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Three Gorges Dam enhanced organic carbon burial within the sediments of Poyang Lake, China

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ABSTRACT

Lakes play a dominant role in the global carbon cycle, serving as crucial long-term carbon (C) sinks. Carbon burial within lakes is influenced by changes in both inflowing and outflowing processes. While considerable attention has been given to studying the former, the latter has often been overlooked and remains insufficiently documented. In this study, we investigated the variations in organic carbon burial within Poyang Lake, the largest freshwater lake in China, which mainly discharges into the Changjiang River. This study focused on the response of organic carbon burial to the regulation of a mega dam, the Three Gorges Dam, along the lake's main channel. The mean organic carbon accumulation rate in Poyang Lake sediments increased substantially by 3.82–4.60 times after the year 2000, compared to the preceding period. Furthermore, the Three Gorges Dam induced an abnormal reduction in lake levels by 1.38 m during the dry season, leading to a translocation of approximately 0.42 billion m^2 of water area toward vegetated systems. The pronounced expansion of vegetation across the shallow floodplain of Poyang Lake is identified as the primary driver behind the enhanced organic carbon burial within the lake sediments. These findings emphasize the imperative to further investigate and address the global issue of organic carbon accumulation in lake floodplain sediments, particularly in the context of riverine dams. These results shed light on the ecological implications of mega-dam regulation on organic carbon dynamics and underscore the significance of understanding and mitigating the associated environmental impacts.

1. Introduction

Lacustrine wetland ecosystems, despite covering only approximately 2 % of the Earth's surface, play a crucial role in carbon (C) storage (C; see Table 1 for the list of abbreviations) within soil and are facing increasing threats from both climate change and human interventions (Dean & Gorham, 1998; Cole et al., 2007; Chmiel et al., 2016; Maavara et al., 2017; Mendonça et al., 2017; Anderson et al., 2020). Understanding the response of C sequestration and storage within lakes to climate and anthropogenic disturbances is not only of vital importance for an accurate assessment of C accumulation within lake ecosystems as well as its contribution to the global C budget but also of scientific significance for the conservation and restoration of lacustrine ecosystems.

Climate change is projected to modify the role of lakes in terms of organic carbon (OC; Table 1) burial by altering precipitation patterns and temperature within lake basins (Tranvik et al., 2009). Specifically, alterations in precipitaion affect the inputs of C to aquatic systems from watersheds (Freeman et al., 2001; Tranvik and Jansson, 2002), while temperature fluctuations impact plant species composition and thus influence the quantity and quality of OC production within the lake (Williams et al., 2007; Sobek et al., 2007). Meanwhile, extensive anthropogenic pressures contribute to substantial OC accumulation within lakes over short timeframes (Heathcote et al., 2015; Drake et al., 2019). For instance, land use practices such as agriculture and land reclamation, often result in increased mass accumulation rates of lake sediments, leading to higher OC preservation potential (Kastowski et al., 2011; Anderson et al., 2013; Drake et al., 2019). Additionally, intensified nutrient inputs lead to eutrophication and augment the OC contents in lake sediments, particularly in basins near densely populated and industrialized regions (Gallant et al., 2020; Anderson et al., 2020). Despite recognizing the growing dominance of climate change and human activities in OC burial within lakes, the impact of large dams

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Table 1
Notation.

Acronym	Description
C	Carbon
OC	Organic carbon
N	Nitrogen
OCAR	Organic carbon accumulation rate
ANOVA	Analysis of variance
GEE	Google Earth Engine
NDVI	Normalized difference vegetation index
mNDWI	Modified normalized difference water index
TGD	Three Gorges Dam

along rivers on downstream connected lakes' OC dynamics remains a great uncertainty.

Dams, particularly large dams, have the potential to substantically alter the C cycle over river basins by changing the downstream hydrological conditions and sediment transport patterns (Galy et al., 2015; Lu et al., 2022; Deemer et al., 2022). Furthermore, dam-induced modifications to the flow regime and river landscape can affect the connectivity between the river and downstream connected lakes (Spinti et al., 2023), as well as the quantity and quality of C entering the lakes, thereby impacting the C burget of the lake system (Kummu and Varis, 2007; Deng et al., 2018). However, while previous research is mainly concerned with how the variations in inflowing lake water affect C burial within the lakes, an understanding of the feedback of outflowing changes to lake C burial still remains elusive. This study aims to fill this knowledge gap by exploring the relationship between changes in Poyang Lake outflow induced by TGD regulation and C burial within the lake.

The Three Gorges Dam (TGD; Table 1), the world's largest hydraulic engineering dam, gained global attention upon its establishment. Located in the upper Changjiang River (Fig. 1A), the TGD has significanty reduced downstream sediment flux by approximately 70 % and led to dramatic riverbed downcutting (Dai et al., 2018). Poyang Lake, the largest freshwater lake in China, is connected to the Changjiang River only through a single outlet (Fig. 1A). The lake mainly receives water and sediment from its five tributeries, occasionally supplemented

