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Chronology and Nutrients Change in Recent Sediment of Taihu Lake, Lower Changjiang River Basin, East China

YAO Shuchun[1], XUE Bin[1], KONG Deyang[2]
(*1. State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China; 2. Nanjing Institute of Environmental Sciences, Ministry of Environmental Protection, Nanjing 210042, China*)

Abstract: Two short sediment cores named ZS and THS dated by the ^{210}Pb or ^{137}Cs method were collected from the northwest and southwest of Taihu Lake respectivly, and total organic carbon (TOC) and nutrients including total nitrogen (TN) and total phosphorus (TP) were determined to analyze the chronology and nutrients change in recent sediment. The results show that ^{137}Cs activities are low (less than 15 Bq/kg) in the two cores, attributed to the ^{137}Cs migration. Based on ^{210}Pb constant rate of supply (CRS) model, the sedimentation accumulation rates range from 0.13 g/(cm^2•yr) to 0.76 g/(cm^2•yr) in the ZS core, and from 0.10 g/(cm^2•yr) to 0.56 g/(cm^2•yr) in the THS core. A remarkable increase in organic matter and nutrients has occurred in the two dated cores since the mid-1980s. The historical changes of organic matter and nutrients in the two cores are consisitent with the monitoring data for surface sediment after the 1960s. The TP accumulation rates after the early 1980s are 0.97 and 0.92 times higher than those from the 1950s to the 1980s in ZS and THS cores, respectively. Higher TP concentrations in the past two-decade deposits of Taihu Lake are due to both diagenetic factors and human activities.

Keywords: ^{210}Pb; ^{137}Cs; Taihu Lake; nutrient; sediment

1 Introduction

Most lakes in the eastern China are now facing eutrophic or high trophic problems at different levels (Qin, 2007). This is due to increased external loadings from catchments in the past decades when China experienced a rapid social progress and economic growth, particularly in the populated and developed region of the mid-lower reaches of the Changjiang (Yangtze) River Basin (Qu *et al*., 2001; Yang *et al*., 2006; Wu *et al*., 2008). Thus, it is scientifically necessary to understand the original environment conditions of the lakes and the water quality changes in the past years.

Monitoring data of lakes can provide useful information on the current status or the historical changes of water and sediment quality. However, the available monitoring records on the lakes around the mid-lower reaches of the Changjiang River only extended to the last two decades, and it is too short to cover the very beginning period of the water deterioration. Given that long-term monitoring data are often lacking, palaeolimnological methods have been employed to reconstruct the history of lake environment in many studies (Mônica and Carlos, 2002; Punning and Leeben, 2003), and such information is essential before any remedial methods are considered (Battarbee, 1999). Sediment as sink of nutrients is able to give information of trends in trophic status of lakes (Brenner *et al*., 2001; Smoak and Swarzenski, 2004).

Chronology is important for reconstructing past environment changes. Natural radionuclide (^{210}Pb) has been widely used for dating the sediment of lake, and artificial radionuclide (^{137}Cs) for confirming the age of ^{210}Pb. There are two models applying for the calculation of sediment ages (Appleby, 2001). One is constant initial concentration (CIC) model which is suitable for calculating constant sediment accumulation rates (SAR), and the other is constant rate of supply (CRS) model which is appropriate for calculating SAR variation over time.

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Corresponding author: XUE Bin. E-mail: bxue@niglas.ac.cn

Taihu Lake is a large shallow lake situated in the lower reaches of the Changjiang River basin. The lake area is significant in the eastern China, as it supports more than 60 million people (600–900 person/km^2) (Chen and Wang, 1999). Previous studies have discussed the impacts of direct inputs of pollutants from municipal and industrial waste water and domestic sewage into Taihu Lake (Qin *et al.*, 2004). Research on the lake sediment has shown that the western Taihu Lake basin had gone through a long history of 11 000 yr (Wang *et al.*, 2001), and some recent work on the short cores from Taihu Lake have proved that atmospheric pollution has become increasingly serious in the last 40 to 50 years (Rose *et al.*, 2004). The eutrophication history of the lake could be traced by the analysis of diatoms (Dong *et al.*, 2008) or isotopes (Wu *et al.*, 2007). The nutrient enrichment in the sediment of Taihu Lake has recently aroused special attention of the scientific community, due to its relationship with the severe eutrophication (Qin *et al.*, 2007).

