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Article

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Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10926140/v1>

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Additional Declarations: No competing interests reported.

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Abstract

Dissolved silica (DSi) is a key nutrient regulating riverine biogeochemical cycling, diatom productivity, and nutrient balance in downstream estuarine and coastal waters. However, how large cascade reservoirs modify DSi transport in the Yangtze River system remains insufficiently constrained, particularly in the lower Jinsha River where intensive hydropower development has recently occurred. Here, we combined field observations from three major Jinsha River cascade reservoirs, Baihetan, Xiluodu, and Xiangjiaba, in April 2025 with long-term monitoring and historical datasets from the Yangtze River main stem to evaluate reservoir-induced changes in DSi transport and their implications for nutrient connectivity.

The Jinsha River reservoirs showed relatively stable DSi concentrations, with a mean value of $102.83 \pm 1.37 \mu\text{mol L}^{-1}$ and no significant difference among the three reservoirs, suggesting a high but spatially homogenized DSi background in this impounded upper reach. In contrast, long-term records from the Yangtze River main stem revealed pronounced spatial and temporal variability. DSi generally showed a high–low–high longitudinal pattern from the upper to middle and lower reaches, and a marked decline occurred in the middle reach around 2008. Decadal observations at Cuntan, Hankou, and Datong further indicated a gradual decrease in DSi over recent decades, with stronger reductions at downstream stations after the operation of the Three Gorges Dam and the Jinsha River cascade reservoirs. These patterns suggest that

reservoir regulation is likely associated with weakened downstream DSi delivery through prolonged water residence time, reduced hydrological connectivity, enhanced particle settling, biological uptake of DSi, and subsequent burial of biogenic silica within impounded reaches. This study highlights the need to incorporate DSi and silica retention processes into long-term water-quality monitoring and ecological risk assessment for large regulated rivers.

Keywords: dissolved silica; cascade reservoirs; nutrient connectivity; silica retention; Yangtze River; ecological risk

1. Introduction

Silicon (Si) is a major crustal element and an essential nutrient for many aquatic silicifying organisms, particularly diatoms that form biogenic silica (BSi). By regulating diatom production and carbon export through the biological pump, Si plays an important role in marine biogeochemical cycling (Brzezinski et al., 2024; Cassarino et al., 2024; Closset et al., 2025; Ragueneau et al., 2000). Rivers connect terrestrial and marine systems by delivering dissolved and particulate materials, including silicon, carbon, and other nutrients, to estuaries and coastal seas, where these inputs influence nutrient balance and biological productivity (De Melo et al., 2025; Jankowski et al., 2025; Ver, 1999). Riverine silicon delivery is controlled by natural processes such as rock weathering, hydrological transport, and climate-driven mobilization, but it is increasingly modified by human activities (Tréguer et al., 1995; Bernard et al., 2010). Among these disturbances, dam construction has received particular attention because reservoirs can alter flow velocity, water residence time, sediment retention, and in-reservoir biological processing, thereby changing dissolved silica (DSi) transport from upstream river sections to downstream reaches (Humborg et al., 1997; Humborg et al., 2000). The rapid expansion of large and small dams has fragmented many river systems

worldwide and weakened the natural continuity of material transport (Nilsson and Berggren, 2000; Laruelle et al., 2013). Reservoir regulation affects silicon cycling not through a single pathway, but through coupled hydrodynamic and biogeochemical processes. Longer residence time, reduced turbulence, higher water temperature, and enhanced particle retention may together modify the transformation and downstream delivery of silicon and other nutrients (Klaver et al., 2007; Friedl and Wüest, 2002; Humborg et al., 2002; Burford, 2011). These effects are especially important in large dammed rivers, where multiple reservoirs may cumulatively reshape river–ocean nutrient connectivity.

The Yangtze River is a key land–ocean transport system in East Asia. It drains approximately 1.8×10^6 km² and flows about 6,300 km from the Tibetan Plateau to the East China Sea, delivering large amounts of freshwater, sediment, and nutrients to the estuary each year (Li et al., 2007). These riverine inputs influence nutrient supply, primary production, and carbon fixation in the East China Sea and adjacent marginal seas. Dissolved silica (DSi) transport in the Yangtze River has therefore been widely studied, especially in relation to nutrient distribution, tributary inputs, and downstream fluxes (Liu et al., 2003). Previous work also showed that both DSi and biogenic silica (BSi) vary along the upper–middle reaches of the Yangtze, and that the Three Gorges Reservoir can modify silica transport through retention and sedimentation processes, with BSi generally showing stronger retention than DSi (Ran et al., 2013).