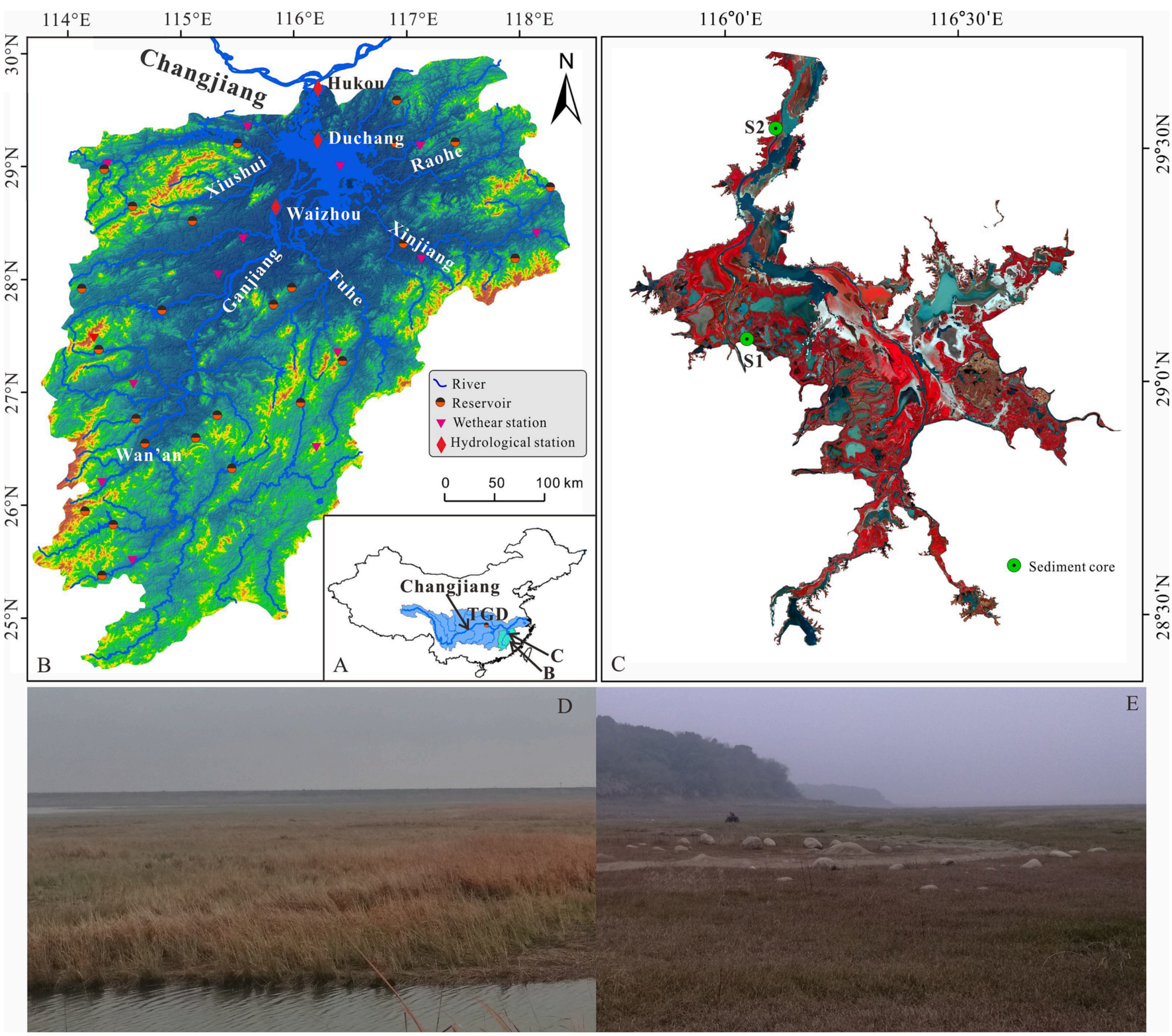

Fig. 1. A) Geographical location of Poyang Lake in relation to the Changjiang River and the Three Gorges Dam, B-C) Map depicting the Poyang Lake Basin and Poyang Lake, and D-E) Photographs showcasing Carex at central lake S1 (captured on 4th Jan 2019) and lake waterway S2 (captured on 9th Jan 2019).

by water from the Changjiang River during the flood season (Dai, 2021). While the global controversy on the TGD is mostly related to its negative impacts on lake ecosystems (Mei et al., 2018; Dai et al., 2018; Chen et al., 2021), few studies, to our knwledge, have documented its potential indirect contribution to OC burial within lake sediments. Thereafter, this study aims to bridge this gap by 1) investigating the long-term OC burial features within Poyang Lake sediments by analysing the vertical sedimentation rate and OC content distributions in typical sediment cores and 2) examing the possible drivers that may affect the OC burial of the lake by investigating climate change and human interference information, with a special focus on the possible influence of TGD regulation. This knowledge will stimulate further research on the C budget in lake floodplain under similar conditions and enables a reassessment of the global C budget to facilitate the effective implementation of the global C neutrality policies.

2. Materials and methods

2.1. Study area

Located at the junction of the southern bank of the lower Changjiang River, Poyang Lake (28°22′-29°45′N, 115°47′-116°45′E) has a basin area of 16.2×10^4 km^2, accounting for 9 % of the Changjiang River drainage area, and serves as the largest freshwater lake in China (Fig. 1A-B). The lake is dominated by a monsoonal system, with an annual precipitation of 1632 m, approximately 30 % of which occurs in the dry season from October to March (Gao et al., 2014). Poyang Lake is generally divided into two subregions according to the topographic elevation, with a relatively flat central lake connecting to the lake tributaries (>16 m) in the south and a narrow 40-km-long lake waterway linking the central lake to the Changjiang River in the north (<12 m) (Fig. 1C). Ganjiang is the largest tributary discharging into Poyang Lake, contributing 62.8 % and 67.9 % of water and sediment input to the lake, respectively (Fig. 1A-B, Mei et al., 2018).

The combined effects of tributary inflows and the interaction with the Changjiang River generate periodic water level fluctuations throughout the year, with the lake area expanding approximately 20 times from the dry season to flood season (Zhang et al., 2014). The ephemeral emergent wetland in the dry season favors vegetation growth (Mei et al., 2016), such as floating vegetation, submerged vegetation, emergent aquatic vegetation and semiaquatic emergent tall vegetation, which are all extremely sensitive to water level dynamics (Fig. 1D-E, Zhao et al., 2011; Sang et al., 2014).

Located approximately 1050 km upstream of Poyang Lake, the TGD's influence spans the entire Changjiang River as well as the adjacent lakes by changing the downstream hydrological regimes (Fig. 1 A). The dam was put into operation in 2003 and became fully functional in 2008, with a flood control capacity of 22.2 billion m^3. The TGD discharges water in May to increase the storage capacity for flood mitigation and stores water in October for electricity generation. The water discharge and storage operation of the TGD coincides with the rainy season and dry season of the Poyang Lake Basin, and consequently alters the relationship between Poyang Lake and the Changjiang River as well as the hydrological regimes in Poyang Lake over an annual cycle (Zhang et al., 2012; Feng et al., 2013; Zhang et al., 2022).

