribution of T-OM experienced a sharp decline to between 8.3% and 24.3%, reaching its minimum in the MW reservoir (8.3%).

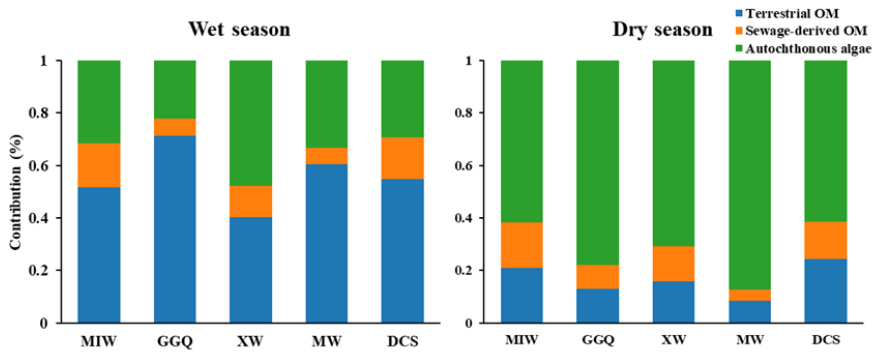

Fig.5 Contributions of different sources to sedimentary organic matter from cascade reservoirs in the middle and lower reaches of the Lancang River

3.4 Relationships between environmental factors and SOM source contributions

The integrated Mantel test and Pearson correlation analysis (Fig.6) elucidate the complex cascade of interactions between hydrological regulation, environmental gradients, and SOM sources. Hydrological factors, including hydraulic retention time (HRT), length of backwater area (LBA), and water depth (WD), exhibited strong correlations with water-column and sedimentary physicochemical properties rather than directly with OM sources. Specifically, HRT, LBA, and WD were significantly positively correlated with WT and sNH_4^+-N. Both HRT and LBA also showed significant positive links with wNO_3^--N, while LBA further exhibited strong positive correlations with pH, wTC and sTN. Additionally, WD was uniquely associated with elevated wNH_4^+-N.

Within the internal network of physicochemical variables, several key parameters emerged as direct predictors of OM provenance. WT, DO, and wTN, along with sediment

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properties such as sTP and sNO_2^--N, demonstrated highly significant correlations with the contributions of A-OM and T-OM. These correlations underscore a mechanism where hydrological regulation alters the thermal and nutrient regimes of the cascade reservoirs, which in turn acts as the proximal driver for the shift between autochthonous primary production and terrestrial detritus accumulation.

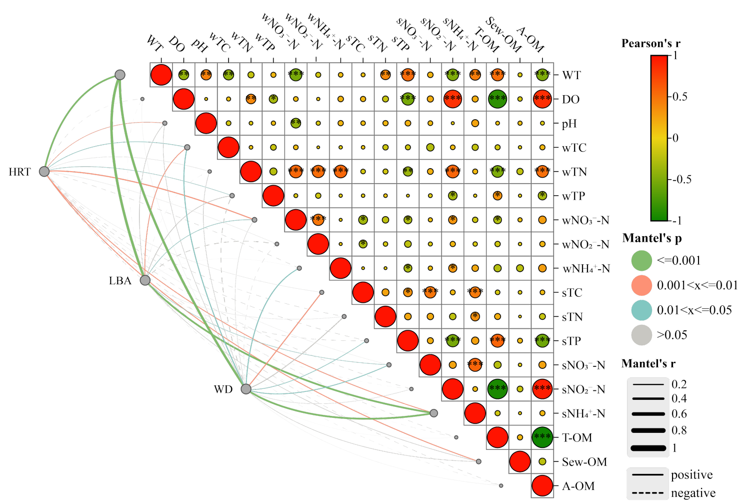

Fig.6 Integrated Mantel test and correlation heatmap showing the relationships between hydrological factors, environmental variables, and sediment organic matter (OM) sources in the Lancang River cascade reservoirs. The left panel presents Mantel test results, illustrating the correlations between hydrological indices, water depth (WD), hydraulic retention time (HRT), and length of backwater area (LBA), and grouped environmental variables as well as OM source contributions. Line thickness indicates the magnitude of correlation strength. Solid lines represent positive correlations, while dashed lines represent negative correlations. Line color reflects statistical significance: green for highly significant relationships, and gray for non-significant relationships. The right panel displays the Pearson correlation matrix