Compared with the middle and lower Yangtze River, the upper reaches have received less attention in DSi studies, particularly the Jinsha River. This region is characterized by steep topography, strong erosion, and active rock weathering, making it a potentially important source area for riverine DSi. In recent decades, the Jinsha River has been increasingly regulated by a series of large hydropower projects, including Wudongde, Baihetan, Xiluodu, and Xiangjiaba. The scale of this cascade development indicates that its influence on water residence time,

sediment retention, and nutrient transport may be comparable to that of major downstream reservoirs (Zhu et al., 2017). However, field-based evidence from the Jinsha River reservoir reaches remains limited. Additional observations are therefore needed to clarify how upstream cascade regulation affects DSi dynamics and downstream silica delivery in the Yangtze River.

We surveyed three large cascade reservoirs in the lower Jinsha River (Baihetan, Xiluodu, and Xiangjiaba) and measured dissolved silica (DSi). We combined these observations with long-term datasets from the upper, middle, and lower Yangtze River to analyze DSi changes before and after cascade reservoir construction and to examine possible mechanisms. This work addresses a key data gap in the Jinsha River reach and improves understanding of how dam regulation affects the silicon cycle. Specifically, our objectives were to: (1) characterize the spatial distribution of dissolved silica (DSi) in the data-scarce Jinsha River reach; (2) analyze changes in DSi before and after dam construction in the Yangtze River; and (3) examine how dam construction alters DSi transport and retention mechanisms and evaluate its implications for basin-scale silicon cycling, thereby providing scientific support for regional water resources management.

2. Study Area and Methods

2.1 Sample Collection

Water samples were collected on 18–19 April 2025 from three cascade reservoirs in the lower Jinsha River: Xiangjiaba Hydropower Station (XJB), Xiluodu Hydropower Station (XLD), and Baihetan Hydropower Station (BHT) (Fig. 1). Prior to fieldwork, permission to collect water samples at all sampling sites was obtained from the relevant reservoir management authorities, and all sampling activities were conducted in accordance with relevant institutional and national regulations. At each site, 2 L of water was collected, of which 1 L was used for laboratory analysis of water-quality parameters, kept at 4 °C, transported to the laboratory under refrigerated conditions, and analyzed for water-quality parameters within one week. A total of 26 samples were collected, including 9 from XJB, 9 from XLD, and 8 from BHT. Laboratory analyses were conducted using an automated discrete multi-parameter water analyzer (SmartChem 200) and a UV–visible spectrophotometer, following the standard methods in Monitoring and Analytical Methods for Water and Wastewater (State Environmental Protection Administration of China, 2002).