2.2. Hydrometeorological data

Monthly precipitation and temperature data over the Poyang Lake Basin, covering a time period from 1956 to 2016, were provided by the National Climatic Centre of the Chinese Meteorological Administration (https://data.cma.cn). These data provide information on climate change over the catchment. The daily water level at Duchang and the monthly water discharge and suspended sediment discharge at Waizhou and Hukou from 1956 to 2016 were acquired from the Changjiang Water Resources Commission (https://www.cjw.gov.cn). These data portray the response of the lake's sediment and water levels to human activities in the lake catchment and Changjiang River. All the data underwent rigorous verification and uncertainty analysis following government protocols to ensure a system-wide confidence level of above 95 %.

2.3. Sampling and sediment characterization

Two sediment cores, namely S1(29°05′28″N, 116°02′47″E) and S2 (29°32′34″N, 116°06′31″E), were taken in January 2019 from the margin of the central lake and lake waterway of Poyang using polyvinyl chloride tubes (1 m in length and 10 cm in diameter) (Fig. 1B). Prior to sampling, a field investigation was carried out to ensure that the selected sampling area were not directly impacted by local human disturbance, such as sand mining and land reclamation. The sediment cores were manually sliced at 1-cm intervals on site. Subsequently, the samples were carefully sealed in polyethylene bags and further analyzed in the laboratory to determine the lake's long-term sedimentary and OC storage features.

The grain size distribution of the sediment samples was measured by a laser particle-size analyser (Beckman Coulter LS13320) after the removal of carbonates by 10 % HCl and organic matter by 10 % H_2O_2, with sodium hexametaphosphate serving as the dispersing agent. The measurement error was found to be within 5 %. Sediments collected from Poyang Lake were divided into three size fractions according to their grain size: clay (<4 μm), silt (4–63 μm), and sand fraction (>63 μm). The sum of clay and silt fractions was further defined as fine-grained sediments.

2.4. Dating with ^{210}Pb and sedimentation fluxes

In this study, the sedimentation of Poyang Lake was investigated by examining the activity of ^{210}Pb in the sediments. The sediment samples were oven-dried and sealed in a plastic box (70 mm in diameter and 35 mm in height) to undergo radioactive decay for at least 3 weeks. The activity of the radioactive isotope ^{210}Pb and ^{137}Cs was measured on a well-type HPGe γ-ray detector (Canberra Be3830, 777 lead shield) with a counting efficiency of 35 %. The activities of ^{210}Pb and ^{137}Cs were determined from the γ-ray peak at 46.5 keV (4.25 %) and 661.6 keV (85 %), respectively. The activity of ^{226}Ra was obtained indirectly by measuring the activities of its daughter isotopes ^{214}Pb and ^{214}Bi, which were determined at 351.9 keV (37.6 %) and 609.3 keV (46.1 %), respectively. The excess ^{210}Pb ($^{210}Pb_{ex}$) was calculated by subtracting the supported ^{210}Pb (i.e., ^{226}Ra) from the total ^{210}Pb (Appleby, 2008; Mabit et al., 2014). An efficiency calibration of the detector systems was conducted by LabSOCS (Bronson, 2003). All data reported in the present work were corrected for radioactive decay to the times of sampling.

To estimate the sedimentation fluxes in the core samples, the activities of $^{210}Pb_{ex}$ were utilized with the constant flux model, which assumes that the sedimentation rate varies throughout the core while the flux of $^{210}Pb_{ex}$ to the surface of the core remains constant (Appleby, 2008; Sanchez-Cabeza and Ruiz-Fernandez, 2012). In addition, the sedimentation of Poyang Lake was also traced by the activity of ^{137}Cs as an independent verification of the results obtained from ^{210}Pb, ensuring the reliability of the chronology.

2.5. Organic carbon, total nitrogen and δ^{13}C determination

To prepare the sediment samples for OC and δ^{13}C (C isotope ratios ^{13}C/^{12}C) analyses, the sediment samples were treated with 1 mol/L HCl and rinsed with deionized water to remove the carbonated fraction. The total nitrogen (N; Table 1) was analysed without acid treatment. The OC and N contents were measured using a Vario EL CHNOS elemental analyser (±5% analytical precision). Analyses of δ^{13}C values were performed using a Thermo Fisher Scientific Finnigan Delta V mass spectrometer (±0.1 ‰ analytical precision).

The weight ratios of C/N and δ^{13}C vary between different plants and can thus provide valuable information about the source of C (Lamb et al., 2006). Specifically, nonvascular phytoplankton are normally enriched with N (C/N ratio of < 10) and have lower $\delta^{13}C$ values (-30 ‰ to −26 ‰), while terrestrial vascular plants typically have less N (C/N ratio > 12) and a wider range of $\delta^{13}C$ values (–32 ‰ to −21 ‰) (Deines, 1980; Meyers, 1994).

The OC accumulation rate (OCAR; Table 1) was calculated for each layer as the product of the sediment deposition rate and the OC content.

2.6. Landsat images and normalized difference vegetation index

All available Landsat TM/ETM+/OLI imagery accessible with Google Earth Engine (GEE; Table 1) between October and March of 1987–2016 were used to build an initial time series image collection for Poyang Lake in the dry season. The cloud masking process was carried out for each image by masking out opaque and cirrus clouds. A new image collection at annual frequency was then composited using a quality band as a per-pixel ordering function. Images that were still covered by clouds after cloud removal measures, such as 1990, 1997 and 1998 imagery, were excluded from the image collection. The normalized difference vegetation index (NDVI; Table 1) (Tucker, 1979) and modified normalized difference water index (mNDWI; Table 1) (Xu, 2006), which are related to vegetation greenness and open surface water bodies, respectively, were calculated and inserted into each image of the cloud masked image collection (Wang et al., 2020a):

$$\mathrm{NDVI} = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \tag{1}$$

$$\mathrm{mNDVI} = \frac{\rho_{green} - \rho_{swir}}{\rho_{green} + \rho_{swir}} \tag{2}$$

where ρ_{red}, ρ_{green}, ρ_{nir} and ρ_{swir} are the red (630–690 nm), green (520–600 nm), near-infrared (760–900 nm) and shortwave-infrared (1550–1750 nm) bands of Landsat TM/ETM imagery, respectively.

A robust decision tree algorithm was used to distinguish between vegetation, water bodies and bare mudflats within the Poyang Lake satellite image. The areas of vegetation, water bodies and mudflats were then calculated to map vegetation variation over 1987–2016. All Landsat image preprocessing tasks were performed in the GEE platform.