In this study, two cores from Taihu Lake were collected and organic matter (TOC) and nutrients including total nitrogen (TN) and total phosphorus (TP) were analyzed for understanding the historical change of nutrients in recent sediment. The nutrient change trends observed in the sediment cores were also compared with the monitoring data of the past 50 years so as to know whether these changes could be used for reconstructing eutrophication history in large shallow lakes.

2 Materials and Methods

2.1 Study area

Taihu Lake in Jiangsu Province, located in the lower reaches of the Changjiang River basin of China, is one of the five largest freshwater lakes (Shun *et al.*, 1987). The lake covered an area of 2 550 km^2 in the early 1950s. High sedimentation in the eastern part of the lake and the expanding farming activities since then reduced the lake area into the current 2 338 km^2 (Sun *et al.*, 1987). Controlled by monsoon climate, the area receives a moderately high precipitation of 905–1956 mm/yr, of which about 37% concentrates in summer. The average annual evaporation is about 1 001 mm, and the annual average temperature is 16℃. Frost-free period is about 220 to 246 days a year and the average annual sunshine time is around 2 000 h (Wang and Dou, 1998).

Freshwater and fertile soil derived from the upper reaches of the Changjiang River nursed the earliest civilization in the eastern coast of China (Wang *et al.*, 2001). Rapid development in the surrounding rural area during the past two decades has created a better life for the people, however, it also causes some serious environmental issues such as the discharge of untreated industrial and domestic sewage. The water quality of Taihu Lake has degraded about 2 to 3 levels from the 1970s to the 1990s based on China water quality standard (Qin, 2002).

2.2 Sampling

Two short cores were collected from Taihu Lake (Fig. 1), and the interval was 0.5 cm or 1 cm. One core named THS (31°4′56″N, 120°5′52″E) with a length of 78 cm was taken from the southwestern part in 2003, and the other named ZS (31°21′27″N, 120°1′59″E), nearly 50 cm long, was from the northwestern part in 2005. The reason for choosing these two sites is based on past studies on this lake (Qu *et al.*, 2001), and these two sites may represent two major sources of pollutant from the southwestern West Tiaoxi River and the northwestern Yili River, respectively.

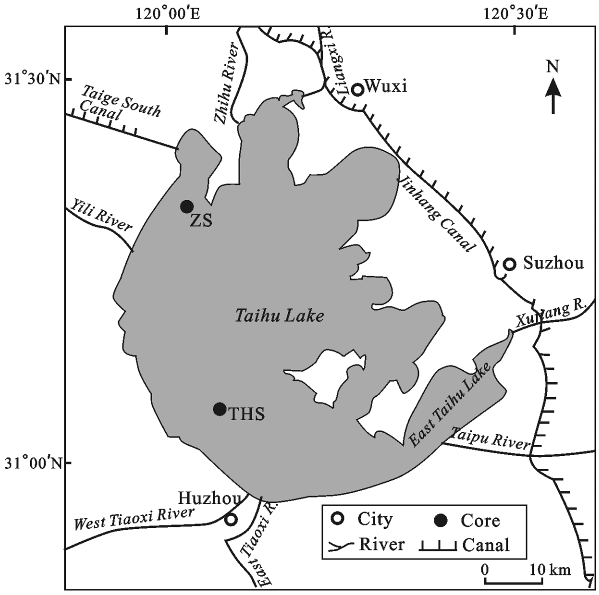


Fig. 1 Location sketch of sampling sites

2.3 Sediment analysis

TOC was determined using the concentrated sulfuric acid-potassium dichromate digestion method. TN was measured by the Kjeldahl technique, and TP was measured by colorimetric analysis treated with molybdenum blue reagent (Institute of Soil Science, Chinese Academy of Sciences, 1978; Professional Committee of Agricultural Chemistry of Chinese Society for Soil Sciences, 1983).

2.4 Estimation of sediment age

Sediment age was estimated using ^{210}Pb and ^{137}Cs, determined with gamma Spectrometry (GWL-120230, EG and G Ortec, USA). ^{137}Cs was measured at 662 keV, while ^{210}Pb was determined via gamma emission at 46.5 keV and ^{226}Ra (supported ^{210}Pb) at 295 and 352 keV γ-rays emitted by its daughter isotope ^{214}Pb (Wan *et al.*, 1987).