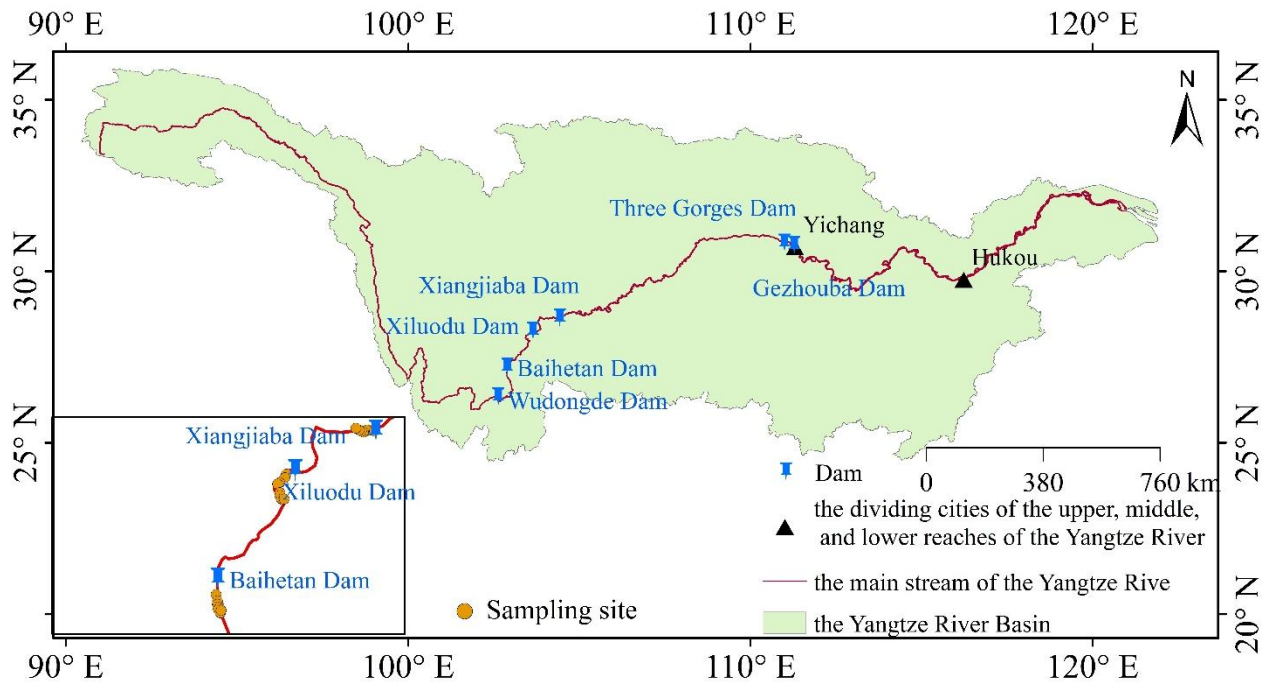


Figure 1. Sampling sites in the Yangtze River Basin and the Jinsha River.

2.2 Sample Analysis and Data Acquisition

In the laboratory, 1 L of water sample was filtered through a Whatman GF/F glass fiber filter with a nominal pore size of 0.7 μm . After filtration, the filter was wrapped in aluminum foil and stored in the dark at low temperature until analysis. The filtrate was stored at 4 $^{\circ}\text{C}$ and subsequently used for the determination of dissolved silica (DSi, SiO_3^{2-}) concentration. DSi concentration was determined using a SmartChem 200 fully automated analyzer via the molybdenum blue spectrophotometric method, with a precision greater than 97%.

2.3 Data Processing and Analysis

To characterize spatiotemporal variation in DSi along the Yangtze River main stem, we combined field measurements from the Jinsha River cascade reservoirs with multi-year DSi datasets compiled from the upper, middle, and lower reaches of the Yangtze River. These datasets were used to examine long-term spatial and temporal patterns in main-stem DSi. All variables were

standardized before analysis. Differences in DSi among the upper, middle, and lower reaches were tested for significance. We also compared DSi before and after dam construction and between upstream and downstream sections relative to the dams. Period-based differences shown in boxplots were evaluated using Mann–Whitney U test, with statistical significance set at $p < 0.05$. Data analysis and figure preparation were mainly performed using Grapher 12, R (v3.2.2), and ArcMap 10.7.

3. Results

3.1 Spatial Variations of DSi in the Cascade Reservoirs of the Jinsha River

The DSi concentrations in the three cascade reservoirs of the Jinsha River averaged $102.83 \pm 1.37 \mu\text{mol L}^{-1}$ (Fig. 2). Among them, the Xiluodu Hydropower Station exhibited relatively lower DSi ($102.1 \pm 1.45 \mu\text{mol L}^{-1}$), while the Baihetan Hydropower Station showed $103.38 \pm 1.13 \mu\text{mol L}^{-1}$. Overall, no significant differences in DSi were observed among the three reservoirs (Fig. 2).

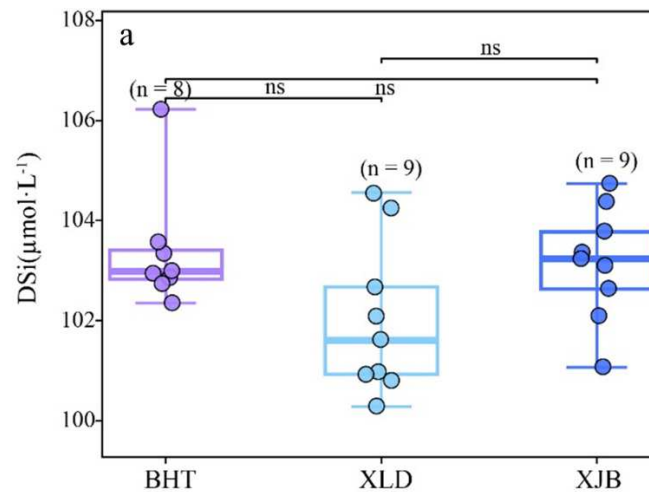


Figure 2. DSi concentrations in the Baihetan, Xiluodu, and Xiangjiaba reservoirs of the Jinsha River.

3.2 Long-term Spatial Variations of DSi Along the Main Stem of the Yangtze River

Using the conventional division into upper, middle, and lower reaches, DSi was generally elevated in the upper reach relative to the middle and lower reaches (Fig. 3).