2.7. Statistical tests

A series of statistical analyses were performed to investigate the relationships between environmental conditions, sedimentation patterns in Poyang Lake, and sediment composition. Specifically, regression analysis was adopted to examine whether significant correlations existed between variables, such as OCAR and climate factors. Analysis of variance (ANOVA; Table 1) was used to test for significant differences among the lake sediments concerning grain size distribution, as well as C and N contents. The *t*-test was adopted to compare the mean values of C, N, and $\delta^{13}C$ between different grain size fractions. Overall, these statistical analyses contribute to a comprehensive understanding of the relationships between environmental conditions, sedimentation processes, and sediment composition in Poyang Lake.

3. Results

3.1. OC burial within Poyang Lake sediments

The sediment composition analysis revealed that Poyang Lake is dominated by fine-grained sediment. In the central lake, the sediments exhibited a fine-grained content range of 82.63 % to 99.68 %, while in the lake waterway, the range was relatively lower, ranging from 64.45 % to 98.52 % (Fig. S1). These findings were consistent with the ANOVA results, which indicated significant differences in grain size distribution between the two cores at a significance level of 5 % (Fig. S2). The sedimentation rates were estimated based on the activities of $^{210}Pb_{ex}$. The cores from the central lake and lake waterway recorded sedimentary rates of 2130 ± 340 g m^{-2} a^{-1} and 4730 ± 560 g m^{-2} a^{-1}, respectively, which was supported by the results of ^{137}Cs time-makers (Fig. S3) and were consistent with the findings of a previous study (Mei et al., 2018).

Analysis of the sedimentation fluxes revealed a notable shift around the year 2000, with an increase observed during the period of 1880–2000, followed by a subsequent decline (Fig. 2A, D). In the central lake, the OC content remained relatively stable before 2000 but exhibited greater variability post-2000 period. Conversely, in the lake waterway, the OC content did not show significant differences between the pre-2000 and post-2000 periods (Fig. 2B, E). Consequently, the OCAR in both the central lake and lake waterway exhibited distinct changes over different stages from the 1880s to the 2010s. During the first phase (pre-2000), the OCAR remained fairly stable, with a relatively low range of 4–29 g m^{-2} a^{-1} in the central lake and 4–24 g m^{-2} a^{-1} in the lake waterway. However, in the second phase (post-2000), the OCAR exhibited a higher and more variable range, specifically 64–90 g m^{-2} a^{-1} in the central lake and 34–69 g m^{-2} a^{-1} in the lake waterway. Comparing these values with pre-2000 period, the mean OCAR indicated an increase, with a rate of 4.60 in the central lake and 3.82 in the lake waterway during the post-2000 period (Fig. 2C, F). The *t*-test analysis also revealed significant differences in the mean values of C between the pre-2000 and post-2000 periods for both cores at a significance level of 5 %.

3.2. C/N ratio and $\delta^{13}C$ value in the sediments

The patterns of N content in the central lake and lake waterway were similar to those observed for OC content. Specifically, the N content displayed sudden variations in the central lake post-2000 but remained relatively stable over the study period in the lake waterway (Fig. 3A, D). A statistically significant correlation was found between the N content and OC content in both cores (Fig. S4), indicating that N in the sediments primarily originated from organic matter. Notably, the central lake presented higher productivity than the lake waterway in terms of N, which agreed well with the ANOVA results, indicating significant differences in OC and N contents between the two cores (Fig. S5-6).

The C/N ratio in the central lake was consistently below or at 7 before 2000 but sharply increased to 9 thereafter (Fig. 3B). The $\delta^{13}C$ value in the central lake ranged around −25 ‰ before 2000 and became less negative, approaching –22 ‰ after 2000 (Fig. 3C). In the lake waterway, the C/N ratio ranged from 3.83 to 7.02, and the $\delta^{13}C$ values ranged from −29.57 ‰ to –22.69 ‰, with $\delta^{13}C$ gradually approaching −30 % since 2000 (Fig. 3E-F). It is important to note that both the central lake and lake waterway showed an obvious increasing in the C/N ratio, indicating a higher contribution of terrestrial vascular plants. The $\delta^{13}C$ values presented further evidence, as they fell within the range of terrestrial vascular plants in the central lake and approached the threshold of terrestrial vascular plants in the lake waterway.

3.3. NDVI indices of Poyang Lake in the dry season

Poyang Lake is covered by water, mudflats and vegetation. The vegetation area in the dry season indicated vast expansion during the past 30 years (Fig. S7), as it increased by 1.48 billion m^2 from 1.50 billion m^2 in 1987 to 2.98 billion m^2 in 1999 and further to 3.74 billion m^2 in 2016 (Fig. 4A-C). At the annual scale, the vegetation area in the dry season increased by 52.94 % from 2.38 billion m^2 during 1987–2002 to 3.64 billion m^2 during 2003–2016 (Fig. 4D). In contrast, the water area of Poyang Lake decreased by 34.43 % from 1.22 billion m^2 during 1987–2002 to 0.80 billion m^2 during 2003–2016, while the mudflat area decreased by 8.93 % from 2.80 billion m^2 to 2.25 billion m^2 (Fig. 4E-F).

