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RESEARCH ARTICLE

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Driver–response relationships in a large shallow lake since the Anthropocene: Short-term abrupt perturbations versus long-term sustainable

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Abstract

Lakes, as integral social-ecological systems, are hotspots for exploring climatic and anthropogenic impacts, with crucial pathways revealed by continuous sediment records. However, the response of multi-proxies in large shallow lakes to typical abrupt events and sustained drivers since the Anthropocene remains unclear. Here, we explored the driver-identification relationships between multi-proxy peaks and natural and anthropogenic events as well as the attribution of short-term perturbations and long-term pressures. To this end, sediment core records, socio-ecological data, and documented events from official records were integrated into a large shallow lake (Dongting Lake, China). Significant causal cascades and path effects (goodness-of-fit: 0.488; total effect: −1.10; $p < .001$) were observed among catchment environmental proxies, lake biogenic proxies, and mixed-source proxies. The peak-event identification rate (PEIR) and event-peak driving rate were proposed, and values of 28.57%–46.43% and 50%–81.25% were obtained, respectively. The incomplete accuracy of depicting event perturbations using sediment proxies was caused by various information filters both inside and outside the lake. PEIRs for compound events were 1.41 (±0.72) and 1.09 (±0.46) times greater than those for anthropogenic-dominated and natural-dominated events, respectively. Furthermore, socio-economic activity, hydrologic dynamics, land-use changes, and agriculture exerted significant and persistent pressures, cumulatively contributing 55.3%–80.9% to alterations in sediment proxies. Relatively synergistic or antagonistic trends in temporal contributions of these forces were observed after 2000, which were primarily attributed to the "Grain for Green" project and the Three Gorges Dam. This study represents one of the few investigations to distinguish the driver–response relationship of multiple proxies in large shallow lakes under typical event perturbations and long-term sustained pressures since the Anthropocene. The findings will help policymakers and managers address ecological perturbations triggered by climate change and human activities over long-term periods.

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KEYWORDS
Anthropocene, anthropogenic impacts, catchment events, driver–response relationships, lake sediments

1 | INTRODUCTION

The Anthropocene (after ~1950) is an imporant epoch of human activities further confirmed by the "golden spike" announced by the Anthropocene Working Group (Witze, 2023). Human activities have transformed many of Earth's ecosystems across local to global scales, resulting in irreversible anthropogenic alterations (Mammides, 2020; Monastersky, 2015). Unraveling the impacts of natural variability and human activities on terrestrial and aquatic ecosystems has been a pivotal and ongoing focus of interdisciplinary scientists specializing in climate, ecology, and limnology; their efforts are directed toward attributing changes to Earth's systems (Dubois et al., 2017). Lake sediments, as natural archives, reveal the predominant influence of anthropogenic forcing on environmental changes at global and regional scales for decades, even in the face of climate warming and increased frequency of extreme events (Smol, 2010). However, an obvious research gap persists regarding the response of multiple proxies of lake sediments to typical abrupt events and long-term sustained drivers, further hindering a comprehensive understanding of the attributes of aquatic ecosystems and environmental changes.

Lakes often integrate and regulate aquatic ecosystems, and their formation and evolution are characterized by regional quasi-synchrony and events (Loewen, 2023; Williamson et al., 2009; Woolway et al., 2020). Pulsed mutations in lake sediments are theoretically feasible rather than a hypothesis for the recording and identification of events; thus, they could offer valuable opportunities to reconstruct the magnitude, frequency, and mechanisms of past event-related deposits (Batt et al., 2017). Research on lake sediment proxies has highlighted the timely or lagged recording of catchment natural-dominated abrupt events (such as extreme floods, earthquakes, and fires) and their quantitative reconstruction (Gilli et al., 2013; Martins et al., 2023). Large-scale events caused by human activities, officially documented as dam construction and afforestation, have frequently been described via sediment records (Dearing et al., 2012; Simon et al., 2023). The timely or lagged recording of events has led to uncertainty regarding the magnitude of typical anthropogenic events recorded in lake sediments, particularly during the Anthropocene, when human activity intensified. Furthermore, various information filters exist in lake watershed systems that can influence the extent to which sediment proxies capture information (McLauchlan et al., 2013; Mills et al., 2017). The identification of typical events by sediment proxies exhibits differences between the proxy and event types. Therefore, it is necessary to conduct in-depth investigations into the degree of identification of both naturally and anthropogenically dominant typical events using multiple proxies in lake sediments.

Climate change and human activities threaten 87% of the Earth's liquid surface waters (Mammides, 2020; Yao et al., 2023). Both lake mass and energy fluxes are controlled by alterations in the catchment environment, including abrupt events and long-term sustainable pressures (Leavitt et al., 2009). Collins et al. (2011) defined the driving mechanism for long-term socio-ecological research in biophysical systems, such as lakes, as the "press-pulse dynamics" framework. Sudden natural and anthropogenic events, such as floods, droughts, damming, and wars, can induce pulsed peaks in sediment properties, which are short-term abrupt perturbations (Sabatier et al., 2022). External pressures such as population growth, land-use changes, and nutrient loading have long-term persistent effects on sediment dynamics (Anderson et al., 2020). Compared with analyses of abrupt event perturbations, investigations of long-term persistent pressures have gained widespread attention in lakes at the individual, regional, and global levels (Bao et al., 2021; Baud et al., 2021; Benito et al., 2021). A generally consistent perspective indicates that the primary drivers of sediment dynamics in lakes during the Anthropocene are the long-term pressures induced by human activities, and most associated studies have been limited to identifying major external pressures. For example, air temperature, sunshine hours, and fertilizer application showed contribution rates of 46.48%–76.4% to the decrease in total nitrogen (TN) and total phosphorus (TP) burial efficiency in sediments from Dianchi Lake (Chen et al., 2020); and agricultural intensification with anthropogenic nutrient loading drove 73% shifts in lake ecological dynamics in Gaoyou Lake (Huang et al., 2022). However, the time at which these major pressures significantly influence the temporal sequence and whether their contributions are positive or negative have not been clarified. In addition, lakes are complex socio-ecological systems wherein the effects of various external pressures often act synchronously rather than in isolation. Together, possible multiple stressors would have additive, synergistic, or antagonistic effects on lake ecosystems (Zhang, et al., 2018). Unfortunately, studies focusing on the combined impact of multiple drivers are still limited and sparse. Lake sediment proxies can detect long-term environmental and short-term perturbations and elucidate the complex dynamics between humans and lake environments (Smol, 2010). Paleolimnology, the study of physical, chemical, and biological information preserved in lake sediments (Dearing et al., 2015; Walton et al., 2023), informs socio-ecological research on lake-catchment systems and provides a valuable resource for setting restoration goals and management strategies.

We focused on Dongting Lake, the second-largest shallow freshwater lake in China, with an area of 2625 km^2. The lake was once the largest freshwater lake in China but has undergone multiple ecological changes in the last hundred years, such as degradation and sedimentation due to disturbances from sudden catchment events and sustained pressure from anthropogenic activities (Yu et al., 2020). Events such as frequent natural disasters (extreme floods in 1954 and 1998) and bend cutting of the Jingjiang River in 1967–1972 and the Three Gorges Dam (TGD) in 2003 have abruptly altered sediment input patterns and hydrological exchange dynamics (Yu et al., 2018). The land use patterns in the basin changed significantly due to the Great Iron and Steel in 1958, the Great Turning Lakes into fields in 1950s–1970s, and the "Grain for Green" project in 2000. Although the social development of Dongting Lake in terms of population, economy, agrarianizing, and urbanization has varied among the sub-basins since 1950, it has continuously affected land-use changes over a long period, thus triggering soil erosion and material deposition in the lake (Wang, et al., 2021; Xiao et al., 2023). These watershed ecological changes recorded in the sediments have been explored in terms of sediment source, material composition, and content dynamics (Du et al., 2001; Ran, et al., 2023; Wang et al., 2023). However, challenges still persist in the socio-ecological integrity of lake-watershed systems regarding different typical events that are timely, lagged, or not captured by lake sediments and regarding the linear or nonlinear impacts of long-term pressures and when they were significant.

Here, we conducted a comprehensive study on the driver–response relationship between sediment proxies and catchment stresses from both short-term event perturbations and long-term sustainable pressures during the Anthropocene. The hypotheses were that multi-proxy peaks exhibited a higher identification rate for anthropogenic-dominated events compared to natural events and that long-term sustained main pressures imposed nonlinear effects on the sediment proxies, manifesting both positive and negative contributions in temporal trends. Accordingly, the main aims were to (i) elucidate the eco-environmental dynamics in Dongting Lake through multiple sediment proxies during the Anthropocene, (ii) quantify the abrupt changes in sediment proxies for typical catchment events, and (iii) reveal the impacts of long-term pressures on lake sediments and their temporal contributions. Our study offers valuable insights into the integral social-ecological linkages in lake catchment ecosystems during the Anthropocene, providing additional support for the protection and management of the ecological environment.

2 | MATERIALS AND METHODS

2.1 | Study area

Dongting Lake (27°39′–29°51′ N, 111°19′–113°34′ E) is the second-largest freshwater lake in China and one of 200 priority ecoregions for global conservation (Global 200; Olson & Dinerstein, 2002). The lake body is currently composed of west Dongting Lake (WDT), south Dongting Lake (SDT), and east Dongting Lake (EDT), which were listed in the Ramsar Convention in 2002, 2002, and 1992, respectively. The area belongs to the subtropical monsoon climate zone, which is prone to natural disasters, with floods and droughts being particularly severe. The years 1954, 1963, and 1998 were considered as typical meteorological disaster years (Wen & Zeng, 2006). Being a complex interconnected river–lake system, an estimated 133.5 million m^3 of watershed sediments were imported annually, of which 73.4% became silted up within the lake (Yu et al., 2018). In addition, human activities such as afforestation, deforestation, land reclamation, and returning of land to the lake have dramatically shifted the land use patterns of Dongting Lake, especially the increase or decrease of forest land and arable land (Yang et al., 2020). Since 1950, the hydrological patterns of Dongting Lake significantly changed due to the cutting and straightening of the lower Jingjiang River and Gezhouba hydraulic project construction in the middle reaches of the Yangtze River. In total, 13,318 reservoirs and many soil and water conservation projects were constructed in the Dongting Lake basin, and they acerbated hydrologic shifts, especially the operation of the TGD. Under the combined effect of natural factors and anthropogenic activities, Dongting Lake shrunk by 48.19% over the past century, causing significant alterations in the depositional environment (Yu et al., 2020).

2.2 | Sediment sampling and measurement

Three sediment sites, Dalianfeizhang (DLFZ, 112°13′28.820″ E, 28°52′41.270″ N), Shangfenggang (SFG, 112°32′2.790″ E, 28°53′5.705″ N), and Lujiao (LJ, 112°59′24.091″ E, 29°7′42.897″ N), were selected owing the most continuous sediment sequences among nine sampling sites investigated in November and December 2020. This selection was supported by the $^{210}Pb_{ex}$ natural and continuous decay law and the reconstructed centennial chronology of $^{210}Pb_{ex}$ and ^{137}Cs radionuclides (Ran, et al., 2023). A total of 120 samples were collected at a core depth of 200 cm with 5 cm equal intervals After pre-processing, we measured 11 indicators—sand (%), $^{210}Pb_{ex}$ (Bq kg^{-1}), mass accumulative rate (MAR, g cm^{-2} year^{-1}), magnetic susceptibility (MS, 10^{-6} m^3 kg^{-1}), total organic carbon (TOC, g kg^{-1}), TN (g kg^{-1}), TP (g kg^{-1}), and total sulfur (TS, g kg^{-1}), the C/N ratio (dimensionless) and stable isotopes ($\delta^{13}C$ and $\delta^{15}N$, ‰). Detailed measurements of these sediment proxies are presented in Text S1. The covered time span of the three sediment cores was 160 ± 1.25 years, as calculated by the CRS or C-CRS model (Figure S1).

Based on their physicochemical properties and general indications of environmental changes, these indicators were grouped into three types of environmental proxies to infer biogeochemical processes in lake-catchment systems (Dearing et al., 2015; Mills et al., 2017; Walton et al., 2023). Catchment environmental proxies primarily represent indicators whose contents are highly influenced by physical processes such as erosion and runoff within regional ecosystems, including sand, $^{210}Pb_{ex}$, MAR, and MS (Kenney et al., 2022; Rose et al., 2010). Lake biogenic proxies, for example, TOC, TN, TP, and TS, are mainly use to infer primary production, nutrient supply, and biogenic states within the lake (Anderson et al., 2020; Ran, et al., 2023). Mixed-source proxies are primary indicators including

C/N ratio, $\delta^{13}C$, and $\delta^{15}N$ for determining the source of organic matter in lakes (e.g., terrestrial exogenous inputs or lake endogenous contributions; Lamb et al., 2006; Sun et al., 2021).

2.3 | Data collections in the catchments

The catchment data required to describe the sediment proxy included meteorological, hydrological, and human activity statistics. Data collected from the Dongting Lake basin since the Anthropocene, a period when the official statistical records of China provided better regional trends for climate, population, land-use changes, and hydrology, were sufficient to conduct an exploration of long-term socio-ecological relationships (Kong et al., 2017; Xiao et al., 2023). A total of 16 indicators were collected. Specific details of the indicators, including abbreviations and sources, are presented in Table S1. The naturally dominant climatic and hydrological variables exhibited similar changes (Figure 1a,b). Pre, Ro, and Wl exhibited stable fluctuations. Tem showed an increasing trend, which was more pronounced in 1970–2005, while Sed exhibited a decreasing trend. The variables dominated by humans fluctuated considerably (Figure 1c–f). Pop and Pop-d increased linearly, with growth rates of 145.6% and 125.02%, respectively. The GDP increased remarkably after 2000. Urr and For-c increased by 624.30% and 72.18%, respectively. Con-b showed a staggering growth of 4985.50% in 1990–2020. The Aff, Crops, Gra-s, Fer, and coal displayed cyclic fluctuations.