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among water physicochemical parameters (e.g., WT, DO, pH, nutrients), sediment properties (e.g., sTC, sTN, sTP), and OM source contributions (T-OM, Sew-OM, and A-OM indicating terrestrial, sewage-derived, and algal OM, respectively). Color gradients represent correlation coefficients (from −1 to +1), with warmer colors indicating positive correlations and cooler colors indicating negative correlations. Asterisks denote statistical significance (*p < 0.05, **p < 0.01).

To further elucidate the direct and indirect influences of reservoir regulation and nutrient dynamics on OM provenance, an SEM was employed (Fig.7). The results indicated that reservoir and seasonal disparities primarily modulate OM contributions through indirect nutrient regulation. Specifically, hydrological indicators exerted significant positive effects on nutrient pools in both the water column and sediments, while WT had a significant negative impact on sedimentary nutrients. In turn, sedimentary nutrients significantly and positively influenced the contributions of T-OM, A-OM, and Sew-OM. These findings suggest that reservoir regulation and seasonal shifts do not directly alter OM provenance; instead, they operate by restructuring nutrient dynamics within the water–sediment continuum.

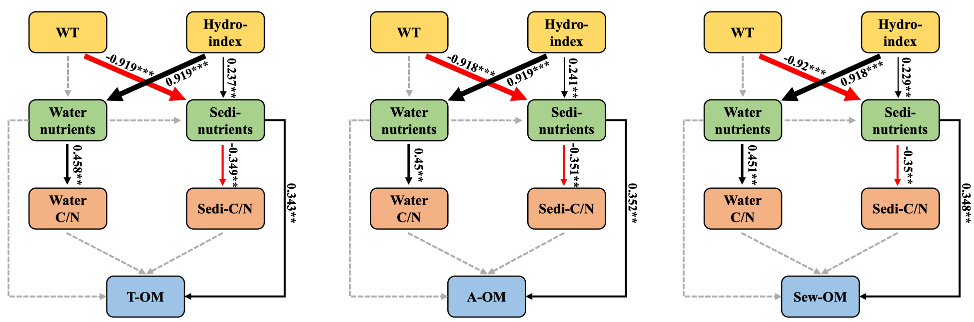

Fig.7 The factors regulating the sediment organic carbon source contribution. In the structural equation model (SEM) analysis, black arrows represent significant positive pathways, red

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arrows represent significant negative pathways, and gray dashed arrows indicate nonsignificant pathways. Values next to the arrows represent standardized effect sizes with statistical significance (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$). The Hydro-index variable in the SEM represents the first component from the principal component analysis (PCA) conducted with the HRT and the LBA data; water and sediment nutrients indicate the first component from the PCA conducted with the TC, total nitrogen and the total phosphorus content of water and sediment samples, respectively; Water C/N and sedi-C/N represent the ratios of TC to nitrogen content in water and sediment, respectively. T-OM, A-OM and Sew-OM indicate the contributions of terrestrial, algal, and sewage-derived organic matter, respectively.

To complement the SEM-based path analysis, Boosted Regression Tree (BRT) models were utilized to quantify the relative importance of individual environmental factors in shaping SOC source contributions (Fig.8). Among all variables, WT and nitrogenous nutrients (wTN, sTN) emerged as the core environmental drivers governing the partitioning of terrestrial and algal inputs, with a cumulative relative influence exceeding 48%. Although HRT was positively correlated with the A-OM proportion, this relationship was not statistically significant (Fig.8c) and possessed limited explanatory power. Notably, for Sew-OM, hydrodynamic processes played a dominant role, with WD (17.7%) and HRT (17.5%) jointly controlling the spatial extent and dilution of point-source pollution (cumulative influence of 35.2%). sTC (11.5%) and wTC (9.2%) followed in importance, while WT showed relatively low explanatory power for A-OM.