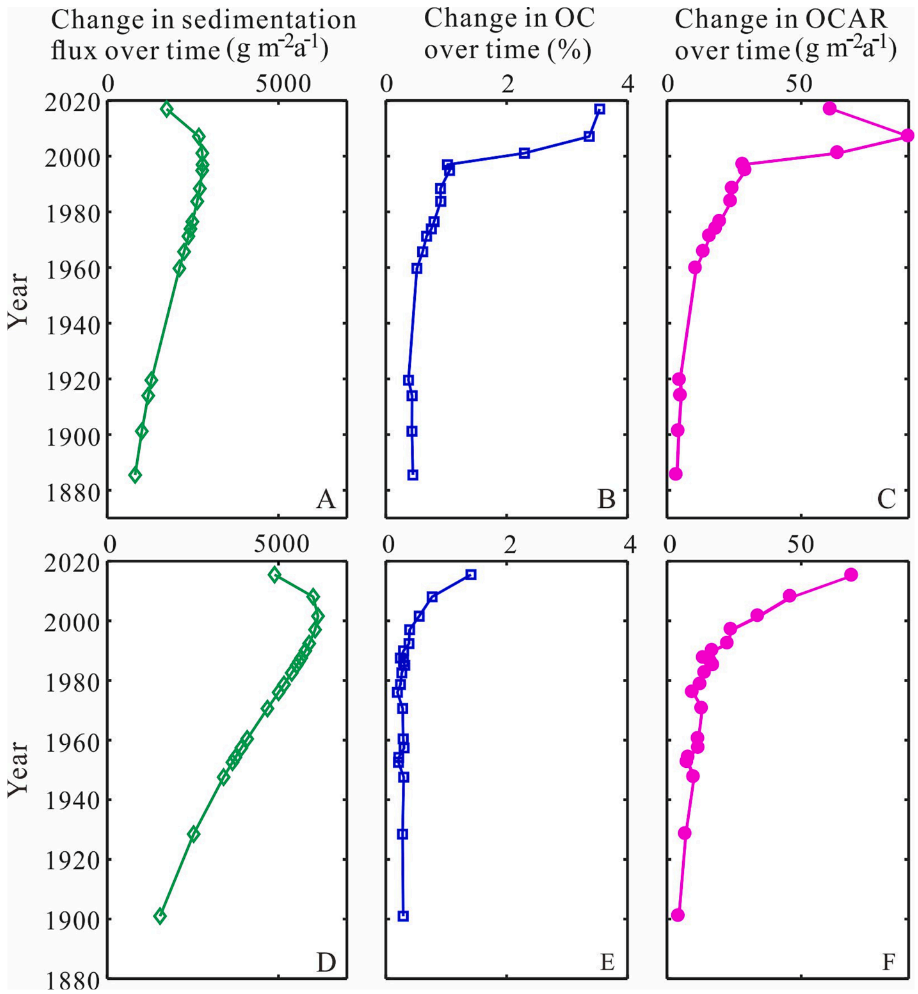

Fig. 2. Temporal variations in sedimentation flux, organic carbon (OC) content, and organic carbon accumulation rate (OCAR) for A-C) central lake S1 and D-F) lake waterway S2.

4. Discussion

OC sequestration by Poyang Lake is closely related to changes in the sediment deposition rate and OC content, with possible explanations generally including the sediment budget, climate change and human interferences (Tranvik et al., 2009; Drake et al., 2019; Beaulieu et al., 2019). In this section, the potential influences of these drivers are further investigated.

4.1. Role of climate change

Climate change, characterized by changes in rainfall and temperature, is expected to have a significant impact on the role of lakes in OC burial through long-term watershed modification and shifts in plant communities (Tranvik et al., 2009). From 1956 to 2017, the Poyang Lake basin experienced relatively little variation in annual mean temperature and precipitation. Compared to the period of 1956–2002, there was a slight decrease of 0.60 % in the annual mean temperature, while the annual mean precipitation remained almost unchanged during 2003–2016 (Fig. 5). Neither temperature nor precipitation showed statistically significant differences following the TGD construction, as indicated by the *t*-test analysis. To further investigate the relationship between climate factors and OCAR in the two cores, we analyzed different time periods. Prior to 2000, OC burial in the cores showed a significant correlation with precipitation, while being less influenced by temperature. However, during post-2000 period, the regression analysis failed to identify a significant correlation between OCAR and climate factors (Fig. S8-9). Based on these findings, we can conclude that natural forcing factors have made only a slight contribution to the observed increase in OC burial in Poyang Lake.

4.2. Role of reservoirs within the Poyang Lake Basin

Since 1960, over 9600 reservoirs have been established within the Poyang Lake Basin, representing significant human interferences that have a severe impact on the lake and its sediment inputs (Mei et al., 2018). A notable example is the Ganjiang River, the largest tributary of Poyang Lake. Prior to 1960, the natural water discharge from the tributary to the lake was approximately 149.07 $\times$ 10^8 m^3 during the dry season. However, during the period of 1960–1990, with the construction of a large-scale dam, the water discharge increased to 178.45 $\times$ 10^8 m^3. Subsequently, after the regulation of Wan'an Dam in 1990, which is currently the largest hydraulic engineering dam in the Poyang Lake Basin, the water discharge further increased to 219.57 $\times$ 108 m^3 (Fig. 6A). Following the construction of Wan'an Dam, there was a significant decline in sediment input from the Ganjiang River to Poyang Lake. The sediment input decreased from approximately 900 $\times$ 10^4 t during the period of 1956–1990 to less than 400 $\times$ 10^4 t thereafter (Fig. 6B). It is important to note that dam regulation within the Poyang Lake Basin predominantly has negative effects on lake OC burial because the decline in sediment supply from the tributary can lead to a reduction of the lake's sedimentation rate. Therefore, human disturbances within