2.4 | Typological classification of officially documented events

Events are deemed unusual or of some importance and can extend to long-term and multifactorial processes, which range from local or regional environmental perturbations to global-scale realignment (Parnell et al., 2008; Waters et al., 2022). In this study, we focused on large-scale events of natural variability and anthropogenic impacts in regional settings, as recorded in official historical documents during 1950–2020. Events were classified into meteorological (MEs), hydraulic (HEs), and land-use events (LUEs) based on their main impacts on regional climate, hydrological conditions, and land-use changes (Table S2). Specifically, MEs are defined as patterns of extreme weather that persist for some time, such as extreme floods and drought. These events are mainly represented by province-wide flood years and province-wide extreme drought years in Hunan Province (Seneviratne et al., 2023). HEs and LUEs are largely attributed to anthropogenic activities. HEs focus on events such as cutting river bends and building large reservoirs and dams that change the hydrological regimes of sediment and runoff transportation (Feng et al., 2013). National major construction projects associated with hydrology and water resources and events that significantly altered hydrological regulation were selected as HEs. LUEs are extensive human-driven processes that modify land-use patterns, such as afforestation, deforestation, urbanization, and agricultural growth (Dearing et al., 2012; Mammides, 2020), and they are mainly represented by national major construction projects in the forestry, key projects in soil erosion management, and large-scale deforestation and tree planting activities. Compound events (CEs), taking a key cue from the IPCC AR6 report (Seneviratne et al., 2023), refer to the simultaneous onset of two or more events under an “allied attack” by extreme climate and intensive human activity. Information on these events was obtained from the Hunan Volume of the Chinese Meteorological Dictionary (Wen & Zeng, 2006) and the Hunan Provincial Institute of Local Chronicles Compilation (http://dfz.hunan.gov.cn). A total of 28 typical events, including 12 MEs, 8 HEs, 3 LUEs, and 5 CEs, were documented in Dongting Lake and its upper catchments in 1950–2020 (Figure 1g and Table S3).

2.5 | Quantification of sediment proxies and catchment events

A bidirectional relationship exists between abrupt changes in lake sediments and typical catchment events. Mutational signatures of environmental proxies in lake sediments are driven by catchment events and simultaneously serve to identify these events in watersheds (Batt et al., 2017; Mills et al., 2017). Generally, comparing the timing of peak changes in sediment proxies with the officially documented dates of large-scale natural and anthropogenic events is a suitable approach for investigating bidirectional relationships in lake-catchment systems (Ahlborn et al., 2015; Rahman et al., 2021). We propose two metrics—the peak-event identification rate (PEIR) and event-peak driving rate (EPDR)—to quantitatively assess the response of sediment proxies to historical events. The PEIR represents the capturing degree of mutations in sediment proxies for typical historical events, which was calculated as the ratio of counts between the rate of change (ROC) peaks at events and all typical events during a specific timespan. The EPDR primarily indicated the proportion of ROC peak changes in sediment proxies that could be attributed to typical events and was calculated as the ratio of counts of the ROC peaks at events to all peaks in a given time. The formula is as follows:

$$\mathrm{PEIR} = \frac{C_{ij}}{A_j} \times 100; \mathrm{EPDR} = \frac{C_{ij}}{B_i} \times 100$$

where A_i indicates the total counts in the type i event; B_j indicates the peak counts for the rate of change (ROC) of sediment proxy j, and C_{ij} was the count of the ROC peaks of proxy j in the current year and the next year for type i event.

2.6 | Data measurement and statistical analysis

Figure 2 presents a flow diagram of the main methodological steps in our study. All sediment proxies and catchment environmental data were converted by z-score normalization. A one-way analysis of

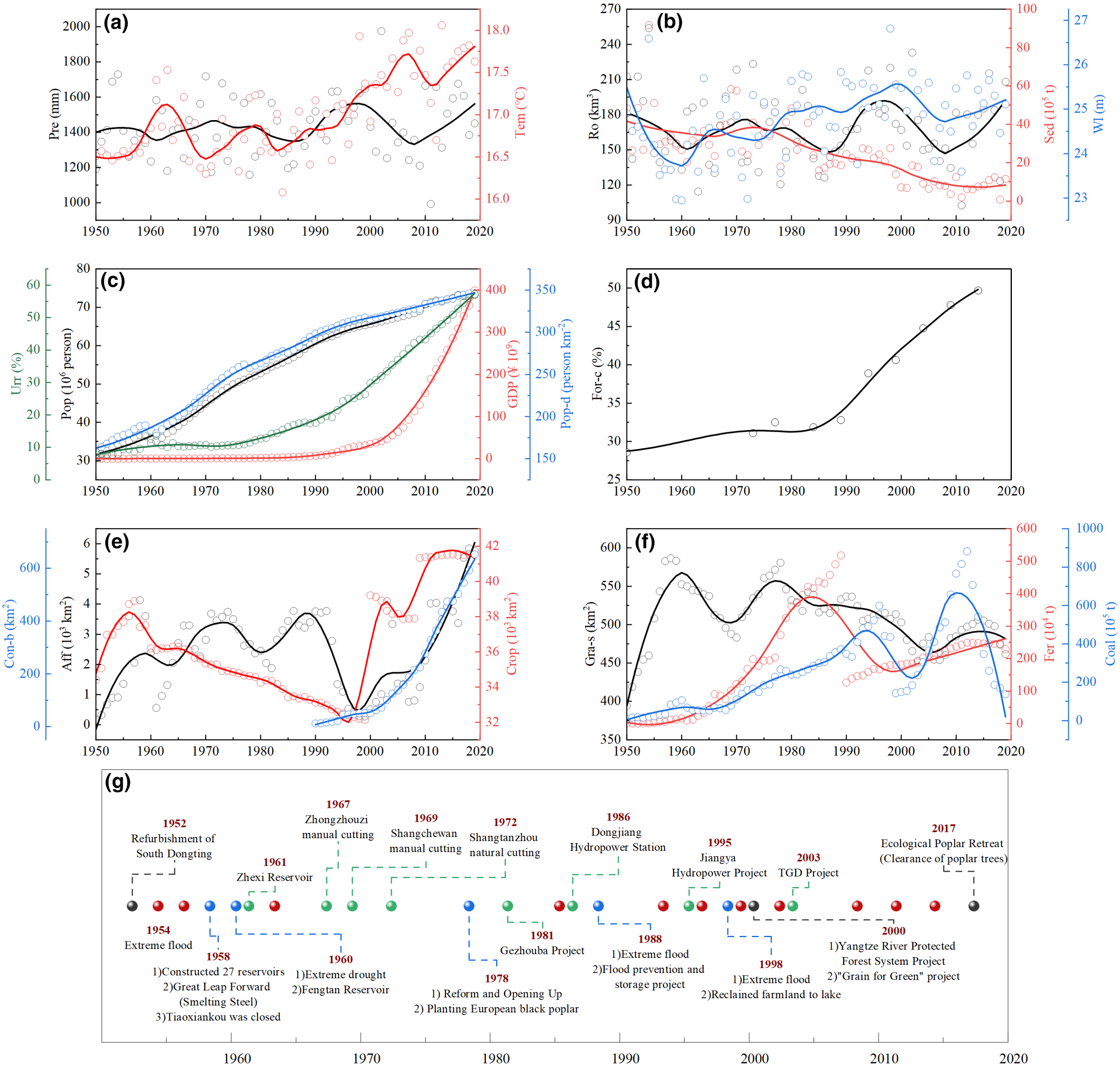

FIGURE 1 Changes in eco-environmental variables in (a) climate, (b) socio-economic activity, (c) hydrologic dynamic, (d) vegetation, (e) land-use changes, and (f) agriculture and industry in the Dongting Lake Basin during 1950–2020. The scatters were the variable contents. The curves showed the smooth lines using LOESS method through the observations to highlight trends. The full names of the variable abbreviations are listed in Table S1. (g) the typical events in the Dongting Lake Basin during 1950–2020. The red, gray, green, and blue points indicated MEs, LUEs, HEs, and CEs, respectively. MEs presented only the most typical years, see Table S3 for details.

variance (ANOVA) was used to evaluate statistical differences among variables. ROC analysis was performed to investigate the temporal variations of sediment proxies using the R package "RRatepol" (Mottl et al., 2021). This package was also used to identify the significant peaks based on extreme peak-finding methods (Seneviratne et al., 2023). The partial least squares path model (PLS-PM) can quantify the impact pathways among different proxy types, and it was implemented using the R package "plspm" (Sanchez, 2013). A multicollinearity test for the predictor variables was performed using a pairwise correlation analysis algorithm and variance inflation factor (VIF; Dormann et al., 2013). Variables with correlation coefficients greater than .8, including Pop, Urr, and For-c, were removed, whereas the others that showed no multicollinearity had VIF values less than 10 (Figure S2). Redundancy analysis (RDA) was conducted to identify the key drivers of sediment proxies using CANOCO version 5. The general additive model (GAM) was selected to quantify the relationship between PC1 extracted from the sediment proxy and the main forcing factors. In this study, the main factors in the GAM were statistically significant variables of the RDA results, which corresponded to the categorized watershed ecosystem factors. The technical work of

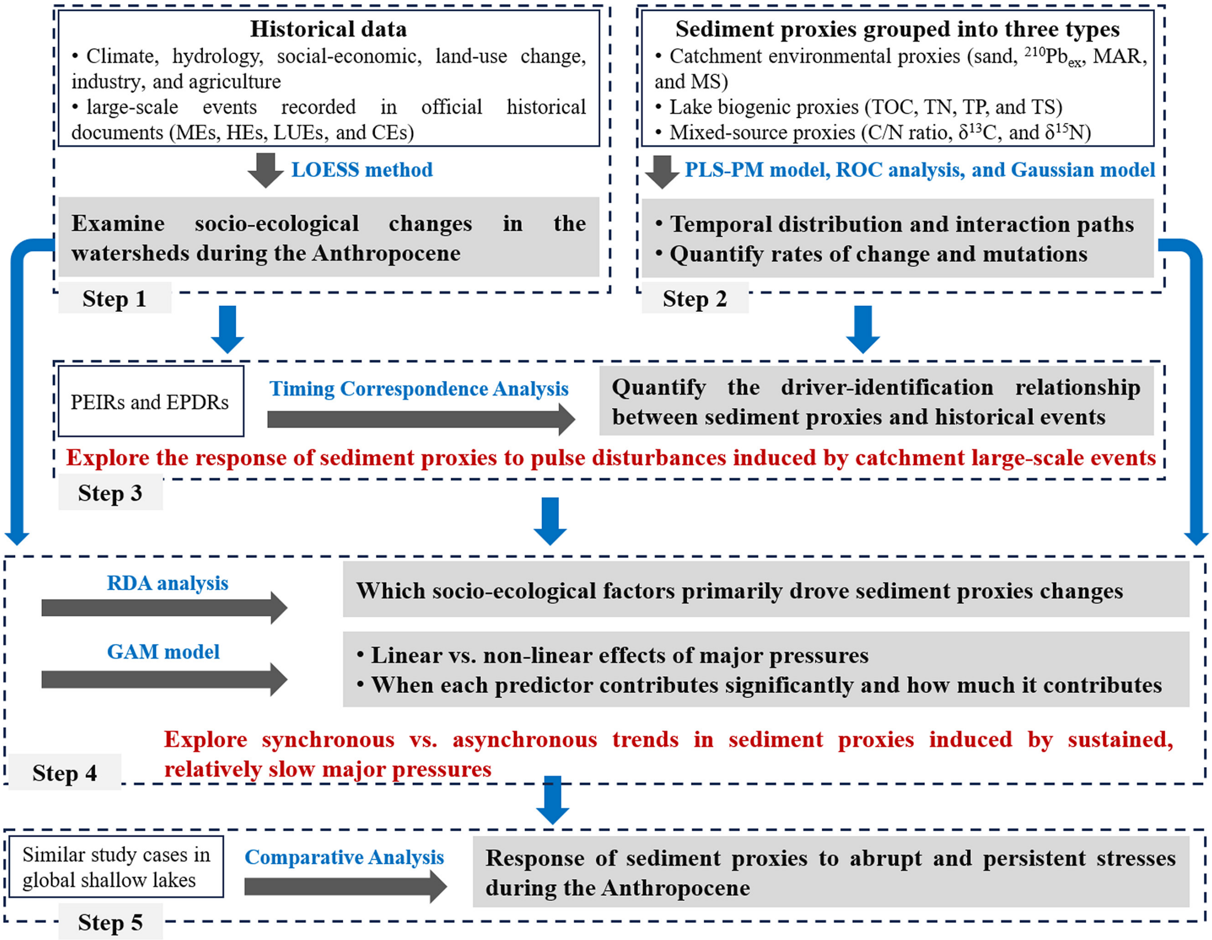

FIGURE 2 Flow diagram illustrating the main methodological steps.

Simpsona and Anderson (2009) and (Lin et al., 2021), revealed that the functions *gam* and *predict*. *gam* from the R package "mgcv" plays a crucial role in determining the statistical significance of each predictor and can be used to quantify the contributions of the predictors to temporal changes in a response variable (Wood, 2017). Among the GAM outputs, time periods in which the temporal contributions of multiple factors are both positive or negative correspond to synergistic effects, and time periods in which there are both positive and negative contributions correspond to antagonistic effects (Capo et al., 2017; Simpsona & Anderson, 2009). Coefficients of variation (CV) were used to determine the event differences among the variables. All analyses were conducted at a significance level of $p<.05$. Data visualization was performed using Origin 2022 (OriginLab Inc., Northampton, MA, USA) and R Studio (version 4.1.3; SPSS Inc., Chicago, IL, USA).