From 1997 to 2018, the spatial pattern of DSi changed from year to year. In 1997, DSi was much higher in the upper reach, and the middle reach had the lowest values. In 2004, spatial differences were weak. In 2006, DSi decreased first and then increased toward the estuary. The 2008 pattern

was broadly similar to that in 1997. In 2017, differences among the three reaches were relatively small, although DSi still showed an overall downstream decrease along the river.

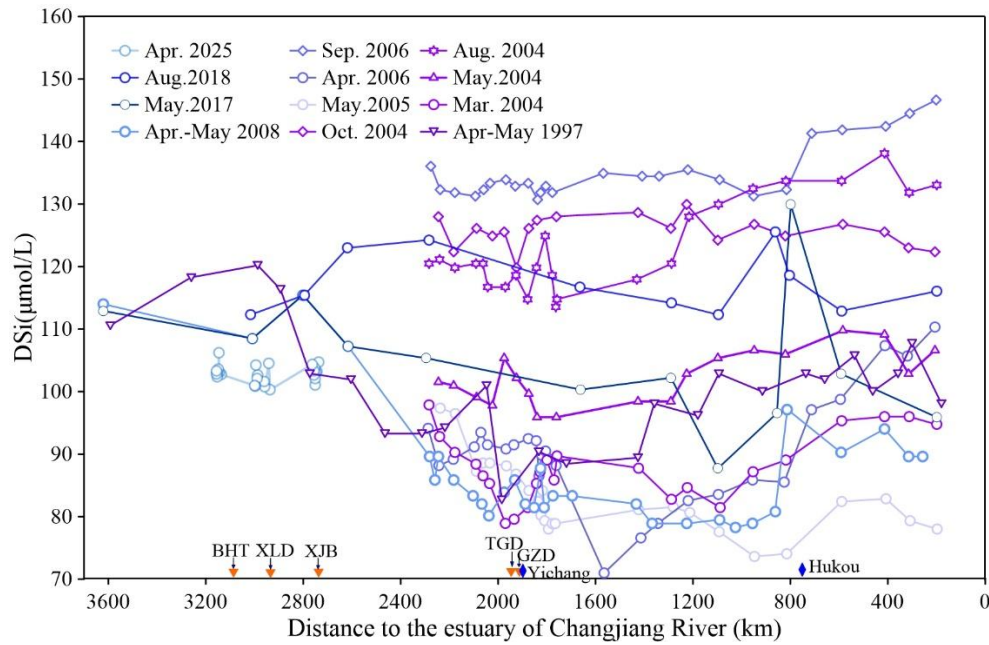


Figure 3. Spatial variation in dissolved silica (DSi) concentrations along the Yangtze River main stem. The dataset covers 1997–2025. Data for April–May 1997 were from Liu et al. (2003); data for March–October 2004 were from Ran et al. (2022); data for 2005 were from Ran et al. (2013); data for April–October 2006 were from Ran et al. (2017); data for 2008–2018 were from Ran et al. (2022); and data for 2025 were generated in this study. Orange inverted triangles mark the five major hydropower stations along the Yangtze River main stem, and blue diamonds mark the boundaries between the upper, middle, and lower reaches.

Following dam construction, formerly free-flowing river reaches are transformed into lentic reservoir systems, substantially increasing water residence time. Extended residence times enhance the settling of particulate diatom-derived silica and the burial of biogenic silica (BSi), thereby promoting DSi retention within reservoirs and reducing the downstream DSi flux (Harrison et al., 2012). The Three Gorges Dam is a major hydraulic project on the Yangtze River. Construction of the Three Gorges Project officially started on 14 December 1994, and the reservoir began to provide power generation and navigation benefits in June 2003 (Niu, 2022). Using 2003 as the breakpoint, we tested whether DSi in the upper, middle, and lower

reaches of the Yangtze River main stem differed before and after the Three Gorges Dam began operation (Fig. 4). Overall, DSi remained relatively high in the upper reach, while values in the middle and lower reaches tended to decrease after dam construction. In 2008 (Fig. 4b), DSi in the middle reach was significantly lower than in the upper reach and then increased toward the lower reach.