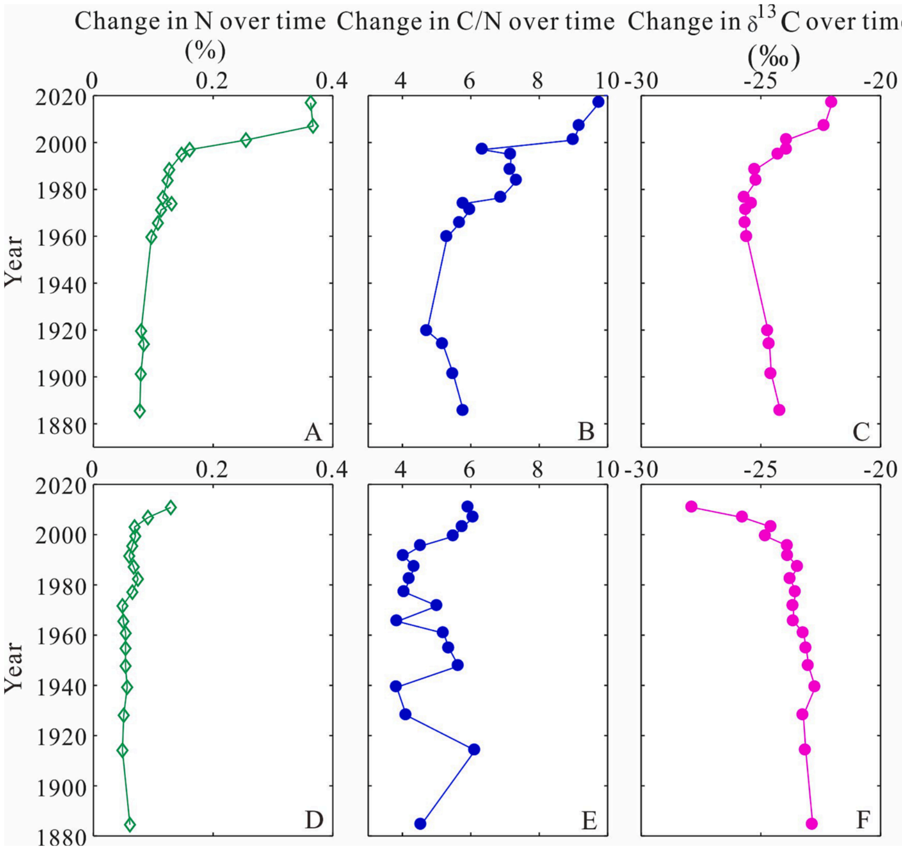

Fig. 3. Temporal changes for total nitrogen (N), organic carbon to total nitrogen ratio (C/N), and carbon isotope ratio ($\delta^{13}C$) for A-C) central lake S1 and D-F) lake waterway S2.

the lake basin cannot account for the observed enhancement in OC burial within the sediments of Poyang Lake.

4.3. Role of the TGD in the Changjiang River

Poyang Lake connects with the Changjiang River through water and sediment interactions, making it susceptible to human interference from the river. Similar to the Poyang Lake Basin, the Changjiang River is severely affected by reservoir regulation, particularly the large-scale TGD (Li et al., 2015; Wang et al., 2020b).

The construction of the TGD has led to substantial sediment trapping behind the dam, disrupting the natural continuity of sediment transport and causing intensive riverbed erosion along the mid-lower Changjiang River (Dai et al., 2018). As a consequence, the topographic gradient between Poyang Lake and the Changjiang River has increased significantly, compelling the lake to discharge a greater volume of water and sediment into the river (Mei et al., 2015). This enhanced sediment discharge from the lake to the Changjiang River, combined with a decrease in sediment supply from the tributaries, reduces the sedimentation flux in Poyang Lake. Consequently, this reduction in sedimentation negatively impacts OC burial within the lake sediments and cannot explain the observed enhanced OC burial within the lake sediments (Fig. 2A, D). The increased water discharge to the Changjiang River has two notable effects. Firstly, it leads to a decrease in the lake's water level during the dry season by 1.38 m (Fig. 7A). Secondly, it prolongs the dry season period by approximately 54 days (Fig. 7B), with the lake entering the dry season approximately one month earlier (Fig. 7C). Consequently, the lake experiences earlier and longer droughts, resulting in extended exposure of land areas, expansion of vegetation, and increased vegetation growth time (Fig. 1 D-E; Fig. 7D). This expansion of wetland vegetation has been frequently observed in Poyang Lake (Wan et al., 2018; Zhao et al., 2023). The stronger signal of terrestrial plants detected from the C/N ratio and $\delta^{13}C$ value in the recent lake sediments support this trend (Fig. 3). Moreover, the increase in vegetation area of Poyang Lake in the dry season by 1.26 billion m^2 from 1987 to 2002 to 2003–2016 provides compelling evidence (Fig. 4D). The redistribution of plant communities from algae to terrestrial vegetation due to lake shrinkage significantly enhances the OC contents within the sediments and consequently result in enhanced OC burial within Poyang Lake.

4.4. Comparation with other lakes

OCAR exhibits obvious spatial variability in Chinese lakes, ranging from 1.4 to 259.5 g m^{-2} a^{-1} (Gui et al., 2013; Wang et al., 2015; Zhang et al., 2017). Among them the Eastern plain lake region, mainly composed by lakes in mid-lower Changjiang River catchment has a mean value of 30.6 g m^{-2} a^{-1} (varying from 5 to 373 g m^{-2} a^{-1}, Dong et al., 2012; Zhang et al., 2017). OCAR of Poyang Lake lies right is this range. Globally, the modern (last ~ 150 years) OCAR in lake sediments for natural lake systems was estimated between 0.8 and 132.0 g m^{-2} a^{-1}, with over 90 % lake below 50 g m^{-2} a^{-1} (Mendonça et al., 2017). The estimated OCAR for the Poyang Lake pre-2000 is similar to the lakes in Northern Europe, Eastern USA and Canada while the much-enhanced OCAR post-2000 is more approximate to the Mid USA and Mid Europe lakes (Fig. S10).

4.5. Implications for lake management

The findings presented in this study have important implications for lake management, particularly in the context of organic carbon (OC) burial within lake sediments. OC plays a vital role in maintaining the global C balance and climate change mitigation (Beaulieu et al., 2019;