3 | RESULTS

3.1 | Relationship among different types of sediment proxies

The sediment proxies exhibited three temporal variations—abrupt changes in stability, increasing fluctuations, and cyclic fluctuations (Figure S3). These proxies exhibited obvious spatial variations within Dongting Lake (Figure S4). The cause–effect relationship among catchment environmental proxies, lake biogenic proxies, and mixed-source proxies was quantified using the PLS-PM model (Figure 3). The goodness-of-fit (GOF) was 0.488. The loadings of the reflective indicators on the sediment proxies varied. Sand and MS loaded on catchment environmental proxies were 1.81 ± 0.13 times more than those for $^{210}Pb_{ex}$ and MAR. On lake biogenic proxies, the loadings of TOC, TN, and TP were 3.20 ± 0.57 times higher than those of TS. On mixed-source proxies, the loadings of the C/N ratio and $\delta^{15}N$ were 2.81 ± 0.03 times higher than those for $\delta^{13}C$. The model results showed a significant cause–effect relationship among the sediment proxies. The total effect of catchment environmental proxies on lake biogenic proxies was −1.10, including a direct effect of −0.64 and an indirect effect of −0.46. The total effects of catchment environmental proxies on mixed-source proxies and mixed-source proxies on lake biogenic proxies were −0.80 and 0.57, respectively, both of which were direct effects.

3.2 | ROCs and peaks of sediment proxies

All sediment proxies showed multi-peak shifts during 1950–2020, as revealed by ROC analysis and the extreme peak-finding method (Figure 4). ROCs between proxies were significantly different

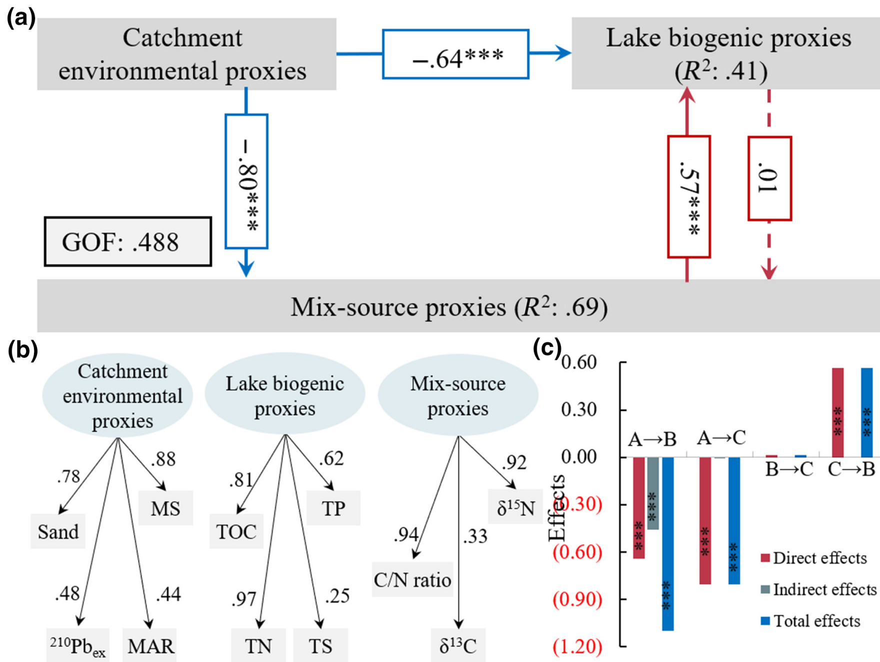

FIGURE 3 Results of the PLS-PM model for sediment proxies. Subplot a indicates the effect relationship among catchment environmental proxies, lake biogenic proxies, and mixed-source proxies. GOF was the goodness-of-fit of the model. Red and blue arrows were positive and negative effects. R^2 shows the determinant coefficient for the corresponding variable, indicating the variance explained by the model. ***$p<.001$. Subplot b presents loadings of reflective indicators for the latent variables. The numbers were the loadings. Subplot c was standardized direct, indirect, and total effects of the PLS-PM model. A, B, and C were proxies of the catchment environmental proxies, lake biogenic proxies, and mixed-source proxies, respectively. ***$p<.001$.

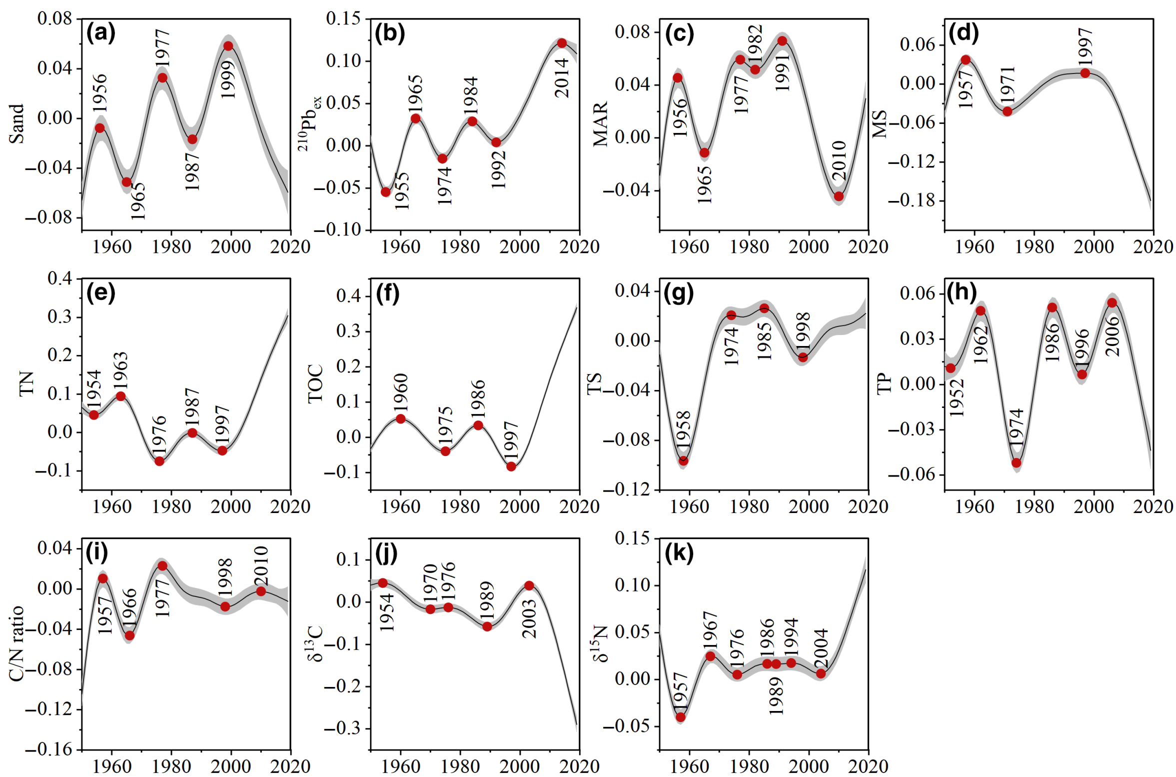

FIGURE 4 The temporal distribution of ROCs and peaks of sediment proxies. Red dots are peak points. Black solid lines indicated ROC values. Gray bands are 95% confidence bands. Subplots a-k are in the order of sand, $^{210}Pb_{ex}$, MAR, MS, TOC, TN, TP, TS, C/N ratio, $\delta^{13}C$ and $\delta^{15}N$.

($p<.05$; Figure S5). $^{210}Pb_{ex}$ and MAR were significantly higher than sand and MS for catchment environmental proxies, TOC and TN were significantly higher than TS and TP for lake biogenic proxies, and $\delta^{15}N$ was significantly higher than the C/N ratio and $\delta^{13}C$ for mixed-source proxies. The counts of ROCS peaks ranged from 3 to 7, with the most being $\delta^{15}N$ and the least being MS. These peaks were mostly observed during the 1970s–1990s. The highest frequency observed in peak years was 3, which occurred in 1957, 1965, 1976, 1977, 1986, and 1997. The year 2000 was the tipping point for the ROC curves and included nine proxies, such as sand and TN. Only five peak years were detected after 2000.

3.3 | Relationship between sediment proxies and catchment typical events

The one-way ANOVA showed that ROCs of sediment proxies were non-significantly different across event types and that only ROCs of the C/N ratio and $\delta^{15}N$ were different between LUEs and CEs (Figure S6). The CVs of the sediment proxies varied significantly among the event types; however, no consistent pattern was observed. For catchment environmental proxies and lake biogenic proxies, the CVs at a specific event may be a maximum as well as a minimum. For example, the CVs at MEs were maximum for sand and MAR and minimum for MS, whereas the CVs at LUEs were maximum for TP and minimum for TN. For the mixed-source proxies, the CVs showed a maximum value at different specific events, whereas the minimum values emerged at the CEs.

Time-point correspondences between the ROC peaks of sediment proxies and major events were used to investigate the response of sediment dynamics to watershed events (Figure 5), and the PEIR and EPDR were obtained (Table 1). A total of 16, 16, and 14 ROC peaks were detected for catchment environmental proxies, lake biogenic proxies, and mixed-source proxies, respectively, of which eight (five MEs, two HEs, and one CEs), 13 (six ME, three HEs, one LUEs, and three CEs), and 10 (three MEs, five HEs, and two CEs) peaks occurred during the current and following years of typical events, respectively. The total PEIRs ranged from 28.57% to 46.43%, and the total EPDRs ranged from 50% to 81.25%; in addition, the two indicators differed significantly ($p < .05$; Figure S7). Among all specific events, PEIRs were ordered in descending sequence as CEs (20%–60%), HEs and LUEs (25%–62.50%), and MEs (25%–50%).

3.4 | Impacts of catchment variables on sediment proxies

The impacts of catchment eco-environmental variables on sediment proxies were assessed using RDA (Figure 6). For the catchment environmental proxies, the explained rate was 40.2%, with 53.54% and 22.53% of the explained fitted variations in PC1 and PC2, respectively. PC1 showed a positive correlation with variables, excluding Sed and Gra-s, whereas PC2 exhibited a negative correlation with variables, excluding Tem, Coal, WI, and Gra-s. Four variables—Pop-d, Con-b, Sed, and Aff—significantly influenced the catchment environmental proxies, with a 32.4% cumulative explanatory rate and an 80.9% cumulative contribution rate. For lake biogenic proxies, the explained rate was 35.5%, with 53.38% and 31.19% explaining fitted variations in PC1 and PC2, respectively. PC1 showed a positive correlation with all variables except coal and grass; PC2 also

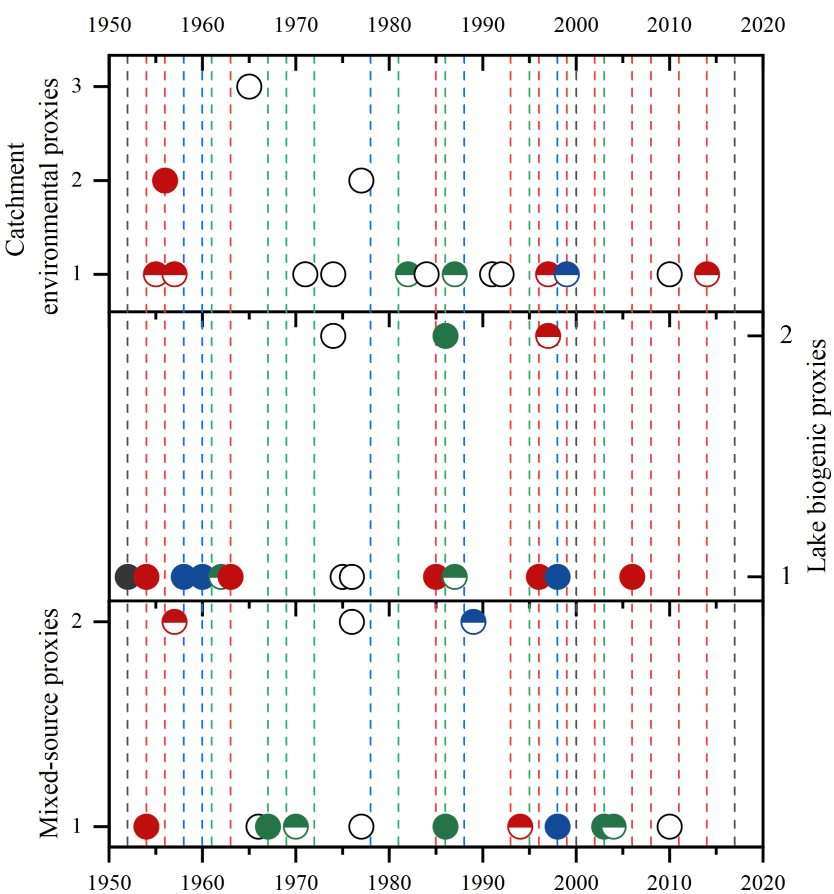

FIGURE 5 The corresponding relationship between peaks of ROCs (dots) and typical events (vertical dashed lines). Solid dots, semicircular dots, and hollow dots indicated that the peaks corresponded to the current year, the following year, and no year of the events, respectively. Red, gray, green, and blue showed MEs, LUEs, HEs, and CEs, respectively.

TABLE 1 The PEIR and EPDR of sediment proxies in Dongting Lake. Values in parentheses are the number of ROC peaks for the corresponding event types.