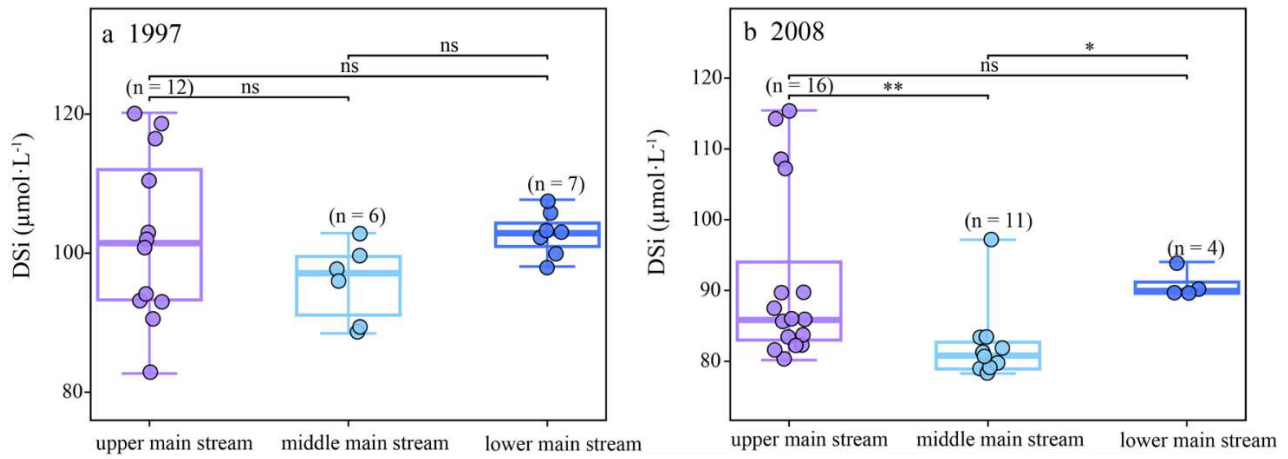


Figure 4. DSi concentrations in the upper, middle, and lower reaches of the Yangtze River main stem. Data for April–May 1997 in panel (a) were from Liu et al. (2003), and data for 2008 in panel (b) were from Ran et al. (2022). Significant differences among the upper, middle, and lower reaches were tested according to the boundary cities defining each reach using the Mann–Whitney U test. Asterisks indicate significance levels: *** $P < 0.001$, ** $0.001 < P < 0.01$, * $P < 0.05$, and ns indicates no significant difference.

3.3 Long-term (Interannual to Decadal) Variations of DSi in the Yangtze River Main Stem

Since 1960, DSi concentrations have generally declined across the upper, middle, and lower reaches of the Yangtze River, with the decrease becoming stronger after the 1980s (Fig. 5). In the early 1960s, DSi concentrations were close to $270 \mu\text{mol L}^{-1}$ at Hankou and approximately $200 \mu\text{mol L}^{-1}$ at Cuntan, this suggests that DSi levels in the Yangtze River were relatively high in the 1960s. DSi then declined

over time as human activities intensified, including dam construction, land reclamation, and urban expansion (Fig. 5a). A comparison of DSi changes before and after the construction of the Three Gorges Dam shows that DSi at Cuntan (upstream of the dam) did not change markedly (Fig. 5b), whereas DSi at Hankou and Datong (downstream of the dam) exhibited a significant decreasing trend after dam construction (Fig. 5c). These results indicate that the Three Gorges Dam has altered downstream DSi fluxes through a retention effect.

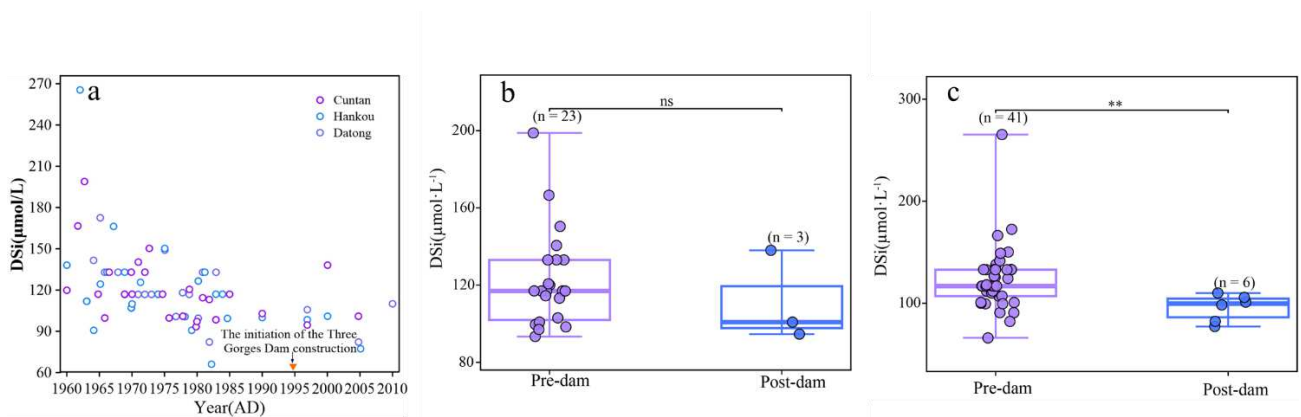


Figure 5. Multi-year changes in DSi in the upper, middle, and lower reaches of the Yangtze River main stem. (a) Temporal trends in DSi at Cuntan, Hankou, and Datong since 1960. (b) Changes in DSi at Cuntan before and after the construction of the Three Gorges Dam. (c) Changes in DSi at Hankou and Datong before and after the construction of the Three Gorges Dam.