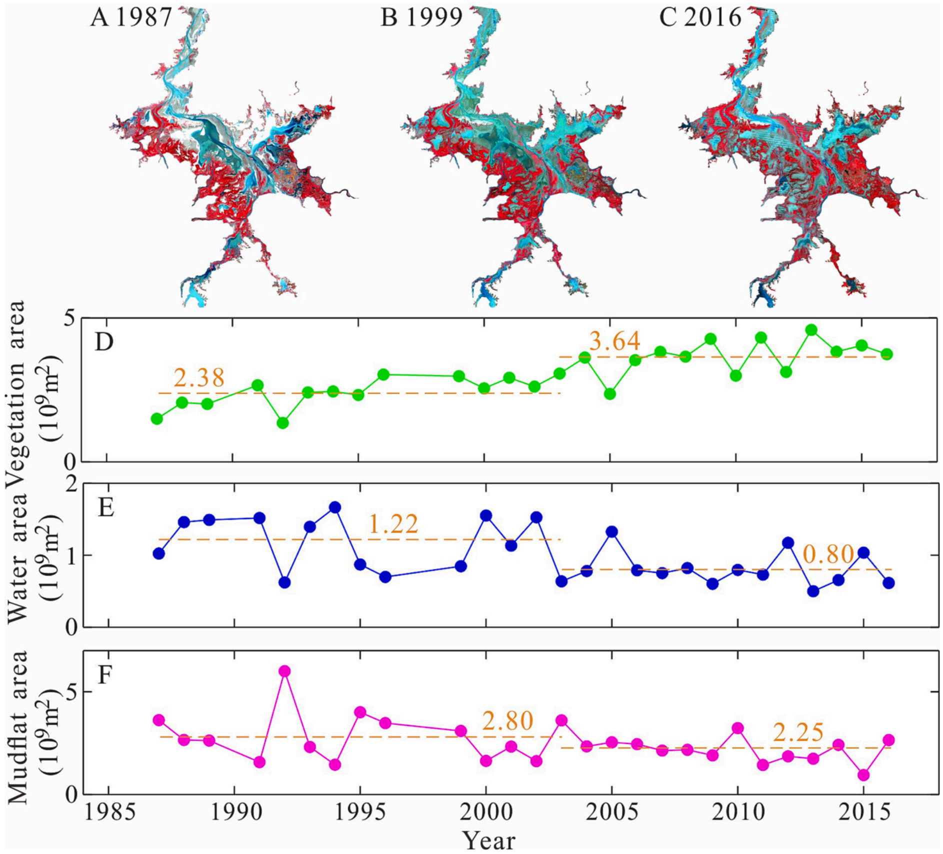

Fig. 4. Landsat imagery illustrating Poyang Lake during the dry season in A) 1987, B) 1999 and C) 2016; and time series analysis displaying D) vegetation area, E) water area, and F) mudflat area from Landsat images during the period 1987-2016.

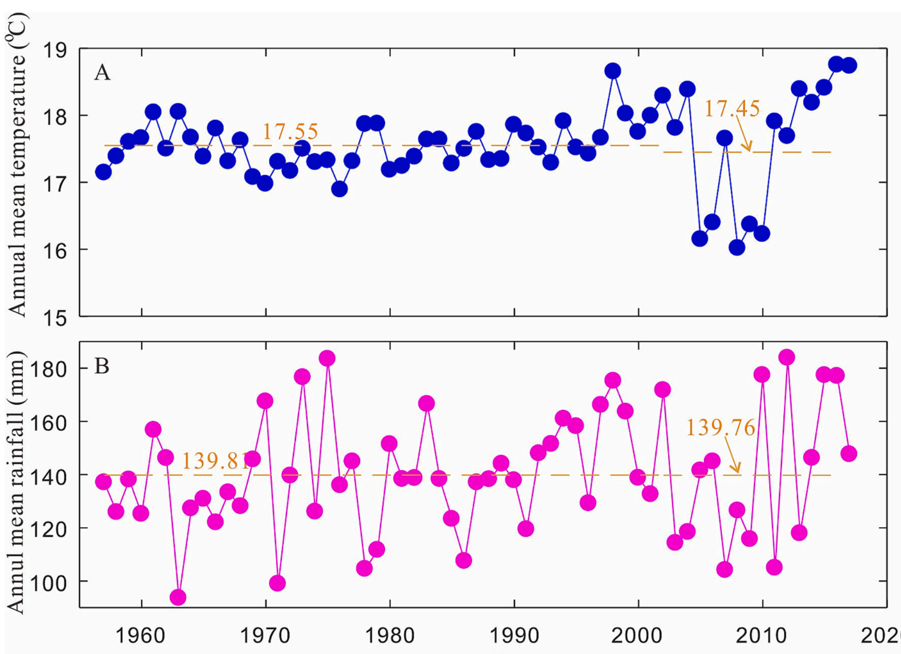

Fig. 5. Average annual A) temperature and B) rainfall in the Poyang Lake Basin during the period 1957–2017.

Anderson et al., 2020). Even small variation in OC can have a considerable influence on sediment organic matter utilization, lake ecosystem productivity, and biological diversity. Stable and healthy OC burial within lake sediments is the basis of sustainable lake ecosystem development. As of Poyang Lake's water level declines, the exposed margin area of the lake will become more exposed to air and undergo a shift in the dominant source of sediment organic material. It is expected to shift from primarily algal material to terrestrial plants, which act

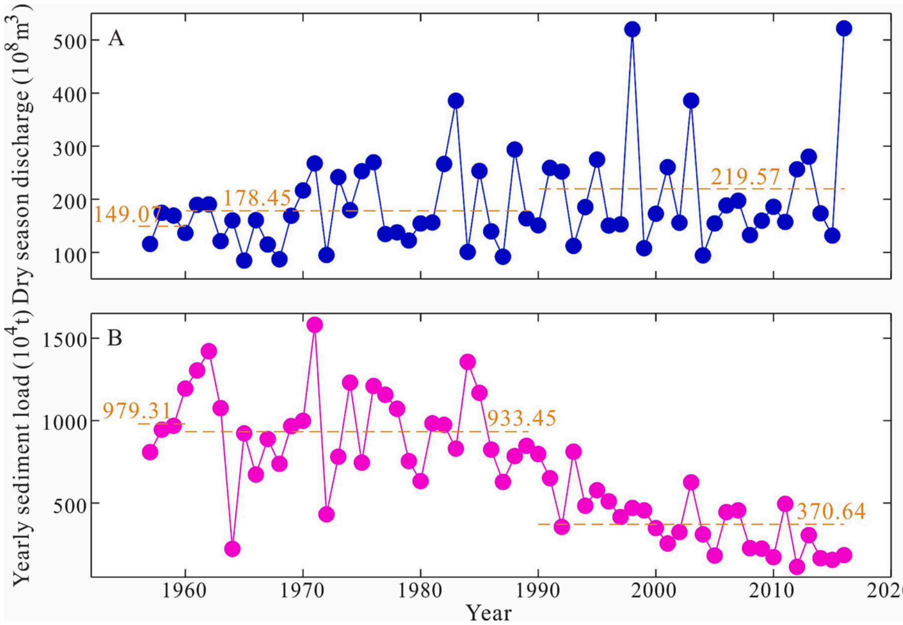

Fig. 6. A) Discharge during the dry season and B) annual sediment load from the Ganjiang River into Poyang Lake.