	Number of peaks	Number of peaks at events	PEIRs for single events				Total PEIRs	Total EPDRs
			MEs	HEs	LUEs	CEs		
Catchment environmental proxies	16	8	41.47 (5)	25 (2)	–	20.00 (1)	28.57	50.00
Lake biogenic proxies	16	13	50.00 (6)	37.50 (3)	33.33 (1)	60.00 (3)	46.43	81.25
Mixed-source proxies	14	10	25.00 (3)	62.5 (5)	–	40.00 (2)	35.71	71.43

exhibited a positive correlation with all variables except for Aff. Four variables (GDP, Sed, WI, and Crop) had a significant effect on lake biogenic proxies, with a 25.3% cumulative explanatory rate and a 71.5% cumulative contribution rate. For the mixed-source proxies, the explained rate was 22.1%, with 78.01% and 18.47% of the explained fitted variations in PC1 and PC2, respectively. PC1 showed a negative correlation with all variables except Sed and Gra-s, and PC2 exhibited a negative correlation with all variables except Sed, Gra-s, Aff, Coal, and Crop. Gra-s and Pop-d had a significant effect on mixed-source proxies, with a 12.3% cumulative explanatory rate and a 55.3% cumulative contribution rate.

Based on the RDA results, socio-economic activity, hydrological dynamic, land-use changes, and agriculture were identified as the key factors influencing the variations of sediment proxies. The GAM assessed the impact and contributions of these main factors on PC1 of sediment proxies (Table 2 and Figure S8). The first three factors, which had nonlinear (edf = 2.825, $p < .001$), linear (edf = 1.000, $p < .001$), and nonlinear (edf = 5.531, $p < .05$) effects, explained 88.20% of the catchment environmental proxies. The same three factors cumulatively explained 68.60% of the variance observed for lake biogenic proxies: socio-economic activity and hydrologic dynamics had significant nonlinear (edf = 8.122, $p < .001$) and linear (edf = 1.000, $p < .05$) effects, whereas land-use changes showed insignificant nonlinear effects (edf = 7.124, $p > .05$). Socio-economic activity and agriculture explained 27.80% of mixed-source proxies, both with significant near-linear effects (edf = 0.907, $p < .01$; edf = 0.912, $p < .01$). The temporal contributions of the three or two significant predictors to the fitted values of the PC1 scores are shown in Figure 7. For catchment environmental proxies, temporal contributions from socio-economic activity and hydrologic dynamics exhibited nearly synergistic trends. Both factors contributed negatively before the 1980s and then shifted to positive. A prominent distinction was that the hydrological dynamics underwent a more intricate and disrupted transformation, particularly after 2003, when its contribution increased. The contributions of land-use changes revealed five alternating cycles of positive and negative changes. For lake biogenic proxies, the temporal contributions of socio-economic activity exhibited a pattern of first decreasing and then increasing, with 2007 as the turning point. Contrastingly, the contributions of the hydrological dynamics displayed four alternating cycles of positive and negative changes, which remained consistently negative after 2003. For mixed-source proxies, contributions from socio-economic sources increased and then decreased, with 1981 as a turning point, and contributions from agriculture showed three decreasing and two increasing periods.

4 | DISCUSSION

4.1 | Interaction among sediment proxies in lakes

Physical, chemical, and ecological processes determine and regulate the structure and function of lake ecosystems, resulting in temporal and geographical alterations in lake sediment proxies (Mills

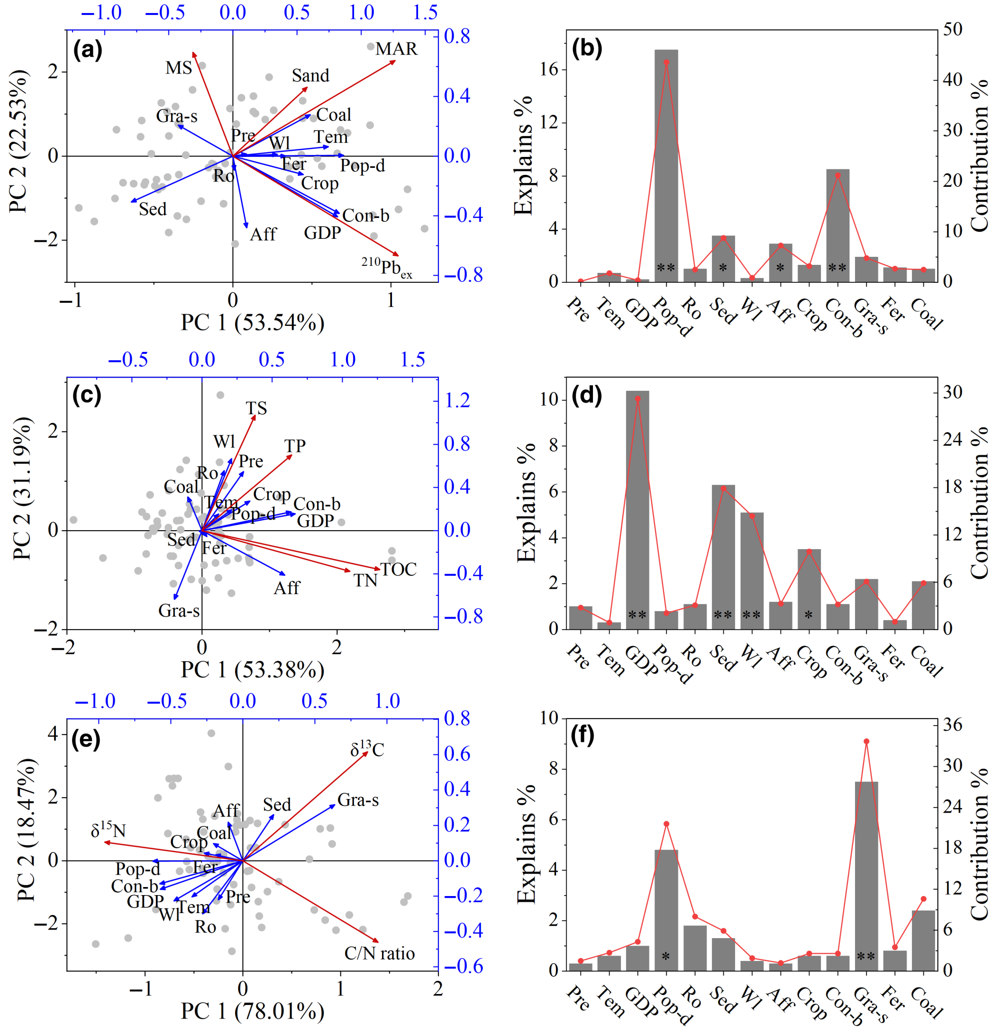

FIGURE 6 Results of RDA analysis for sediment proxies and catchment eco-environmental variables. Subplot a, c, and e presented the results for catchment environmental proxies, lake biogenic proxies, and mixed-source proxies. The red arrows were sediment proxies (explanatory variables) and the blue arrows were catchment ecological factors (response variables). Subplots b, d, and f indicated the explanations (bars) and contributions (lines) of the response variables. *$p<.05$ and **$p<.01$.

TABLE 2 GAM model parameter results for sediment proxies in Dongting Lake. *y*1, *y*2, and *y*3 are PC1 values extracted from catchment environmental proxies, lake biogenic proxies, and mixed-source proxies. *x*1, *x*2, *x*3, and *x*4 are factors of socio-economic activity, hydrologic dynamic, land-use changes, and agriculture, respectively.

Response variable	Explanatory variable	edf	F	p	Dev.Expl (%)	Model	R^2
*y*1	*x*1	2.85	20.96	.000	88.20	$y1=s0+s(x1)+s(x2)+s(x3)+\varepsilon$	.863
	*x*2	1.00	12.05	.001			
	*x*3	5.53	2.79	.014			
*y*2	*x*1	8.12	5.32	.000	68.20	$y1=s0+s(x1)+s(x2)+s(x3)+\varepsilon$	.589
	*x*2	1.00	5.25	.026			
	*x*3	7.12	1.59	.147			
*y*3	*x*1	0.91	1.14	.001	27.80	$y3=s0+s(x1)+s(x4)+\varepsilon$	.259
	*x*4	0.91	1.08	.002			

et al., 2017; Williamson et al., 2009). Previous studies focused on the temporal variability of single types of environmental proxies, such as organic matter (Martins et al., 2023), diatoms (Zhang, et al., 2018), and sediment fluxes (Kenney et al., 2022). The contents of the 11 sediment proxies in Dongting Lake demonstrated three different patterns over the past century: stability, cyclical fluctuation, and temporal

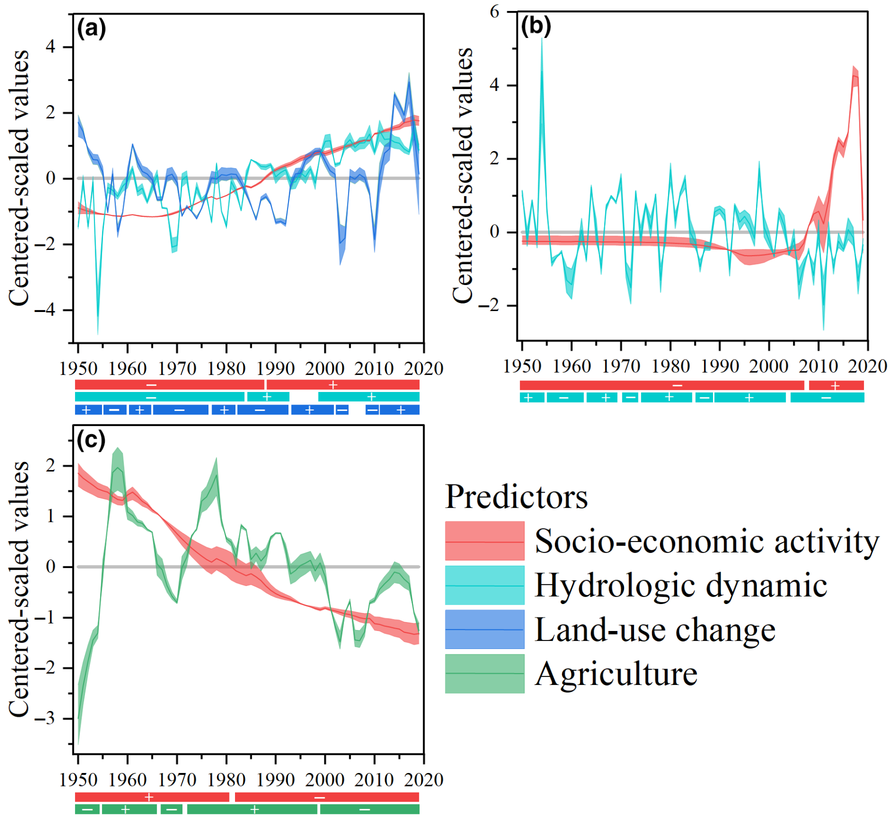

FIGURE 7 Time-series curves depicting the contribution of main factors (predictors) to PC1 (response variables) extracted from catchment environmental proxies (a), lake biogenic proxies (b), and mixed-source proxies (c), as derived from the GAMs results. The shade bands are 95% confidence intervals on the estimated. The reference of the zero lines is the shade binds included in the lines indicating a statistically insignificant contribution to the explanatory variable. Horizontal bars represent the periods for which a significant contribution of the predictors was found; the signs + and –, respectively, correspond to an increase and a decrease in the response variables.

increases (Figure S3). However, temporal variations in the same sediment proxies were not consistently characterized. For example, in catchment environmental proxies, $^{210}Pb_{ex}$ and MAR contents were increased continuously, MS contents were relatively stable, and sand contents exhibited periodic changes. Over the past three decades, proxies that exhibited cyclical variations shared a consistent pattern of very steady values with low fluctuations. Simultaneously, significant differences were present in the internal spatial distributions of most sediment proxies and CVs across the same type of environmental proxy (Figure S4). The contrasts and similarities identified in Dongting Lake suggest an interaction influence between the types of lake sediment proxies (Dean, 1999; Ran, et al., 2023). Theoretically, distinct types of lake sediment proxies can exhibit causal links in addition to temporal and spatial variations (Leavitt et al., 2009). However, the causality and effect pathways among the sediment proxies that reflect different environmental conditions remain difficult to interpret. In this study, owing to the inner and outer model compositions, the PLS-PM model measured the causality and effect pathways of the sediment proxies (Figure 3), in an attempt to address the limitations of previous research. Model loadings and GOF values indicated a significant path influence among catchment environmental proxies, lake biogenic proxies, and mixed-source proxies. Two influencing processes were revealed by the path coefficients of the model and their significance levels. Changes in catchment environmental proxies directly altered exogenous substance inputs and biogenic element contents in lakes at a significance level of .001. Empirical investigations suggested that the increase in lake sedimentation rates since the Anthropocene has altered the structure of internal and external source material inputs and accelerated TOC, TN, and TP accumulation in lake sediments (Anderson et al., 2020; Bao et al., 2021). Contrarily, the causal cascade of catchment environmental, mixed-source, and lake biogenic proxies was significant, with a total effect of −0.46. The interactions between the chemical and physical properties of lake sediments can rationally reflect and infer the ecological processes of lake-catchment systems because lakes act as integrators of energy and mass fluxes (Leavitt et al., 2009; Williamson et al., 2009). The cascading relationship among catchment environmental changes, organic matter imports, and lake biogenic regimes is suggested by the PLS-PM results quantified by sediment proxies' types in Dongting Lake. The findings of the multi-proxy approach for lake sediments challenged the conventional understanding of the watershed environment, lake material inputs, and nutrient concentrations, which mostly relies on source qualification and environmental monitoring data (Bernardino et al., 2020; Hampton et al., 2008; Kong et al., 2017; Wang et al., 2023). Our research provides insights into the cause-effect cascade relationships and interaction pathways among different types of sediment proxies, thus providing quantitative knowledge of the relationships among multiple attributes in lake sediments.