4. Discussion

4.1 Spatiotemporal Variations in DSi in the Yangtze River and Potential Mechanisms

Variations in dissolved silica (DSi) concentrations are controlled by both natural climatic factors and human disturbances. At the basin scale, DSi dynamics are closely related to silicate-rock lithology and weathering rates (Chetelat et al., 2008), and may also be affected by forest cover (Conley et al., 2008). In the Yangtze River basin, previous work suggested that a 1 °C increase in mean annual air temperature could raise silicate chemical weathering rates by ~9 %; this is similar in magnitude to the observed warming from the 1960s to the 2000s and may therefore be an important driver of DSi-load change in the Yangtze River (Ran et al., 2022). Deforestation and agricultural expansion can also change the Si cycle by increasing erosion and promoting dissolution of amorphous silica (ASi), which may increase riverine DSi, whereas crop harvesting removes Si from soils and may reduce riverine DSi export (Conley et al., 2008; Sarath et al., 2022). Silica retention in river bends and dammed reaches can further enhance deposition and lower DSi concentrations in the water column (Ran et al., 2016; Xiao et al., 2019). In line with this mechanism, DSi showed a significant decreasing trend after dam construction (Fig. 5c), suggesting that the Three Gorges Dam reduced downstream DSi fluxes through retention.

In recent years, DSi concentrations in the Yangtze River basin have shown a persistent decline (Fig. 5a). Besides natural climatic effects such as drought (Ran et al., 2022), this trend is likely linked to multiple human activities. Agricultural expansion may reduce riverine DSi by changing biogeochemical Si cycling pathways (Conley et

al., 2008; Struyf et al., 2010). Large-scale deforestation is also important because vegetation removal weakens biological Si cycling (Carey & Fulweiler, 2012). Meanwhile, paddy fields and dry croplands can increase soil erosion and runoff, which may raise the proportion of particulate silica (PSi) and reduce the relative contribution of DSi (Struyf & Conley, 2012). In the middle and lower Yangtze, rice cultivation has expanded, and this may further reduce downstream DSi supply, because more Si is stored in crop biomass and removed during harvest (Song et al., 2012). Together with the construction of cascade reservoirs along the Yangtze River main stem, these processes have ultimately led to a marked decline in DSi flux to the river mouth, with important ecological effects on Si-limited phytoplankton (e.g., diatoms) in the East China Sea, including potential shifts in community structure.

4.2 Impacts of Dam Construction on DSi in the Yangtze River Main Stem

Dam construction can change downstream silica cycling and nutrient limitation patterns, and it may also delay downstream responses. Dams increase hydraulic residence time and retain biogenic silica (BSi), which can reduce downstream DSi concentrations and make a relative “silica-deficient” condition more likely during high-flow periods. Meanwhile, reservoir-induced DSi retention may shift nutrient limitation patterns across seasons and may lead to seasonal changes in algal community composition (Makareviciute-Fichtner et al., 2024; Ran et al., 2013).

In recent decades, growing socio-economic demand has promoted large-scale dam construction, which has changed both the amount and composition of materials delivered from rivers to the ocean (Ittekkot, 2012; Ittekkot et al.,

2000) and has also altered natural river environments (Humborg et al., 2006; Milliman, 1997). After impoundment began at the Three Gorges Dam in 2003, two major reservoirs in the Jinsha reach—Xiangjiaba and Xiluodu—were impounded and entered operation in 2012 and 2013, respectively (Lu et al., 2019). Together with the Wudongde Reservoir (operational since 2020) and the Baihetan Reservoir (impounded in 2021), they constitute the world's largest cascade reservoir system (Lu et al., 2019). This large reservoir cascade strongly affects nutrient retention and river ecology in the Yangtze River, which is likely to influence DSi dynamics.