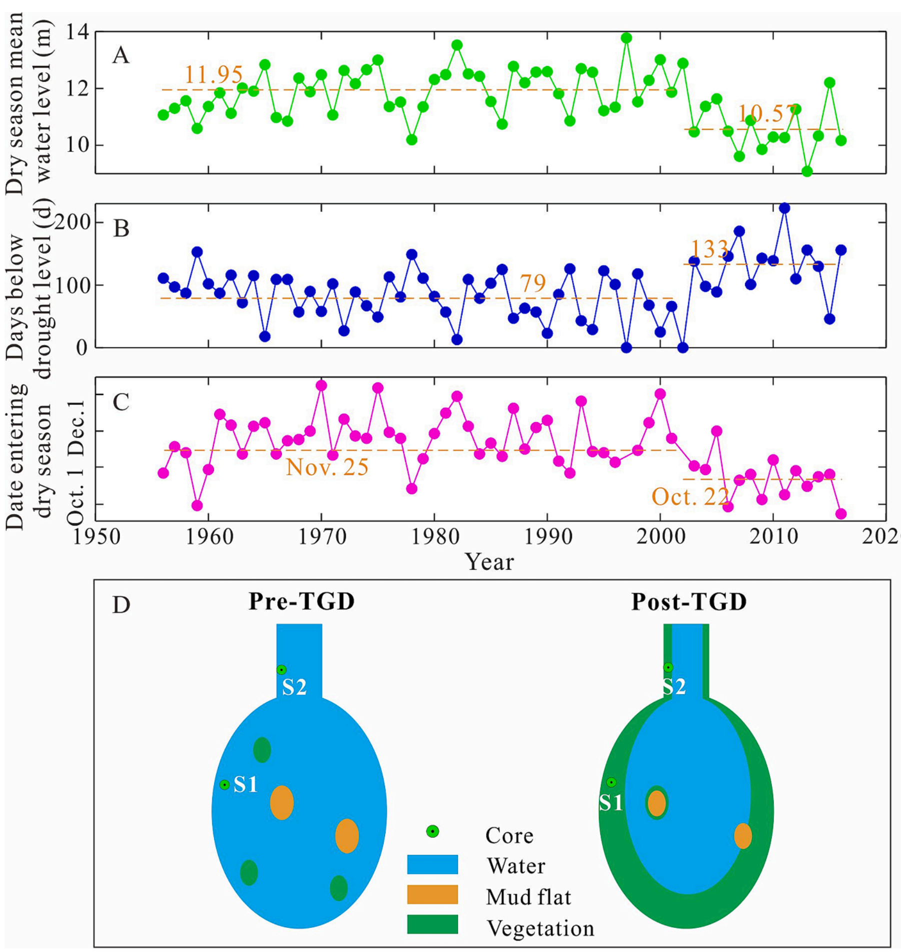

Fig. 7. A) Mean water level during the dry season, B) number of days below the drought level, C) date of entering the dry season at Duchang during 1956–2016, and D) a diagram showing the transition within Poyang Lake following TGD regulation.

positive C sinks in the lake sediments. This highlights the potential for sustainable OC burial within lake sediments and provides a basis for the development of a healthy lake ecosystem. Furthermore, the implications extend beyond Poyang lake. The mid-lower Changjiang River is a lake-rich system, containing 651 lakes with a total lake area over 21×10^9 m^2 (Dong et al., 2012; Gui et al., 2013). These lakes are experiencing similar shrinking areas due to the regulation of TGD (Wang et al., 2014). The colonization of terrestrial plants in the margin areas of these lakes represents a vital potential OC pool in China. Therefore, the results of this study have regional-scale implications, demonstrating the potential for hydraulic engineering projects to C burial in lacustrine regions.

The data and analysis presented here provide a way forwards to estimate the OC burial benefits associated with dam regulation scenarios and lake shrinkage processes. However, the negative impacts on the ecosystem should never be neglected. In particular, the reduction in sedimentation flux resulting from dam regulation can have wide-ranging effects on physical, chemical and biological processes within lakes, which includes impacts on oxygen availability, water column reaeration, heat budget, nutrient concentration, and the support of aquatic food webs through OC (Donohue & Molinos, 2009; Lin et al., 2021). These changes can alter the structure and functioning of biological communities, as well as modify biological diversity and productivity. In addition, the shift from algal to terrestrial plants, while favoring OC burial within the sediment, may also lead to land salinization and desertification. These processes can have detrimental effects on human populations who rely on the lake for various purposes (Reverey et al., 2016). Therefore, it is essential to carefully consider the trade-offs and potential ecological consequences when implementing hydraulic engineering projects and managing lake ecosystems.

5. Conclusions

As the largest freshwater lake along the Changjiang River, Poyang Lake holds a unique position in the landscape, and the storage of OC within its sediment has significant implications for the C budget of the river. This study presents a pioneering investigation into the changes in OC burial within Poyang Lake sediment and provides insights into the underlying drivers of these variations. The main findings are summarized as follows:

(1) The OCAR in Poyang Lake underwent a significant shift during the period of 1880s-2010s, exhibiting relative stability before 2000 but showing a substantial increase and greater variability after 2000. Compared to the pre-2000 period, the OCAR in the lake has increased by 3.82–4.60 times in this century.
(2) At an annual scale, the vegetation area of Poyang Lake during the dry season increased by 52.94 %, from 2.38 billion m^2 during 1987–2002 to 3.64 billion m^2 during 2003–2016. This expansion of vegetation has contributed to enhanced OC burial within the lake sediments.
(3) Despite the risk associated with Poyang Lake shrinkage, the increase in lake outflows and decline in lake levels resulting from the TGD regulations has led to vegetation expansion during the dry season. This made the shallow floodplain over lake system a significant C sink.

The assessment demonstrates the positive aspect of operational hydraulic engineering on the C sink of lake ecosystems. Specifically, the TGD regulations have the potential to turn downstream connected lake floodplain into substantial C sink in China. This phenomenon may also be observed globally, as mega rivers fragmented by large dams often experience water level declines and OC burial due to increased vegetation coverage. The study highlights the importance of future research on the long-term impacts of dams on lake ecosystems and their surrounding floodplain systems using additional sediment cores. Furthermore, a comprehensive evaluation of the trade-offs between the positive effects of dams on OC burial and the negative effects on biodiversity, water quality, and local communities is necessary.

CRediT authorship contribution statement

Xuefei Mei: Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. **Zhijun Dai:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Jinzhou Du:** Data curation, Formal analysis. **Jinping Cheng:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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