4.2 | Responses of lake sediment proxies to typical natural and human events in the catchment

Lake sediments provide critical records of major and abrupt events because of their unique ability to document natural variability and human impacts on up-catchment changes without being disturbed by the events themselves (Loewen, 2023; Mills et al., 2017). The sediment proxies in the lakes have undergone abrupt shifts since the Anthropocene, as confirmed by the multi-peak changes observed in their ROC curves from 1950 to 2020 (Figure 4). These shifts suggest that catchment event disturbances are well-recorded using these proxies (Rahman et al., 2021; Schneider et al., 2010). Merely tallying ROC values of sediment proxies across various event types does not yield a uniform distribution of these proxies across events (Figure S6), thereby hindering the differentiation of the impact magnitude among event types. Comparable numbers of ROC peaks were observed in the three proxy types for Dongting Lake, suggesting that no variability existed in the sensitivity of specific types of sediment proxies to environmental change. Because of the intricate hydrological and biogeochemical processes that occur in lakes as well as the influence of anthropogenic factors and climate (Catalan et al., 2013; Dean, 1999; Leavitt et al., 2009), it was difficult to derive common insights into changes in sediment-proxies across different types of events in catchments using statistical analyses and data comparisons. Thus, we considered the temporal correspondence in the years during which ROC peaked in lake sediments and typical events in the catchment to gain insights into the response relationship in lake-catchment systems (Figure 5). The majority of the peaks manifested in the year that the event occurred and subsequent years, with a notable concentration observed for events from the 1950s to the 1980s. Frequent disturbances from anthropogenic events during this period were the primary cause of the rapid response of sediment dynamics to catchment events (Dearing et al., 2012). Deforestation, soil erosion, and wetland shrinkage in the region were exacerbated by steel refining, grain-based farming, and lake encirclement. As these external factors alter the original land-use patterns, a significant amount of terrestrial material is imported and deposited in the lake along with runoff and sediments, thus causing changes in sediment proxies (Liu et al., 2016; Mammides, 2020). The material exchange mechanism in Dongting Lake was significantly affected by water conservation initiatives during this time, including the Jingjiang River flood diversion project and the Gezhouba Dam reservoir (Li et al., 2009; Yu et al., 2018). Moreover, the year 2000 served as the demarcation point of the ROC curves for most proxies. Subsequently, fluctuations in proxies were more monotonous and showed fewer peaks. The major contributors to the local and regional environmental changes that had numerous effects on the transportation of terrestrial materials to the lake were the execution of China's "Grain for Green" project in 2000 and the TGD project in 2003. These two important events had two impacts. First, they promoted vegetation fixation and dam retention, which hindered the movement of many land materials (Feng et al., 2013; Yang et al., 2022). Second, they affected the photosynthesis and mineralization of organic matter within the lake by influencing various biogeochemical processes through water-level changes and vegetation growth, including the microclimate, plants, and microorganisms (Wang et al., 2020; Zhao et al., 2023). Both large reservoir/dam buildings and regional land-use changes at the global scale have an impact on the source-sink processes of material transport (Best, 2018; Loewen, 2023). Examples include tropical deforestation, the Belo Monte Dam on the Amazon River, and the Aswan Dam on the Nile River (Best, 2018; Li et al., 2022; Pendrill et al., 2022). Exploring the response of sediment proxies to typical historical events based solely on temporal correspondence is insufficient, and a more explicit degree of correspondence between them should be revealed clearly.

Using continuously deposited lake sediments as recorders and regulators of catchment information (Williamson et al., 2009), we proposed two metrics, PEIR and EPDR, to quantitatively distinguish the response of peaks in sediment proxies to typical events and their differences between events (Table 1). Overall, the results, with EPDRs (50%–81.25%) higher than PEIRs (28.75%–46.43%) at $p < .05$ significance (Figure S7), indicated that the event-driven changes in sediment peaks exceeded the capture degree of events by peaks in sediment proxies. Event-driven ecological modifications are not perfectly preserved in lake sediments, supporting the view that lake sediments possess limited depictions of historical event perturbations in the catchment (Leavitt et al., 2009). Sediment proxies were subject to various information filters from both inside and outside the lake. The hydroclimate filter incorporates all of the physical, chemical, and biological processes in lakes that transform input-forcing variables into something other than a simple output recording (Mills et al., 2017; Smol, 2010). Biogeochemical changes in sediment proxies are meanwhile influenced by post-depositional information filters, especially bioturbation and diagenesis (Anderson et al., 2006; Dubois et al., 2017). Under information filters, the original signals induced by catchment events are weakened or delayed upon their arrival at the lake and are not completely or fully accurately recorded by the depositional agents. Furthermore, the response of peaks in sediment proxies to external forcing events varies depending on the type of proxy and event (McLauchlan et al., 2013). In Dongting Lake, the PEIRs of the catchment environmental and lake biogenic proxies were greater in MEs than in HEs and LUEs, suggesting that a quicker response in the physical and organic properties of lake sediments is more likely to result from the ecological changes caused by MEs (Sabatier et al., 2022). Extreme floods and droughts (MEs) in lake-catchment systems are relatively discrete and represent abrupt disturbances with distinct consequences that can be detected by rapid peak changes in sediment composition (Kenney et al., 2022; Rose et al., 2010). In contrast, the effects of human HEs and LUEs on sediment proxies are sustained and chronic (Rahman et al., 2021). The highest PEIRs (62.50%) observed in mixed-source proxies in the HEs indicate that the abrupt peaks of organic matter inputs in Dongting Lake during the Anthropocene were mainly driven by HEs. Specifically, the most notable events were the Jingjiang cutting bend in 1967–1972 and the TGD operation in 2003. The split ratios from the three mouths of the Yangtze River to Dongting Lake were estimated to be 19.4% and 12% after the two events and 32% before the first HE (Hu et al., 2014). Both events affected the sediment input from the Yangtze River to Dongting Lake, thereby altering the exogenous material import structure of the lake (Wang et al., 2023; Yu et al., 2018). These significant HEs were successfully recorded using mixed-source proxy peaks in lake sediments. Additionally, we found that the PEIRs of CEs were the highest among those for all event types, 1.41 ± 0.72 times and 1.09 ± 0.46 times higher than those for fully anthropogenic-dominated (HEs and LUEs) and fully natural-dominated events (MEs), respectively. The quantitative results suggested that ecological alterations due to the compounded effects of human activities and natural variability were tracked by lake sediments (Dearing et al., 2012; Liu et al., 2016). These findings strongly align with the notion that human activities have been the predominant factor in shaping land-surface ecological processes since the Anthropocene (Dubois et al., 2017; Mammides, 2020; Syvitski et al., 2020; Witze, 2023).

4.3 | Drivers of long-term sustained ecological pressures

Rapid human-induced changes to the Earth's surface have posed severe ecological and managerial challenges during the Anthropocene. One-third of the global lakes were under considerable human pressures including pollution (e.g., nutrient enrichment), hydrologic modification (e.g., dams and reservoirs), and overexploitation (e.g., sand mining and deforestation; Han et al., 2023; Mammides, 2020). These external drivers can be classified into long-term disturbances and short-term pulse events, explaining the prolonged, sustained, and sudden peaks in biophysical systems such as lake ecosystems (Collins et al., 2011). Lake sediment proxies can provide long-term records of sustained disturbances and abrupt events in the flow of energy and material between a lake and its surroundings (Dubois et al., 2017; McLauchlan et al., 2013). In Dongting Lake, the ROCs of sediment proxies showed multiple peaks indicating the presence of abrupt changes; additionally, the PEDRs ranging from 50% to 81.25% suggested that these peaks were largely caused by typical events, especially MEs (Table 1, Figure 5). Naturally driven MEs are typical abrupt disturbance events marked by discreteness that are capable of rapidly inducing compositional changes in lakes (Kenney et al., 2022; Liu et al., 2016). Anthropogenic HEs and LUEs, while exhibiting typical occurrences, may not necessarily trigger an immediate response in the lake ecosystem itself, at least not initially; instead, they tend to exert long-term, sustained pressures on the transport of terrestrial materials to lakes (Kong et al., 2017; Leavitt et al., 2009). Socio-economic activities, hydrological dynamics, land-use changes, and agriculture were identified as long-term pressures via RDA analysis, with cumulative contributions in the range of 55.3%–80.9%. As the first large lake regulating the water and sediments of the Yangtze River, Dongting Lake covers approximately $2.67 \times 10^5\,km^2$ watershed area and $2625\,km^2$ water area. Over the past century, the significant impacts of human-induced modifications on hydrologic conditions, sediments, vegetation, and biogeochemical processes within the lake were widely discussed and uniformly acknowledged (Li et al., 2009; Ran, et al., 2023; Yu et al., 2020, 2018). These long-term variables were the primary drivers of the dynamics of shallow lake sediments both globally and regionally (Benito et al., 2021). Watershed activities associated with agriculture, urbanization, land-use changes, and hydrologic dynamics have accelerated by approximately threefold on MAR average in the global lakes since 1950 (Baud et al., 2021; Ran, et al., 2023; Rose et al., 2010). Nutrients and warming mainly forced alterations in the ecological states of mountains and shallow lakes using lake sediments (Huang et al., 2022; Oleksy et al., 2020).

Long-term impacts of multiple anthropogenic factors on lakes are the norm rather than the exception. Theoretically, cumulative, synergistic, and antagonistic effects can occur when multiple stressors act together (Zhang, et al., 2018). GAMs analysis can identify potential covariate effects of explanatory variables on the dependent variable over time, and thus determine the response effects (Capo et al., 2017; Simpsona & Anderson, 2009). In Dongting Lake, the main focus was on determining the potential synchronic or antagonistic effects of four long-term regulatory pressures on the sediment proxy types (Figure 7, Table 2, and Figure S8). Socio-economic activity, land-use changes, and agriculture had significant nonlinear effects on specific proxy types, and hydrologic dynamics had significant linear effects. The temporal contributions of socio-economic activity were characterized by two phases, with the cut-off point occurring after 1980, which corresponds to the rapid development of GDP and the population explosion over the past 40 decades (Figure 1b). The periodic positive and negative contributions of hydrologic dynamics reflected the fluctuation of sediments and water levels in Dongting Lake. Land-use changes exhibited frequent alternations between positive and negative contributions, with the alternating times often occurring after typical events, indicating that the complex influences of land use were superimposed on short-term abrupt events. The temporal contributions of agriculture aligned with the trends in the grain-seeding area (Figure 1f). The interaction of multiple led to synergistic superimposed effects in a few periods and antagonistic effects in most periods, thereby increasing the difficulty of lake management and ecological governance (Kong et al., 2017). After 2000, synergistic or antagonistic effects showed obvious trends that were mainly attributed to the “Grain for Green” project in 2000 and the TGD in 2003, although extreme flooding events also occurred in 1998. Naturally oriented pulsed events are limited drivers of long-term changes in lake sediment proxies, and large-scale human activities can alter material fluxes within ecosystems through long-term sustained processes (Collins et al., 2011; Leavitt et al., 2009; Sabatier et al., 2022). Specifically, after implementing the “Grain for Green” project, a notable improvement in vegetation cover and a decrease in soil erosion and sediment loss were observed (Hu et al., 2021), and they mitigated the input of upstream materials into the lake (Yu et al., 2020). The long-term effects of the TGD project on the hydrological dynamics of Dongting Lake resulted from the fundamental reversal of the Yangtze River sediment inflow (Feng et al., 2013; Yu et al., 2018). The few peaks in the depositional proxies after 2000 also provide evidence of the impact of these two typical events (Figure 3). These findings highlight the influence of significant drivers and temporal contributions of multiple proxies to lake sediments during the Anthropocene.