Cascade reservoir development increases the retention and sediment burial of silica in multiple forms, including particulate silica (PSi) and dissolved silica (DSi). We tested this by comparing DSi across the upper, middle, and lower Yangtze before and after the Three Gorges Dam began impoundment. (Figs. 5b and 5c), we found no significant change in DSi at Cuntan (upstream of the dam) (Fig. 5b).

In contrast, significant declines were observed at Hankou and Datong downstream of the dam after its construction ($p < 0.01$), indicating that damming can exert a strong influence on riverine DSi. The reduction in riverine DSi is associated with both physical trapping by dams and transformations among silica pools (Fig. 6). On the one hand, large dams convert fast-flowing river reaches into lentic, low-velocity reservoir environments, promoting the settling of particulate silica and enhancing biological uptake of DSi, which can subsequently be converted into BSi and buried in reservoir sediments (Maavara et al., 2020). Reservoirs also extend water residence time, which can support algal growth and increase the conversion of DSi to biogenic silica (BSi). Much of this BSi is then retained through sedimentation, and only a small part may return to the water column through re-dissolution and be transported downstream. Over time, reservoirs can therefore act as long-term sinks for DSi (Maavara et al., 2020; Nelson et al., 1995).

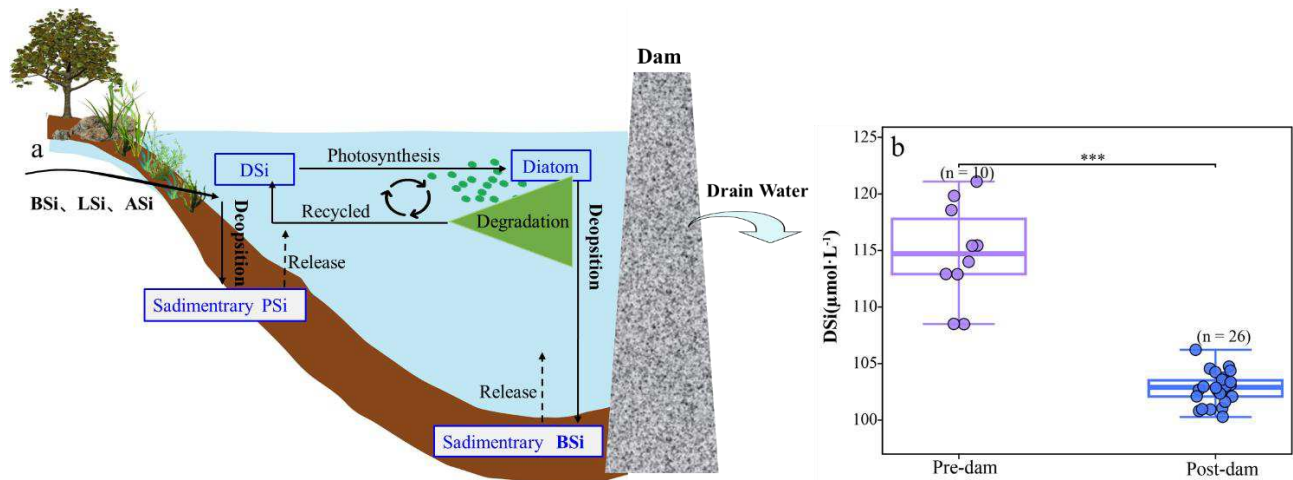


Figure 6. Effects of dam interception on silica cycling. In panel (a), DSi denotes dissolved silica, BSi biogenic silica, LSi lithogenic (terrestrial) silica, ASi amorphous silica, and PSi particulate silica. Panel (a) shows silica burial processes after dam construction, and panel (b) shows changes in DSi before and after cascade reservoir construction in the Jinsha River. Pre-dam DSi data were obtained from Liu et al. (2003) for 1997 and Ran et al. (2022) for 2008 and 2017, using measurements collected at sites located more than 2,800 km upstream of the Yangtze River mouth. Post-dam DSi data were obtained from the present study.

Over the past decades, DSi concentration in the middle and lower Yangtze River have both decreased markedly, and

dam construction appears to be a major cause. Cascade reservoirs extend water residence time, which promotes biological uptake of DSi and BSi burial, particulate silica settling, followed by conversion to BSi and burial in sediments, and these processes together reduce downstream transport. In the Yangtze River, dam-related DSi decline is likely associated with reservoir trapping, enhanced sedimentation, and in-reservoir biogeochemical transformations. This may further disturb downstream Si:N:P stoichiometry, reduce the competitive advantage of diatoms, and contribute to ecosystem changes in the East China Sea. A common consequence of river “reservoirization” is higher water transparency and longer hydraulic residence time. These conditions can support greater diatom biomass, and the subsequent deposition and preservation of biogenic remains can cause temporary or permanent BSi burial in reservoirs, which increases total DSi retention and is often described as the “reservoir retention effect” (Fig. 6) (Beusen et al., 2009; Humborg et al., 1997; Ran et al., 2017).