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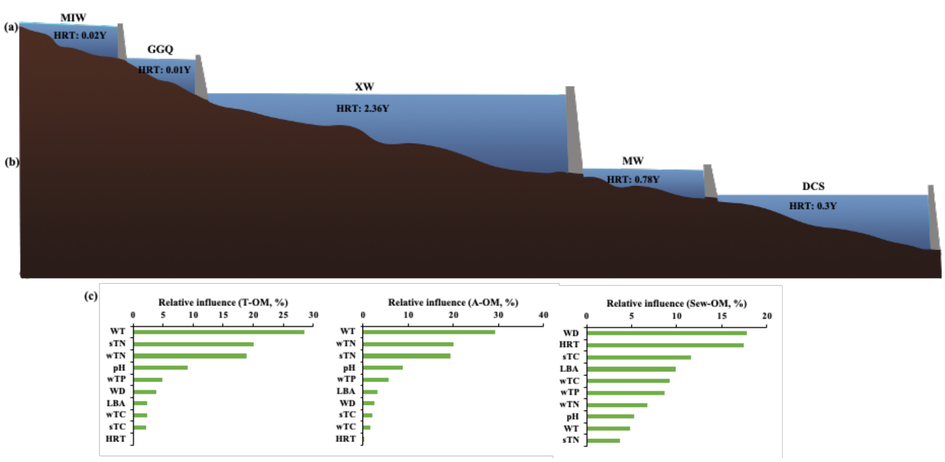

Fig.8 Conceptual diagram of the sources and impacts of sediment OM in the cascade reservoirs in the middle and lower reaches of the Lancang River. (a) Conceptual Diagram of Water Depth and Hydraulic Retention Time in a Cascade of Five Reservoirs; (b) The relationships of the OM contribution of autochthonous algae and hydraulic residence time in wet season and dry season. (c) The relative influences (%) of predictor variables in the boosted regression tree model (BRT) for the OM source.

4. Discussion

4.1 Spatiotemporal heterogeneity of environmental drivers under cascade regulation

Our findings underscore the pronounced spatiotemporal variability of environmental factors in cascade-regulated reservoirs, which fundamentally governs the provenance and dynamics of SOM. WT exhibited a distinct seasonal pattern, exceeding 25°C during the wet season (September) and decreasing to 13–18°C in the dry season. This thermal variation corresponded with a shift in stratified conditions: warmer temperatures in the wet season promoted thermal stratification and moderate oxygen depletion (approximately 5–6 mg L^{-1}),

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whereas enhanced vertical mixing in the dry season elevated DO levels (approximately 8–11 mg L^{-1}, Table.S3). Such seasonal fluctuations are consistent with observations in other cascade systems, where hydrological regimes modulate oxygen dynamics and nutrient cycling (Shi et al. 2023, Yang et al. 2025). Seasonal precipitation and runoff pulses induced sharp fluctuations in water total carbon (wTC). However, the timing and magnitude of these changes varied among reservoirs due to differences in hydraulic regulation. In the dry season, extended HRT and reduced flushing favored nutrient accumulation, particularly in inorganic nitrogen forms (NO_3^--N, NH_4^+-N). This pattern aligns with studies indicating that prolonged retention times in cascade reservoirs can lead to increased nutrient concentrations and altered biogeochemical processes (Ouyang et al. 2025, Zhang et al. 2025).

Sediment stoichiometry further reflected these seasonal differences. During the wet season, lower carbon-to-nitrogen (C/N) ratios (approximately 1–2.5) and higher total nitrogen (TN) and total phosphorus (TP) contents indicated enhanced deposition of nitrogen-rich terrestrial material fueled by watershed inputs. In contrast, some reservoirs exhibited higher C/N ratios in the dry season, accompanied by elevated NH_4^+-N and NO_3^--N concentrations in sediments, suggesting intensified organic matter mineralization and nitrogen cycling under prolonged retention and stronger bottom–surface coupling (Schneider et al. 2010, Jiang et al. 2025). These findings are consistent with research demonstrating that sediment nutrient dynamics in cascade reservoirs are influenced by both hydrological conditions and anthropogenic activities (Kuriata-Potasznik et al. 2020, Szatten and Habel 2020).