4.4 | Global explorations for the driver–response relationship in lake-catchment systems

Numerous investigations conducted for different temporal durations, different regional scales, and different lake types have shown that lake sediment proxies can respond to changes in the watershed eco-environment. The Anthropocene reflected a great global acceleration in human impacts after 1950. However, the impacts of human activities on lake ecosystems largely predate 1950 (Dubois et al., 2017). To comprehend the advantages of paleolimnology for long-term socio-ecological studies within lake-catchment systems, globally comparable cases within the last 200 years were investigated. Case studies published before March 2023 that documented the driver–response relationships of lake-catchment systems over the past two centuries were collected from the Web of Science database and the China National Knowledge Infrastructure. By excluding investigations that did not explore the impacts of catchment abrupt events, we were able to obtain 19 cases, with 14 studies conducted on individual lakes and five conducted on regional lakes. Table 3 presents the research cases that focused on global lakes and showcased the responses of lake sediment proxies to typical historical event disturbances and long-term pressures, and Figure S9 presents the global study locations. The limited explorations suggest that the use of lake sediments as a natural archive for integrated socio-ecological research has not been fully realized, at least in terms of exploring the effects of short-term abrupt perturbations and long-term persistent stresses. In addition, the correspondence in timing between sudden changes in sediment proxies and related events has frequently been used to obtain broader insights into the response of sediment dynamics to HEs (Ahlborn et al., 2015), warming and flood events (Kenney et al., 2022; Zhan et al., 2010), wars (Zhu et al., 2020), regional religious activities (Ma et al., 2022), dam construction (Hobbs et al., 2012), and political events (Dearing et al., 2012). These investigations relied more on qualitative descriptions when examining on how lake depositional proxies captured disturbances caused by abrupt events. The apparent spatial and temporal heterogeneity of global lake-scale effects and information filtering increased the difficulty of summarizing universal patterns of short-term abrupt event impacts (Leavitt et al., 2009; Mills et al., 2017). The two proposed metrics PEIR and EPDR can quantitatively distinguish the driving and recognizing between lake sediment dynamics and catchment events since the Anthropocene. Typical natural and anthropogenic events in the catchment drove half to three-quarters of the peaks of sediment proxies, but only 28.57%–46.43% of the peak changes were matched to events. We found that the PEIRs of combined events were 1.09 (±0.46) and 1.41 (±0.72) times higher than those of anthropogenic-dominated and natural-dominated events, respectively. The two metrics proposed in our investigation are operationalized in a bold attempt to examine the effects of short-term abrupt perturbations. During the Anthropocene, the long-term driving pressures on lake sediment have been acknowledged. Over the past 200 years, land-use changes, population growth, eutrophication, and other long-term sustained pressures accelerated by human activities have had a dominant impact on the ecological environment of lakes (Dearing et al., 2015; Poraj-Górska et al., 2017; Rahman et al., 2021). These pressures also played a significant role in shallow lakes, such as Dongting Lake (Figure 6). When considering multiple factors acting together, the interactions over time have both synergistic and antagonistic effects (Figure 7), thereby increasing the difficulty of providing a basis for policy formulation and environmental protection strategies to achieve ecological civilization. Nevertheless, the "press-pulse dynamics" conceptual framework implies that limnological evidence continues to represent a dependable source for carrying out long-term socio-ecological research in aquatic systems, such as lakes (Collins et al., 2011; Zhang, et al., 2018). Therefore, we should carry out further in-depth research on the limnological features of worldwide lakes to differentiate between the effects of short-term pulse disturbances and long-term sustained pressures, especially in terms of continued climate variability and increasing human activities. Such work will offer unbiased and distinctive perspectives on ecological preservation and sustainable growth.

4.5 | Limitations and prospects

According to the "press–pulse dynamics" framework proposed by Collins et al. (2011) for socio-ecological research, effectively distinguishing the impacts between short-term sudden pulse events and long-term widespread sustained pressures is a significant current challenge (Mills et al., 2017). Leveraging the continuity, archival nature, and high resolution of lake sediments, we examined socio-ecological pressures in lake-catchment systems since the Anthropocene using a typical freshwater lake, Dongting Lake of China, as an example. To the best of our knowledge, this is the first exploratory attempt at addressing this critical challenge. Three sediment cores from various locations in the lake center were analyzed consistently, reducing uncertainties associated with a single core (Kong et al., 2017). However, the spatiotemporal heterogeneity of lake-watershed systems is still evident at the watershed scale. Previously, we investigated lake sediment dynamics and their responses to human activities within different subbasins (Xiao et al., 2023). Nevertheless, the pathways of short-term abrupt events and long-term pressures at the sub-basin scale remain unclear. The physical, chemical, and biological attributes of lake sediment can serve as proxies for studying ecological information (Dearing et al., 2015; Walton et al., 2023). We focused on recording the functions of selected proxies related to physical and organic chemical properties, with insufficient attention paid to biological proxies. There has been widespread interest in recording the potential of biological proxies such as diatoms and microorganisms in lake sediments for aquatic ecological environments (Capo et al., 2017; Rodriguez-Miret et al., 2023). Future research should integrate the diversity and comprehensiveness of sediment

TABLE 3 Case studies of sediment proxies responding to sudden perturbations and long-term sustained pressures. "—" indicated corresponding information not available directly in the originals.

No.	Name	Latitude and longitude	Lake type	Time span	Sediment proxy	Sudden perturbations	Long-term sustained pressures	Reference
1	Tian E Zhou	29.78°N, 112.56°E	Oxbow lake	70	TOC, TN, $\delta^{13}C$, Lignin phenols	Flood events	—	Li et al. (2020)
2	Cueifong Lake	24°30′ N, 121°36′ E	—	150	TOC, TN, $\delta^{13}C$	Forest fire events, deforestation	Land-use changes, eutrophication	Lin et al. (2023)
3	Lake Montcortès	42°19′50″ N, 0°59′41″ E	Karstic lake	297	Diatom	Heavy rains, droughts, and massive hemp harvesting	Warming, land use, soil erosion, and eutrophication	Rodriguez-Miret et al. (2023)
4	LGZ	32°18′23.6″ N, 119°45′13.1″ E	Shallow lake	150	Grain size, TOC/TN ratio	Flood events	—	Zhan et al. (2010)
5	Lake Christina	46.09848°N, 95.74298°W	Shallow lake	110	TP, Diatom, TCHl-a, TOC accumulation rate	Dam construction, biomanipulation	Eutrophy, regime shift	Hobbs et al. (2012)
6	Garud Lake	29.3570°N, 79.5312°E	Small montane lake	70	$\delta^{13}C$, $\delta^{15}N$	Fires	Land-use changes and population growth	Rahman et al. (2021)
7	Lake Issyk-Kul	42.1752°N, 77.4943°E	Montane lake	350	Grain-size, TOC, TN, MS	Hydrologic events, earthquakes	Climate, hydrological changes	Wang, Wu, et al. (2021)
8	Qianyong lake	28°53′ N, 90°13′ E	Montane lake	178	Cr, Ni, Cd contents	Wars	Glacial Meltwater and Anthropogenic Activities	Zhu et al. (2020)
9	Green lake	—	Montane lake	70	Varve	Extreme sediment delivery events	—	Schiefer et al. (2006)
10	Selenga Delta Lake; Black Lake	52°15′52.5″ N, 106°40′35.6″ W; 51°24′14.2″ N, 106°29′25.5″ W	Shallow lakes	179, 99	*n*-Alkanes	Earthquake, floods	Agricultural and livestock population	Martins et al. (2023)
11	Lake Gonghai	38°54′ N, 112°14′ E	Small montane lake	2000; 175	Silt component, chl-a	Dust storms, afforestation	Global warming, vegetation coverage, primary production	Liu et al. (2022)
12	Lake Dalzong	35°14′32.28″ N, 102°43′7.95″ E	Freshwater lake	922	Black carbon	Regional religious activities	Socio-economic development	Ma et al. (2022)
13	TT lake	31.10°N, 86.57°E	Shallow lake	1100	MS, $CaCO_3$, TOC, TN, C/N, water content, grain size	Hydrologic events (mainly precipitation events)	Pastoralism in the watershed.	Ahlborn et al. (2015)

(Continues)

TABLE 3 (Continued)

No.	Name	Latitude and longitude	Lake type	Time span	Sediment proxy	Sudden perturbations	Long-term sustained pressures	Reference
14	Lake Jaczno	53°51′18″ N, 21°57′07″ E	–	174	Sedimentation rate, MS, TOC, TN, TS, Pollen	Fires, deforestation	Agriculture, land-use changes, soil erosion	Poraj-Górska et al. (2017)
15	South American	Region	–	600	Tree rings	Hydroclimatic events	–	Morales et al. (2020)
16	Wax Lake Delta	Region	Delta	63	^{210}Pb	Flood events	–	Kenney et al. (2022)
17	Southern Québec	Region	Floodplain	140	Sedimentation rates	Flood events	–	Saint-Laurent et al. (2010)
18	Middle and Lower Yangtze Basin	Region	Floodplain	26–59	Sediment components	Extreme flood events	–	Liu et al. (2019)
19	Lower Yangtze Basin	Region	Shallow lakes	212	TP, diatom-inferred TP, MS, lead	Political events	Rapid economic growth, population increases, agricultural intensification	Dearing et al. (2012)

properties to systematically study the ecological changes in lake watershed systems. Additionally, the different lake types are driven by distinct mechanisms. Large shallow lakes such as Dongting Lake and Lake Superior experience ecological and environmental changes primarily driven by human activities (O'Beirne et al., 2017). Remote mountains and deep lakes are influenced to a greater extent by climate change than other regions (Catalan et al., 2013; Shimoda et al., 2011). It is essential to study the differential response mechanisms of sediment records from various lake types to short- and long-term pressures in watersheds, which will contribute to the necessary differentiation between climate change and human activities.

5 | CONCLUSIONS

By combining multiple sediment proxies, documented typical events, socio-ecological data, and global surveys, we conducted a systematic investigation of the response of lake sediments to socio-ecological pressures, both from abrupt event disturbances and long-term sustained factors since the Anthropocene. The proposed PEIR and EPDR metrics quantified the driver-identification relationship between sediment proxies and typical events and measured the correlation between depositional agents and typical events. Although the sediment proxy peaks did not fully capture typical event information, they exhibited increased rates of identifying human-induced events on average. Long-term pressures that exerted linear or nonlinear significant effects on specific proxy types included socio-economic activity, land-use changes, hydrologic dynamics, and agriculture. Their temporal contributions showed antagonistic effects at most times and synergistic interactions. These findings highlight the first effort to deconstruct the recording patterns and response mechanisms of shallow lake sediments to sudden and persistent ecological pressures in catchments since the Anthropocene, deepening the socio-ecological integrity of lake-catchment systems. Further research on lake types, environmental proxy types, and cross-scale ecological constraints under the combined effects of climate change and human activity should be conducted to better manage, govern, and protect lake ecosystems.

AUTHOR CONTRIBUTIONS

Fengwei Ran: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. **Shilan Wang:** Data curation; formal analysis; investigation; methodology; software; writing – review and editing. **Xiaodong Nie:** Conceptualization; funding acquisition; project administration; resources; supervision; writing – review and editing. **Tao Xiao:** Formal analysis; investigation; visualization. **Changrong Yang:** Formal analysis; investigation; methodology. **Yaojun Liu:** Formal analysis; writing – review and editing. **Zhongwu Li:** Conceptualization; funding acquisition; project administration; resources; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

We declare no competing financial interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in Figshare at http://doi.org/10.6084/m9.figshare.25441399.

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REFERENCES

Ahlborn, M., Haberzettl, T., Wang, J., Alivernini, M., Schlütz, F., Schwarz, A., Su, Y., Frenzel, P., Daut, G., Zhu, L., & Mäusbacher, R. (2015). Sediment dynamics and hydrologic events affecting small lacustrine systems on the southern-central Tibetan plateau—The example of TT Lake. *The Holocene*, *25*(3), 508–522. https://doi.org/10.1177/0959683614561885

Anderson, N. J., Bugmann, H., Dearing, J. A., & Gaillard, M. J. (2006). Linking palaeoenvironmental data and models to understand the past and to predict the future. *Trends in Ecology & Evolution*, *21*(12), 696–704. https://doi.org/10.1016/j.tree.2006.09.005

Anderson, N. J., Heathcote, A. J., Engstrom, D. R., & Globocarb data contributors. (2020). Anthropogenic alteration of nutrient supply increases the global freshwater carbon sink. *Science Advances*, *6*(16), eaaw2145. https://doi.org/10.1126/sciadv.aaw2145

Bao, K., Zhang, Y., Zaccone, C., & Meadows, M. E. (2021). Human impact on C/N/P accumulation in lake sediments from northeast China during the last 150 years. *Environmental Pollution*, *271*, 116345. https://doi.org/10.1016/j.envpol.2020.116345

Batt, R. D., Carpenter, S. R., & Ives, A. R. (2017). Extreme events in lake ecosystem time series. *Limnology and Oceanography Letters*, *2*(3), 63–69. https://doi.org/10.1002/lol2.10037

Baud, A., Jenny, J.-P., Francus, P., & Gregory-Eaves, I. (2021). Global acceleration of lake sediment accumulation rates associated with recent human population growth and land-use changes. *Journal of Paleolimnology*, *66*(4), 453–467. https://doi.org/10.1007/s10933-021-00217-6

Benito, X., Luethje, M., Schneider, T., Fritz, S. C., Baker, P. A., Pedersen, E. J., Gaüzère, P., de Novaes Nascimento, M., Bush, M., & Ruhi, A. (2021). Ecological resilience in tropical Andean lakes: A paleolimnological perspective. *Limnology and Oceanography*, *67*, S23–S37. https://doi.org/10.1002/lno.11747

Bernardino, A. F., Sanders, C. J., Bissoli, L. B., Gomes, L. E. D. O., Kauffman, J. B., & Ferreira, T. O. (2020). Land use impacts on benthic bioturbation potential and carbon burial in Brazilian mangrove ecosystems. *Limnology and Oceanography*, *65*(10), 2366–2376. https://doi.org/10.1002/lno.11458

Best, J. (2018). Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, *12*(1), 7–21. https://doi.org/10.1038/s41561-018-0262-x

Capo, E., Debroas, D., Arnaud, F., Perga, M. E., Chardon, C., & Domaizon, I. (2017). Tracking a century of changes in microbial eukaryotic diversity in lakes driven by nutrient enrichment and climate warming. *Environmental Microbiology*, *19*(7), 2873–2892. https://doi.org/10.1111/1462-2920.13815

Catalan, J., Pla-Rabes, S., Wolfe, A. P., Smol, J. P., Ruehland, K. M., Anderson, N. J., Kopáček, J., Stuchlík, E., Schmidt, R., Koinig, K. A., Camarero, L., Flower, R. J., Heiri, O., Kamenik, C., Korhola, A., Leavitt, P. R., Psenner, R., & Renberg, I. (2013). Global change revealed by palaeolimnological records from remote lakes: A review. *Journal of Paleolimnology*, *49*(3), 513–535. https://doi.org/10.1007/s10933-013-9681-2

Chen, Q., Ni, Z., Wang, S., Guo, Y., & Liu, S. (2020). Climate change and human activities reduced the burial efficiency of nitrogen and phosphorus in sediment from Dianchi Lake, China. *Journal of Cleaner Production*, *274*, 122839. https://doi.org/10.1016/j.jclepro.2020.122839