4.3 Impacts of Reduced Riverine Silicon Inputs on Marine Ecosystems

Silicon is the second most abundant element in the Earth’s crust and an important nutrient in the ocean. It is required for the growth of diatoms and some sponges, and it is also used by radiolarians, silicoflagellates, and several groups of flagellates (Tréguer & Rocha, 2013). Diatoms are among the most widespread in the modern ocean and contribute more than 40% of total marine primary production (Malviya et al., 2016; Nelson et al., 1995).

In the absence of substantial human perturbation, silicon in the modern ocean is estimated to have a residence time of about 15,000–17,000 years (Laruelle et al., 2009; Tréguer et al., 1995), which suggests a near steady-state system under natural conditions. However, increasing evidence shows that human activities are changing this cycle, including dam construction that lowers DSi concentrations in rivers and estuaries (Laruelle et al., 2009). Along the

land–ocean aquatic continuum (LOAC), Si is transported and supports freshwater and marine food webs. Because dams slow transport and increase residence time in the LOAC, many dammed rivers function more like “in-stream reactors”. With longer residence time, more nutrients can be converted from dissolved to particulate forms through primary production, and these particles are more likely to settle and be retained, thereby altering nutrient delivery to coastal waters. (Maavara et al. 2020; Fig. 6).

The Yangtze River is about 6,300 km long, with a discharge of about 900 km³ yr⁻¹, ranking fourth globally. It delivers large nutrient loads to the estuary and adjacent seas and is an important material source for the East China Sea and adjacent western North Pacific marginal seas, where river inputs strongly affect coastal ecosystems (Chen et al., 2002; Li et al., 2007). The Three Gorges Dam on the main stem began impoundment in 2003. In the Jinsha River reach, the Xiangjiaba and Xiluodu reservoirs were impounded and began operation in 2012 and 2013, respectively (Lu et al., 2019). Further upstream, the Wudongde and Baihetan reservoirs began operation in 2020 and 2021, respectively. Together, these four projects form the world’s largest cascade reservoir system (Lu et al., 2019).

5. Conclusions

In April 2025, we investigated DSi in three reservoirs on the Jinsha River (Baihetan, Xiluodu, and Xiangjiaba) to elucidate DSi dynamics and underlying mechanisms in the cascade-reservoir system of the upper Yangtze River. We further compiled field survey data (1997–2025) along the Yangtze River main stem from the upper to lower reaches, together with available historical records, to examine DSi transport and variability before and after cascade-reservoir construction and to assess the roles of natural processes and anthropogenic influences.

Spatial-scale patterns. DSi showed different spatial patterns along the Yangtze River main stem in different years. Before the Three Gorges Dam began operation

(1997), DSi did not differ significantly among the upper, middle, and lower reaches. By 2008, DSi in the middle reach had decreased significantly, indicating a dam-related spatial decline in DSi.

Decadal-scale trends. Long-term records from Cuntan, Hankou, and Datong show a gradual decline in DSi from the 1960s to the present. After Three Gorges Dam impoundment, DSi decreased significantly at Hankou and Datong (both downstream of the dam), while no significant change was detected at Cuntan (upstream). DSi also decreased significantly after cascade reservoirs were built in the Jinsha River reach, suggesting that dam construction can substantially reduce riverine DSi.

Implications of cascade reservoirs for land–sea Si export. Six large cascade reservoirs are distributed along the Yangtze River main stem. Reservoir formation can play an important role in nutrient uptake and burial—particularly of silica—thereby reducing riverine Si fluxes to the ocean and potentially affecting marine ecosystems. Further studies are needed to quantify the amount of Si (across different forms) sequestered by cascade-reservoir construction and to evaluate its ecological impacts, especially in the East China Sea.

Declaration of Generative AI and AI-assisted technologies in the writing process: During the preparation of this manuscript, GPT was used for partial translation and language polishing. After using this tool, the authors carefully reviewed and edited the manuscript and take full responsibility for the accuracy, originality, and final content of the work.

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Acknowledgments

This project was supported by the Yunnan Provincial Department of Science and Technology Project (202301BA070001-098) and the Department of Education of Yunnan Province (JG2023216).

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Competing interests

The authors declare no competing interests.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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