The CIC and CRS models can be used for calculating dates from ^{210}Pb activity (Appleby, 2001). The CIC model is:

$$t_x = \lambda^{-1}\ln(C_0/C_x) \tag{1}$$

where t_x is the age in years; λ is the decay constant for ^{210}Pb (0.03114/yr); C_0 is the $^{210}\mathrm{Pb}_{\mathrm{ex}}$ (unsupported ^{210}Pb) activity at the sediment-water interface (Bq/kg); and C_x is the $^{210}\mathrm{Pb}_{\mathrm{ex}}$ activity at depth x in the sedimentary section (Bq/kg).

The CRS model is:

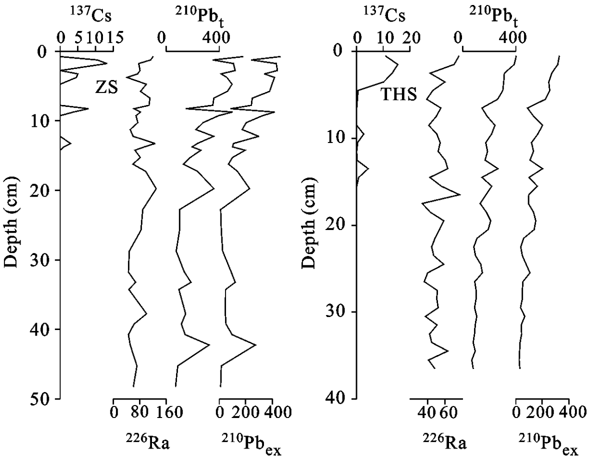
$$t_x = \lambda^{-1}\ln(A_0/A_x) \tag{2}$$

where A_0 is inventory of $^{210}\mathrm{Pb}_{\mathrm{ex}}$ in core (Bq/cm^2); A_x is the inventory of $^{210}\mathrm{Pb}_{\mathrm{ex}}$ below depth x (Bq/cm^2).

3 Results

3.1 Radionuclide and nutrients in ZS core

In Fig. 2, the results of radionuclide analysis including ^{137}Cs, ^{226}Ra and ^{210}Pb of the ZS core are presented. ^{226}Ra profile displays a high and variable distribution (41.26–129.64 Bq/kg) in this core. The profile of unsupported ^{210}Pb activity (10.18–460.64 Bq/kg) is similar to that of total ^{210}Pb activity (70.42–580.34 Bq/kg). The inventory of unsupported ^{210}Pb is 3.84 Bq/cm^2. As shown in Fig. 2, unsupported ^{210}Pb activities present a non-exponential form, so the CRS model rather than the CIC model is used to calculate the sedimentation rates in the core. Sediment accumulation rates are calculated based on mass depth in corresponding interval and its age from ^{210}Pb CRS model, and the results show that the sediment accumulation rates range from 0.13 g/(cm^2•yr) to 0.76 g/(cm^2•yr) in ZS core (Fig. 3). ^{137}Cs shows peaks but not clearly in the profile (Fig. 2), and the first appearance in ^{137}Cs activity is recorded at 13.25 cm in the sediment core. If ^{137}Cs peak in 13.25 cm could be dated as 1963, the calculated sedimentation rate would be 0.31 cm/yr. The result is in agreement with the estimated average sediment rate in the past 50 years based on the CRS model.



$^{210}\mathrm{Pb}_{\mathrm{ex}}$ denotes unsupported ^{210}Pb; $^{210}\mathrm{Pb}_t$ denotes total ^{210}Pb

Fig. 2 ^{137}Cs, ^{226}Ra and ^{210}Pb depth profiles in cores from Taihu Lake (Bq/kg)

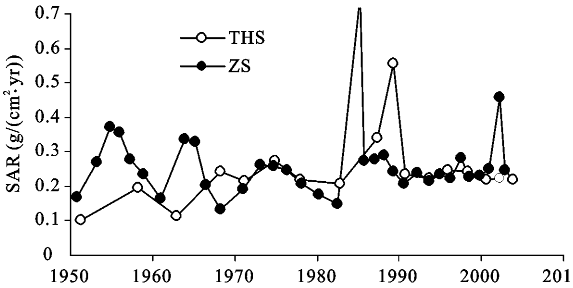


Fig. 3 Sediment accumulation rate (SAR) in past 50 years in Taihu Lake cores

Relative higher concentrations of TOC and nutrients including TN and TP are found in deeper sediment (Fig. 4). Previous studies found that the sediment might be thousand years old (Wang *et al.*, 2001). In recent time, concentrations of TOC, TN and TP are also high, and generally show an increasing trend in the ZS core. Constantly low values (below 5.94 g/kg) of TOC concentrations are found in sediment deposited from 30.25 cm to 56.5 cm, and fluctuate slightly from 5.25 cm to 30.50 cm with an average of 6.50 g/kg, then increase from 6.59 g/kg at 5.25 cm to 9.11 g/kg at 0 cm in sediment. The profile of TN concentrations roughly parallels with that of TOC concentrations. TP concentrations oscillate through the core, however, show an increase in the top 15 cm. Generally, values of TOC/TN molar ratio are stable in the profile except one anomy value at the depth of about 30 cm.