Collins, S. L., Carpenter, S. R., Swinton, S. M., Orenstein, D. E., Childers, D. L., Gragson, T. L., Grimm, N. B., Grove, M., Harlan, S. L., Kaye, J. P., Knapp, A., Kofinas, G., Magnuson, J. J., McDowell, W. H., Melack, J. M., Ogden, L., Robertson, G. P., Smith, M. D., & Whitmer, A. C. (2011). An integrated conceptual framework for long-term social–ecological research. *Frontiers in Ecology and the Environment*, *9*(6), 351–357. https://doi.org/10.1890/100068

Dean, W. E. (1999). The carbon cycle and biogeochemical dynamics in lake sediments. *Journal of Paleolimnology*, *21*, 375–393. https://doi.org/10.1023/A:1008066118210

Dearing, J. A., Acma, B., Bub, S., Chambers, F. M., Chen, X., Cooper, J., Crook, D., Dong, X., Dotterweich, M., Edwards, M. E., Foster, T. H., Gaillard, M.-J., Galop, D., Gell, P., Gil, A. F., Jeffers, E. S., Jones, R., Krishnamurthy, A., Langdon, P. G., … Zhang, K. (2015). Social-ecological systems in the Anthropocene: The need for integrating social and biophysical records at regional scales. *The Anthropocene Review*, *2*(3), 220–246. https://doi.org/10.1177/2053019615579128

Dearing, J. A., Yang, X., Dong, X., Zhang, E., Chen, X., Langdon, P. G., Zhang, K., Zhang, W., & Dawson, T. P. (2012). Extending the timescale and range of ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(18), E1111–E1120. https://doi.org/10.1073/pnas.1118263109

Dormann, C. F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., García Marquéz, J. R., Gruber, B., Lafourcade, B., Leitão, P. J., Münkemüller, T., McClean, C., Osborne, P. E., Reineking, B., Schröder, B., Skidmore, A. K., Zurell, D., & Lautenbach, S. (2013). Collinearity: A review of methods to deal with it and a simulation study evaluating their performance. *Ecography*, *36*(1), 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Du, Y., Cai, S. M., Zhang, X. Y., & Zhao, Y. (2001). Interpretation of the environmental change of Dongting Lake, middle reach of Yangtze River, China, by 210 satellite image analysis. *Geomorphology*, *41*, 171–181. https://doi.org/10.1016/S0169-555X(01)00114-3

Dubois, N., Saulnier-Talbot, É., Mills, K., Gell, P., Battarbee, R., Bennion, H., Chawchai, S., Dong, X., Francus, P., Flower, R., Gomes, D. F., Gregory-Eaves, I., Humane, S., Kattel, G., Jenny, J. P., Langdon, P., Massaferro, J., McGowan, S., Mikomägi, A., … Valero-Garcés, B. (2017). First human impacts and responses of aquatic systems: A review of palaeolimnological records from around the world. *The Anthropocene Review*, *5*(1), 28–68. https://doi.org/10.1177/2053019617740365

Feng, L., Hu, C., Chen, X., & Zhao, X. (2013). Dramatic inundation changes of China's two largest freshwater lakes linked to the Three Gorges Dam. *Environmental Science & Technology*, *47*(17), 9628–9634. https://doi.org/10.1021/es4009618

Gilli, A., Anselmetti, F. S., Glur, L., & Wirth, S. B. (2013). Lake sediments as archives of recurrence rates and intensities of past flood events. In: M. Schneuwly-Bollschweiler, M. Stoffel, & F. Rudolf-Miklau (Eds.), *Dating torrential processes on fans and cones. Advances in Global Change Research*, vol 47. Springer, Dordrecht. http://doi.org/10.1007/978-94-007-4336-6_15

Hampton, S. E., Izmest'eva, L. R., Moore, M. V., Katz, S. L., Dennis, B., & Silow, E. A. (2008). Sixty years of environmental change in the world's largest freshwater lake—lake Baikal, Siberia. *Global Change Biology*, *14*(8), 1947–1958. https://doi.org/10.1111/j.1365-2486.2008.01616.x

Han, Y., Xu, W., Liu, J., Zhang, X., Wang, K., Wang, D., & Mei, Z. (2023). Ecological impacts of unsustainable sand mining: Urgent lessons learned from a critically endangered freshwater cetacean. *Proceedings of the Royal Society B*, *290*(1990), 20221786. https://doi.org/10.1098/rspb.2022.1786

Hobbs, W. O., Hobbs, J. M. R., LaFrançois, T., Zimmer, K. D., Theissen, K. M., Edlund, M. B., Michelutti, N., Butler, M. G., Hanson, M. A., & Carlson, T. J. (2012). A 200-year perspective on alternative stable state theory and lake management from a biomanipulated shallow lake. *Ecological Applications*, *22*(5), 1483–1496. https://doi.org/10.1890/11-1485.1

Hu, G. W., Mao, D. H., Li, Z. Z., & Tian, C. H. (2014). The impact analysis of the relations between Dongting Lake and the three outlets of the Jingjiang River after the three Gorges Project operation. *Oceanologia et Limnologia Sinica*, *45*(3), 15–23. https://doi.org/10.11693/hyhz20130108001

Hu, X., Li, Z., Chen, J., Nie, X., Liu, J., Wang, L., & Ning, K. (2021). Carbon sequestration benefits of the grain for Green Program in the hilly red soil region of southern China. *International Soil and Water Conservation Research*, *9*(2), 271–278. https://doi.org/10.1016/j.iswcr.2020.11.005

Huang, S., Zhang, K., Lin, Q., Kattel, G., & Shen, J. (2022). Lake ecosystem regime shifts induced by agricultural intensification: A century scale paleolimnological investigation from the Huai River Basin (China). *Quaternary Science Reviews*, *285*, 107522. https://doi.org/10.1016/j.quascirev.2022.107522

Kenney, W. F., Shields, M. R., Bianchi, T. S., Kolker, A. S., & Mohrig, D. (2022). Excess ^{210}Pb as an indicator of flood-stage sediments in prograding, Wax Lake Delta, USA. *Marine Geology*, *453*, 106914. https://doi.org/10.1016/j.margeo.2022.106914

Kong, X., He, Q., Yang, B., He, W., Xu, F., Janssen, A. B., Kuiper, J. J., van Gerven, L., Qin, N., Jiang, Y., Liu, W., Yang, C., Bai, Z., Zhang, M., Kong, F., Janse, J. H., & Mooij, W. M. (2017). Hydrological regulation drives regime shifts: Evidence from paleolimnology and ecosystem modeling of a large shallow Chinese lake. *Global Change Biology*, *23*(2), 737–754. https://doi.org/10.1111/gcb.13416

Lamb, A. L., Wilson, G. P., & Leng, M. J. (2006). A review of coastal palaeoclimate and relative sea-level reconstructions using δ^{13}C and C/N ratios in organic material. *Earth-Science Reviews*, *75*(1–4), 29–57. https://doi.org/10.1016/j.earscirev.2005.10.003

Leavitt, P. R., Fritz, S. C., Anderson, N. J., Baker, P. A., Blenckner, T., Bunting, L., Catalan, J., Conley, D. J., Hobbs, W. O., Jeppesen, E., Korhola, A., McGowan, S., RÜhland, K., Rusak, J. A., Simpson, G. L., Solovieva, N., & Werne, J. (2009). Paleolimnological evidence of the effects on lakes of energy and mass transfer from climate and humans. *Limnology and Oceanography*, *54*(6part2), 2330–2348. https://doi.org/10.4319/lo.2009.54.6_part_2.2330

Li, J. B., Yin, H., Lu, C. Z., & Zhou, H. (2009). Sedimentation effects of the Dongting Lake area. *Journal of Geographical Sciences*, *19*, 287–298. https://doi.org/10.1007/s11442-009-0287-6

Li, Y., Brando, P. M., Morton, D. C., Lawrence, D. M., Yang, H., & Randerson, J. T. (2022). Deforestation-induced climate change reduces carbon storage in remaining tropical forests. *Nature Communications*, *13*(1), 1964. https://doi.org/10.1038/s41467-022-29601-0

Li, Z., Wu, Y., Yang, L., Du, J., Deng, B., & Zhang, J. (2020). Carbon isotopes and lignin phenols for tracing the floods during the past 70 years in the middle reach of the Changjiang River. *Acta Oceanologica Sinica*, *39*(4), 33–41. https://doi.org/10.1007/s13131-020-1543-y

Lin, Q., Zhang, K., McGowan, S., Capo, E., & Shen, J. (2021). Synergistic impacts of nutrient enrichment and climate change on long-term water quality and ecological dynamics in contrasting shallow-lake zones. *Limnology and Oceanography*, *66*(9), 3271–3286. https://doi.org/10.1002/lno.11878

Lin, T. W., Kaboth-Bahr, S., Bahr, A., Yamoah, K. A., Su, C. C., Wang, L. C., Wang, P. L., & Löwemark, L. (2023). Disentangling the impact of anthropogenic and natural processes on the environment in a subtropical subalpine lake catchment in northeastern Taiwan over the past 150 years. *Science of the Total Environment*, *866*, 161300. https://doi.org/10.1016/j.scitotenv.2022.161300

Liu, H., Xu, X., Lin, Z., Zhang, M., Mi, Y., Huang, C., & Yang, H. (2016). Climatic and human impacts on quasi-periodic and abrupt changes of sedimentation rate at multiple time scales in Lake Taihu, China. *Journal of Hydrology*, *543*, 739–748. https://doi.org/10.1016/j.jhydrol.2016.10.046

Liu, J., Chen, J., Chen, S., Yan, X., Dong, H., & Chen, F. (2022). Dust storms in northern China and their significance for the concept of the Anthropocene. *Science China Earth Sciences*, *65*(5), 921–933. https://doi.org/10.1007/s11430-021-9889-8

Liu, X. J., Min, F. Y., & Kettner, A. J. (2019). The impact of large to extreme flood events on floodplain evolution of the middle and lower reaches of the Yangtze River, China. *Catena*, *176*, 394–409. https://doi.org/10.1016/j.catena.2019.01.027

Loewen, C. J. G. (2023). Lakes as model systems for understanding global change. *Nature Climate Change*, *13*(4), 304–306. https://doi.org/10.1038/s41558-023-01624-5

Ma, X., Wu, D., Liang, Y., Yuan, Z., Wang, T., Li, Y., & Gyatso, N. N. (2022). Changes in regional religious activities in the last millennium recorded by black carbon in Lake Dalzong, northeastern Tibetan Plateau. *Science China Earth Sciences*, *66*(2), 303–315. https://doi.org/10.1007/s11430-022-9982-1

Mammides, C. (2020). A global assessment of the human pressure on the world's lakes. *Global Environmental Change*, *63*, 102084. https://doi.org/10.1016/j.gloenvcha.2020.102084

Martins, C. C., Adams, J. K., Yang, H., Shchetnikov, A. A., Di Domenico, M., Rose, N. L., & Mackay, A. W. (2023). Earthquake, floods and changing land use history: A 200-year overview of environmental changes in Selenga River basin as indicated by n-alkanes and related proxies in sediments from shallow lakes. *Science of the Total Environment*, *873*, 162245. https://doi.org/10.1016/j.scitotenv.2023.162245

McLauchlan, K. K., Williams, J. J., & Engstrom, D. R. (2013). Nutrient cycling in the palaeorecord: Fluxes from terrestrial to aquatic ecosystems. *The Holocene*, *23*(11), 1635–1643. https://doi.org/10.1177/0959683613496289

Mills, K., Schillereff, D., Saulnier-Talbot, É., Gell, P., Anderson, N. J., Arnaud, F., Dong, X., Jones, M., McGowan, S., Massaferro, J., Moorhouse, H., Perez, L., & Ryves, D. B. (2017). Deciphering long-term records of natural variability and human impact as recorded in lake sediments: A palaeolimnological puzzle. *Wiley Interdisciplinary Reviews: Water*, *4*(2), e1195. https://doi.org/10.1002/wat2.1195

Monastersky, R. (2015). Anthropocene: The human age. *Nature*, *519*(7542), 144–147. https://doi.org/10.1038/519144a

Morales, M. S., Cook, E. R., Barichivich, J., Christie, D. A., Villalba, R., LeQuesne, C., Srur, A. M., Ferrero, M. E., González-Reyes, Á., Couvreux, F., Matskovsky, V., Aravena, J. C., Lara, A., Mundo, I. A., Rojas, F., Prieto, M. R., Smerdon, J. E., Bianchi, L. O., Masiokas, M. H., & Boninsegna, J. A. (2020). Six hundred years of South American tree rings reveal an increase in severe hydroclimatic events since mid-20th century. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(29), 16816–16823. https://doi.org/10.1073/pnas.2002411117

Mottl, O., Grytnes, J.-A., Seddon, A. W. R., Steinbauer, M. J., Bhatta, K. P., Felde, V. A., Flantua, S. G. A., & Birks, H. J. B. (2021). Rate-of-change analysis in paleoecology revisited: A new approach. *Review of Palaeobotany and Palynology*, *293*, 104483. https://doi.org/10.1016/j.revpalbo.2021.104483

O'Beirne, M. D., Werne, J. P., Hecky, R. E., Johnson, T. C., Katsev, S., & Reavie, E. D. (2017). Anthropogenic climate change has altered primary productivity in Lake Superior. *Nature Communications*, *8*, 15713. https://doi.org/10.1038/ncomms15713

Oleksy, I. A., Baron, J. S., Leavitt, P. R., & Spaulding, S. A. (2020). Nutrients and warming interact to force mountain lakes into unprecedented ecological states. *Proceedings of the Royal Society B*, *287*(1930), 20200304. https://doi.org/10.1098/rspb.2020.0304