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Compared with natural lakes or single reservoirs, where HRT often emerges as the primary control of organic matter dynamics, cascade systems exhibited more complex patterns (Chen et al. 2020, Du et al. 2021). In our study, upstream reservoirs partially buffered terrestrial inputs by trapping sediments and organic matter, while downstream reservoirs received both attenuated upstream pulses and additional allochthonous inputs, leading to asynchronous responses along the cascade. This cascade-induced stratification of hydrodynamic conditions disrupted the direct and linear relationship between HRT and OM dynamics observed in single-reservoir systems. Similar cascade effects have been reported in the Mekong and Yangtze River basins, where cumulative regulation resulted in nutrient and carbon dynamics divergent from those of individual reservoirs (Shi et al. 2017, Chen et al. 2024).

4.2 Mechanisms of spatiotemporal variability in organic matter sources under reservoir regulation

The three-endmember mixing model, integrated with SEM and BRT analysis, elucidates a sophisticated regime shift in the provenance of SOM across the Lancang cascade. Our SEM results (Fig.7) suggest that the shift in SOM provenance is an indirect consequence of altered nutrient stoichiometry and thermal stratification, which reorganize the biogeochemical template of the water-sediment continuum.

Specifically, hydrological indicators (Hydro-index, representing HRT and LBA) exert significant positive effects on nutrient pools in both the water column and sediments. During the dry season, prolonged HRT transforms these reservoirs from mere transport conduits into active biogeochemical reactors, favoring the proliferation of A-OM. The stoichiometric

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composition of SOM provides further evidence for these seasonal dynamics. In the dry season, A-OM exhibited relatively higher C/N ratios (Table.S2), which likely stems from the preferential mineralization of nitrogen-rich labile components, leaving behind residual carbon-rich refractory matter (Meyers 1994, Harning 2013). This interpretation is robustly supported by the elevated concentrations of sedimentary NH_4^+-N and NO_2^--N observed during the dry season, suggesting accelerated nitrogen cycling and intensified benthic-pelagic coupling under prolonged retention (Kuypers et al. 2018).

Notably, this sedimentary signature is mirrored in the overlying water column, where dissolved total nitrogen (DTN) concentrations in April (dry season) significantly exceeded those in September (wet season), with more pronounced disparities in downstream reservoirs (MW and DCS) compared to upstream sites (Table.S3). This consistency implies that the mineralization of algal-derived OM serves as a secondary nitrogen source to the water column, explaining the seasonal enrichment of DTN in the dry season (Liu 2018, Wang et al. 2021). Such sediment-water coupling effects underscore how cascade damming exacerbates spatiotemporal heterogeneity.

Contrary to conventional paradigms in isolated lakes where HRT is often the "master variable" dictating OM dynamics (Zhang et al. 2023, Ouyang et al. 2025), our BRT analysis reveals that HRT alone has limited explanatory power for the variance in OM provenance (Fig.8). This deviation from traditional expectations can be attributed to the cascade cumulative effect: upstream reservoirs intercept suspended sediments and attenuate terrestrial signals, while downstream reservoirs integrate these attenuated fluxes with additional inputs from

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tributary catchments and enhanced in situ production. This longitudinal feedback mechanism breaks the simple linear relationship between HRT and OM composition typically found in solitary lentic systems. Similar observations in the Mekong and Yangtze cascades confirm that sequential damming significantly intensifies the spatial heterogeneity of nutrient and carbon dynamics (Maavara et al. 2017, Chen et al. 2020, Maavara et al. 2020). Consequently, the interplay of monsoonal "pulse-shunt" delivery in the wet season and the "biogeochemical reactor" effect in the dry season, mediated by cascade-driven nutrient restructuring, defines the modern carbon cycle of the Lancang River.