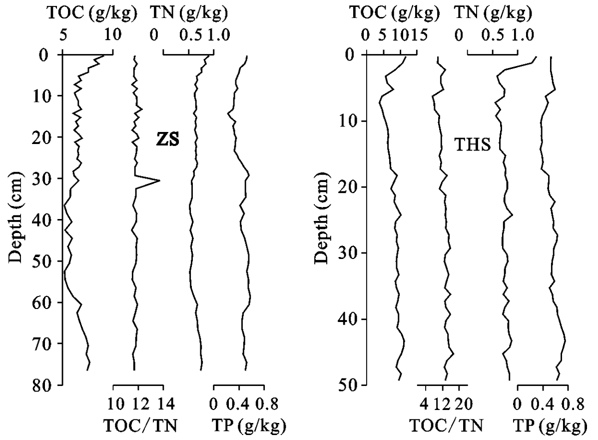


Fig. 4 Variation of TOC, TN, TOC/TN and TP in ZS and THS cores

3.2 Radionuclide and nutrients in THS core

As is shown in Fig. 2, total ^{210}Pb activities range from 67.56 Bq/kg to 404.32 Bq/kg, ^{226}Ra activities is between 34.09 Bq/kg and 76.17 Bq/kg, and unsupported ^{210}Pb activities varies from 26.42 Bq/kg to 328.56 Bq/kg in THS core sediment (Fig. 2). The inventory of unsupported ^{210}Pb was 2.97 Bq/cm^2. The CRS model was also used to calculate the sedimentation rates of the THS core. The sedimentation accumulation rates range from 0.10 g/(cm^2•yr) to 0.56 g/(cm^2•yr) in THS core (Fig. 3). Three peaks of ^{137}Cs are observed in the core. Relatively higher activity of ^{137}Cs occurs in the surface sediment, which indicates recent time immigration of ^{137}Cs (Yao *et al.*, 2006). Using depth recorded in 1963 as the datum level, the average sedimentation rate is calculated to be 0.34 cm/yr, which is consistent with the CRS age.

The changes of TOC, TN and TP in the THS core are generally similar to those in the ZS core. Nutrient concentrations in the uppermost sediment of the THS core are slightly higher than those in the ZS core. In detail, TOC concentrations vary between 3.8 g/kg and 11.2 g/kg, with an average of 8.3 g/kg. The range of TN concentrations is from 0.55 g/kg to 1.37 g/kg， with an average of 0.83 g/kg. The concentrations of TP range from 0.36 g/kg to 0.75 g/kg, with an average of 0.53 g/kg (Fig. 4). The TOC concentrations show an increasing tendency in the top 8 cm sediment, as well as in the top 3 cm for TN concentrations. In general, the profile of TN concentrations is similar to that of TOC concentrations. However, the profile of TP concentrations does not parallel with that of TOC concentrations. TOC/TN pattern of the THS core is different from that of the ZS core, and TOC/TN ratio shows a slightly decrease from bottom to 10 cm and a small subsurface bulge**.**

4 Discussion

4.1 Chronology and sedimentation rate

In this study, ^{137}Cs activities are very low in the two cores, which is consistent with other sites from the Taihu Lake area (Liu *et al.*, 2004; Liu and Wu, 2006). Lower ^{137}Cs activities may be attributed to ^{137}Cs migration. Upcore transference of ^{137}Cs peak of Chernobyl disaster is partially caused by high contents of water and organic matter in the THS core sediment (Yao *et al.*, 2006). ^{226}Ra (supported ^{210}Pb) activities are high and fluctuated, indicating that unsupported ^{210}Pb values should be obtained by subtracting ^{226}Ra from total ^{210}Pb level. The high and variable ^{226}Ra activities in Taihu Lake are similar to the findings in many Florida lakes (Brenner *et al.*, 1999; 2000; 2001). A general decline in the ^{210}Pb activities with increasing sediment depth is observed in Fig. 2, suggesting that the radionuclide can be used to date recent deposits.