Olson, D. M., & Dinerstein, E. (2002). The Global 200: Priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden*, *89*(2), 199–224. https://doi.org/10.2307/3298564

Parnell, A. C., Haslett, J., Allen, J. R. M., Buck, C. E., & Huntley, B. (2008). A flexible approach to assessing synchroneity of past events using Bayesian reconstructions of sedimentation history. *Quaternary Science Reviews*, *27*(19–20), 1872–1885. https://doi.org/10.1016/j.quascirev.2008.07.009

Pendrill, F., Gardner, T. A., Meyfroidt, P., Persson, U. M., Adams, J., Azevedo, T., Bastos Lima, M. G., Baumann, M., Curtis, P. G., De Sy, V., Garrett, R. D., Godar, J., Goldman, E. D., Hansen, M. C., Heilmayr, R., Herold, M., Kuemmerle, T., Lathuilliere, M. J., Ribeiro, V., … West, C. (2022). Disentangling the numbers behind agriculture-driven tropical deforestation. *Science*, *377*(6611), eabm9267. https://doi.org/10.1126/science.abm9267

Poraj-Górska, A. I., Żarczyński, M. J., Ahrens, A., Enters, D., Weisbrodt, D., & Tylmann, W. (2017). Impact of historical land use changes on lacustrine sedimentation recorded in varved sediments of Lake Jaczno, northeastern Poland. *Catena*, *153*, 182–193. https://doi.org/10.1016/j.catena.2017.02.007

Rahman, A., Rathi, A., Nambiar, R., Mishra, P. K., Anoop, A., Bhushan, R., & Kumar, S. (2021). Signatures of natural to anthropogenic transition in lake sediments from the Central Himalaya using stable isotopes. *Applied Geochemistry*, *134*, 105095. https://doi.org/10.1016/j.apgeochem.2021.105095

Ran, F., Nie, X., Wang, S., Liao, W., & Li, Z. (2023). Evolutionary patterns of the sedimentary environment signified by grain size characteristics in Dongting Lake during the last century. *Journal of Lake Science*, *35*(3), 1111–1125. https://doi.org/10.18307/2023.0328

Ran, F., Nie, X., Wang, S., Xiao, T., Yang, C., Liu, Y., Wang, L., Liu, Y., Chu, X., Li, Z., & Li, Z. (2023). A significant loop of lake sedimentation state links catchment eco-surroundings and lake biogenic regime shifts. *Limnology and Oceanography*, *68*(8), 1775–1790. https://doi.org/10.1002/lno.12385

Rodriguez-Miret, X., Del Carmen Trapote, M., Sigro, J., & Vegas-Vilarrubia, T. (2023). Diatom responses to warming, heavy rains and human impact in a Mediterranean lake since the preindustrial period. *Science of the Total Environment*, *884*, 163685. https://doi.org/10.1016/j.scitotenv.2023.163685

Rose, N. L., Morley, D., Appleby, P. G., Battarbee, R. W., Alliksaar, T., Guilizzoni, P., Jeppesen, E., Korhola, A., & Punning, J.-M. (2010). Sediment accumulation rates in European lakes since AD 1850: Trends, reference conditions and exceedence. *Journal of Paleolimnology*, *45*(4), 447–468. https://doi.org/10.1007/s10933-010-9424-6

Sabatier, P., Moernaut, J., Bertrand, S., Van Daele, M., Kremer, K., Chaumillon, E., & Arnaud, F. (2022). A review of event deposits in Lake sediments. *Quaternary*, *5*(3), 34. https://doi.org/10.3390/quat5030034

Saint-Laurent, D., Lavoie, L., Drouin, A., St-Laurent, J., & Ghaleb, B. (2010). Floodplain sedimentation rates, soil properties and recent flood history in southern Québec. *Global and Planetary Change*, *70*(1–4), 76–91. https://doi.org/10.1016/j.gloplacha.2009.11.009

Sanchez, G. (2013). PLS path modeling with R. *Berkeley: Trowchez Editions*, *383*(2013), 551.

Schiefer, E., Menounos, B., & Slaymaker, O. (2006). Extreme sediment delivery events recorded in the contemporary sediment record of a montane lake, southern Coast Mountains, British Columbia. *Canadian Journal of Earth Sciences*, *43*(12), 1777–1790. https://doi.org/10.1139/e06-056

Schneider, H., Höfer, D., Irmler, R., Daut, G., & Mäusbacher, R. (2010). Correlation between climate, man and debris flow events—A palynological approach. *Geomorphology*, *120*(1–2), 48–55. https://doi.org/10.1016/j.geomorph.2009.09.014

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., & Zhou, B. (2023). Weather and climate extreme events in a changing climate. In C. Intergovernmental Panel on Climate (Ed.), *Climate change 2021—The physical science basis: Working group I contribution to the sixth assessment report of the intergovernmental panel on climate change* (pp. 1513–1766). Cambridge University Press.

Shimoda, Y., Azim, M. E., Perhar, G., Ramin, M., Kenney, M. A., Sadraddini, S., Gudimov, A., & Arhonditsis, G. B. (2011). Our current understanding of lake ecosystem response to climate change: What have we really learned from the north temperate deep lakes? *Journal of Great Lakes Research*, *37*(1), 173–193. https://doi.org/10.1016/j.jglr.2010.10.004

Simon, M. P., Schatz, M., Böhm, L., Papp, I., Grossart, H. P., Andersen, T. J., Bálint, M., & Düring, R. A. (2023). Dissent in the sediment? Lake sediments as archives of short- and long-range impact of anthropogenic activities in northeastern Germany. *Environmental Science and Pollution Research*, *30*(36), 85867–85888. https://doi.org/10.1007/s11356-023-28210-8

Simpsona, G. L., & Anderson, N. J. (2009). Deciphering the effect of climate change and separating the influence of confounding factors in sediment core records using additive models. *Limnology and Oceanography*, *54*(6part2), 2529–2541. https://doi.org/10.4319/lo.2009.54.6_part_2.2529

Smol, J. P. (2010). The power of the past: Using sediments to track the effects of multiple stressors on lake ecosystems. *Freshwater Biology*, *55*(s1), 43–59. https://doi.org/10.1111/j.1365-2427.2009.02373.x

Sun, Y., Nie, X., Li, Z., Wang, S., Chen, J., & Ran, F. (2021). The applicability of commonly-used tracers in identifying eroded organic matter sources. *Journal of Hydrology*, *603*, 126949. https://doi.org/10.1016/j.jhydrol.2021.126949

Syvitski, J., Waters, C. N., Day, J., Milliman, J. D., Summerhayes, C., Steffen, W., Steffen, W., Zalasiewicz, J., Cearreta, A., Gałuszka, A., Hajdas, I., Head, M. J., Leinfelder, R., McNeill, J. R., Poirier, C., Rose, N. L., Shotyk, W., Wagreich, M., & Hajdas, I. (2020). Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch. *Communications Earth & Environment*, *1*(1), 1–13. https://doi.org/10.1038/s43247-020-00029-y

Walton, R. E., Moorhouse, H. L., Roberts, L. R., Salgado, J., Ladd, C. J. T., Do, N. T., Panizzo, V. N., Van, P. D. T., Downes, N. K., Trinh, D. A., McGowan, S., Taylor, S., & Henderson, A. C. G. (2023). Using lake sediments to assess the long-term impacts of anthropogenic activity in tropical river deltas. *The Anthropocene Review*. (In press) https://doi.org/10.1177/20530196231204334

Wang, J., Wu, J., Zhan, S., & Zhou, J. (2021). Records of hydrological change and environmental disasters in sediments from deep Lake Issyk-Kul. *Hydrological Processes*, *35*(4), e14136. https://doi.org/10.1002/hyp.14136

Wang, S., Li, H., Wei, X., Zhu, N., Sun, P., Xia, L., Tang, C., Han, Q., Zhang, G., Liu, C., Wang, X., Dolfing, J., Wu, Y., Peñuelas, J., & Zhu, Y. G. (2020). Dam construction as an important anthropogenic activity disturbing soil organic carbon in affected watersheds. *Environmental Science & Technology*, *54*(13), 7932–7941. https://doi.org/10.1021/acs.est.9b06304

Wang, S., Nie, X., Ran, F., Liao, W., Yang, C., Xiao, T., Liu, Y., Liu, Y., & Li, Z. (2023). Human activities control the source of eroded organic carbon in lake sediments over the last 100 years: Evidence from stable isotope fingerprinting. *Fundamental Research*. (In press) https://doi.org/10.1016/j.fmre.2023.04.015

Wang, Y., Huang, Y., Tian, J., Li, C., Yu, K., Zhang, M., Lang, X., & Sun, T. (2021). A sediment record of terrestrial organic matter inputs to Dongting Lake and its environmental significance from 1855 to 2019. *Ecological Indicators*, *130*, 108090. https://doi.org/10.1016/j.ecolind.2021.108090

Waters, C. N., Williams, M., Zalasiewicz, J., Turner, S. D., Barnosky, A. D., Head, M. J., Wing, S. L., Wagreich, M., Steffen, W., Summerhayes, C. P., Cundy, A. B., Zinke, J., Fiałkiewicz-Kozieł, B., Leinfelder, R., Haff, P. K., McNeill, J. R., Rose, N. L., Hajdas, I., McCarthy, F. M. G., & Jeandel, C. (2022). Epochs, events and episodes: Marking the geological impact of humans. *Earth-Science Reviews*, *234*, 104171. https://doi.org/10.1016/j.earscirev.2022.104171

Wen, K., & Zeng, Q. (2006). *China meteorological disaster dictionary Hunan volume*. Meteorological Press.

Williamson, C. E., Saros, J. E., Vincent, W. F., & Smol, J. P. (2009). Lakes and reservoirs as sentinels, integrators, and regulators of climate change. *Limnology and Oceanography*, *54*(6), 2273–2282. https://doi.org/10.4319/lo.2009.54.6_part_2.2273

Witze, A. (2023). This quiet lake could mark the start of a new Anthropocene epoch. *Nature*, *619*(7970), 441–442. https://doi.org/10.1038/d41586-023-02234-z

Wood, S. N. (2017). *Generalized additive models: An introduction with R* (2nd ed.). Chapman and Hall/CRC.

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth and Environment*, *1*(8), 388–403. https://doi.org/10.1038/s43017-020-0067-5

Xiao, T., Ran, F., Li, Z., Wang, S., Nie, X., Liu, Y., Yang, C., Tan, M., & Feng, S. (2023). Sediment organic carbon dynamics response to land use change in diverse watershed anthropogenic activities. *Environment International*, *172*, 107788. https://doi.org/10.1016/j.envint.2023.107788

Yang, L., Wang, L., Yu, D., Yao, R., Li, C. A., He, Q., Wang, S., & Wang, L. (2020). Four decades of wetland changes in Dongting Lake using Landsat observations during 1978–2018. *Journal of Hydrology*, *587*, 124954. https://doi.org/10.1016/j.jhydrol.2020.124954

Yang, Y., Zheng, J., Zhu, L., Zhang, H., & Wang, J. (2022). Influence of the Three Gorges Dam on the transport and sorting of coarse and fine sediments downstream of the dam. *Journal of Hydrology*, *615*, 128654. https://doi.org/10.1016/j.jhydrol.2022.128654

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J.-F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743–749. https://doi.org/10.1126/science.abo2812

Yu, S., Wang, L., Xia, W., Yu, D., Li, C. A., & He, Q. (2020). Spatio-temporal evolution of riparian lakes in Dongting Lake area since the late Qing Dynasty. *Acta Geographica Sinica*, *75*(11), 2346–2361. https://doi.org/10.11821/dlxb202011006

Yu, Y., Mei, X., Dai, Z., Gao, J., Li, J., Wang, J., & Lou, Y. (2018). Hydromorphological processes of Dongting Lake in China between 1951 and 2014. *Journal of Hydrology*, *562*, 254–266. https://doi.org/10.1016/j.jhydrol.2018.05.015

Zhan, W., Yang, S., Liu, X., Li, J., & Choi, M. (2010). Reconstruction of flood events over the last 150 years in the lower reaches of the Changjiang River. *Chinese Science Bulletin*, *55*, 2268–2274. https://doi.org/10.1007/s11434-010-3263-8

Zhang, K., Yang, X., Xu, M., Lin, Q., Kattel, G., & Shen, J. (2018). Confronting challenges of managing degraded lake ecosystems in the Anthropocene, exemplified from the Yangtze River Basin in China. *Anthropocene*, *24*, 30–39. https://doi.org/10.1016/j.ancene.2018.11.001

Zhang, Q., Dong, X., Chen, Y., Yang, X., Xu, M., Davidson, T. A., & Jeppesen, E. (2018). Hydrological alterations as the major driver on environmental change in a floodplain Lake Poyang (China): Evidence from monitoring and sediment records. *Journal of Great Lakes Research*, *44*(3), 377–387. https://doi.org/10.1016/j.jglr.2018.02.003

Zhao, X., Fan, X., Griffis, T. J., Xiao, K., Li, X., Liu, Y., Lai, X., Wan, R., & Li, T. (2023). Three Gorges Dam operations affect the carbon dioxide budget of a large downstream connected Lake. *Geophysical Research Letters*, *50*(12), e2022GL102697. https://doi.org/10.1029/2022gl102697

Zhu, T., Wang, X., Lin, H., Ren, J., Wang, C., & Gong, P. (2020). Accumulation of pollutants in proglacial lake sediments: Impacts of glacial meltwater and anthropogenic activities. *Environmental Science & Technology*, *54*(13), 7901–7910. https://doi.org/10.1021/acs.est.0c01849

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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