4.3 Ecological Implications of Changes in Organic Carbon Inputs to Reservoirs

The pronounced seasonal alternation between algal-dominated (dry season) and terrestrial-dominated (wet season) OM reflects a sophisticated coupling of hydrological forcing and biogeochemical responses. In the dry season, the synergistic combination of hydrodynamic stability (prolonged HRT and expanded LBA) and favorable nutrient stoichiometry (e.g., elevated inorganic nitrogen and sTP) triggers a “biogeochemical reactor” effect, where autochthonous production becomes the primary sedimentary carbon source. Conversely, the wet season "pulse-shunt" mechanism flushes allochthonous soil organic carbon into the system, effectively suppressing in situ primary production through physical scouring and reduced light availability (Casas-Ruiz et al. 2020, Catalan et al. 2023).

Crucially, our study demonstrates that in the Lancang cascade, indirect nutrient-mediated pathways supersede direct hydrodynamic variables as the proximal drivers of SOC dynamics. While HRT is traditionally viewed as the “master variable” in isolated lakes, the cumulative

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impacts of cascade regulation, characterized by inter-reservoir feedbacks and high-frequency regulation, attenuate the singular influence of residence time. Instead, a “nutrient–thermal filtering” mechanism emerges. As evidenced by our SEM, hydrological indicators (Hydro-index) primarily act by restructuring nutrient pools, while WT exerts a strong negative constraint on sedimentary nutrient retention.

This shift has significant ecological ramifications. As anthropogenic nutrient loading and global warming intensify, the “algalization” of sedimentary carbon may escalate, particularly in mid-stream sections like MW, where agricultural nutrient runoff further stimulates in situ primary production. The accumulation of labile, algal-derived OM in these reservoirs creates potential “biogeochemical hotspots” for mineralization. This process may accelerate greenhouse gas emissions (e.g., CH_4 and CO_2), thereby complicating carbon-neutrality strategies in regulated tropical and subtropical basins (Tranvik et al. 2009, Raymond et al. 2016, Zhou et al. 2024).

5 Conclusion

This study provides a comprehensive assessment of SOC provenance and its environmental drivers within a major monsoonal cascade reservoir system. Our findings reveal that while seasonal climate variability establishes the baseline pattern of organic matter (OM) succession, oscillating between allochthonous dominance in the wet season and autochthonous dominance in the dry season, cascade regulation introduces a significant layer of biogeochemical complexity. Integrated evidence from isotopic mixing models and sedimentary

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stoichiometry confirms that the SOC pool is collectively governed by the interplay of watershed inputs, internal nutrient cycling, and thermal constraints.

Notably, the anomalously enriched $\delta^{13}C$ features observed in the mid-stream reservoirs (e.g., Manwan) underscore the substantial influence of local C4-based agricultural runoff and the enriched DIC pools characteristic of carbonate-rich basins. These site-specific findings highlight the inherent spatial heterogeneity of cascade systems and justify the calibration of end-member values based on regional hydrochemical contexts. Furthermore, this study challenges existing paradigms by demonstrating that nutrient-mediated and thermal drivers supersede direct hydraulic control (e.g., HRT) in modulating SOC dynamics. To fully elucidate the long-term fate and stability of this carbon, future research should integrate isotopic methods with molecular biomarkers and ^{14}C dating. These multidimensional insights are crucial for refining global carbon models and improving the ecological management of dam-dense river networks worldwide.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Competing interests

The authors declare that they have no competing interests.

Funding

This work was supported by the National Key R&D Program of China (2023YFC3207803), Nanjing Overseas Returnees Science and Technology Innovation Project (Rc924005), Nanjing Hydraulic Research Institute Youth Fund (Y924007), Graduate Dissertation Fund of Nanjing Hydraulic Research Institute (Yy924006).

Author contributions

Huimin Sun: Writing-original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. Xudong Zhou: Writing-review & editing, Methodology, Investigation. Bingcan Jiang: Writing-review & editing, Visualization. Yuqing Lin: Writing-review & editing, Visualization, Conceptualization. Yuchen Chen: Investigation, Formal analysis, Data curation. Xingcheng Yan: Writing-review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Acknowledgements

Not applicable.

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