Sediment in deep depth is assigned artificially "too old" dates by the CRS model and dates earlier than about 80–100 years ago begin to diverge greatly from the "true" date (Binford, 1990). At Taihu Lake, the deposition process of sediment is complex partly due to the shallow water depth and the large water area, and the deviation time of the sediment of CRS method should be less than 80 years. The first appearance of ^{137}Cs can be used to confirm CRS age only in the early 1950s for lake sediment in this study. Thus the sediment accumulation rates are calculated only since the 1950s in the two cores (Fig. 3). In the two cores, the fluctuation of sedimentation accumulation rates is observed. The highest sedimentation rates are about six times of the lowest in the ZS (0.13 g/(cm^2•yr) to 0.76 g/(cm^2•yr)) and the THS (0.10 g/(cm^2•yr) to 0.56 g/(cm^2•yr)) cores. The inventories of unsupported ^{210}Pb of the THS and ZS cores (2.97 Bq/cm^2 and 3.84 Bq/cm^2) are significantly higher than the estimated average atmospheric flux (1.11Bq/cm^2) based on the measurement of soil cores around Taihu Lake (Yao *et al.*, 2006). It is indicated that there has been sediment focusing to sites ZS and THS. According to recent completed Taihu Lake investigation

(Fan and Zhang, 2009), the Taihu sediment is not uniform. For example, there are no soft sediment in many sites of the Zhushan Bay and the Meiliang Bay, where there should be large amounts of sediment from the local catchment. The sediment can be resuspended and transferred to other places due to the shallow depth of the lake, and the distribution of sediment may be mainly controlled by the catchment source and lake water current.

4.2 Historical change of organic matter and nutrient input to Taihu Lake

TOC/TN can be used to distinguish sedimentary organic matter from aquatic as opposed to land sources (Meyers *et al.*, 1995). Enhanced TOC and slightly varied TOC/TN values in the top 8 cm sediment of the ZS core indicate increasing aquatic-derived and land source organic matter in sediment since the mid 1980s. It is possible that the enhanced nutrient input is biologically available for uptake. Therefore, the increase in nutrient input contributes to a productivity increase within the lake. At the THS site, the 2.0–7.5 cm interval corresponding to 1945–1987 shows a decreasing TOC/TN ratio and TOC concentration, which represents relatively greater input of aquatic material in the lake and decreasing organic matter deposited in the sediment in the core THS. After 1987, TOC and TN showed an upcore increase with a relatively high TOC/TN ratio, which suggested that land-derived organic matter might have left some greater influence.

Increases in TOC and the nutrients accumulation rates are observed after the early 1980s in the two cores (Fig. 5). High bulk sediment accumulation rates are responseble for high rates of nutrient accumulation in some periods (e.g. the mid 1980s of the ZS core). The high nutrients flux in the two cores after the early 1980s agrees well with Chang′s conclusion that accelerated eutrophication began in 1983/1984 in Taihu Lake (Chang, 1996). Rose *et al.* (2004) also reported that nitrogen levels increased dramatically in the northern parts of Taihu Lake from the mid 1980s, which was in agreement with nitrogen concentrations in lake water.

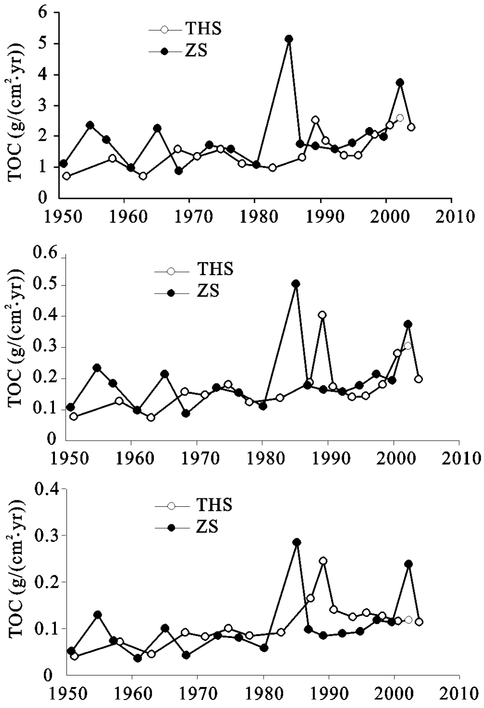


Fig. 5 Changes of TOC, TN and TP accumulation rates in ZS and THS cores

Survey studies have demonstrated a positive correlation between TP concentration of surface sediment and water-column phosphorus concentration (Brenner and Binford, 1988) or phosphorus loading (Sondergaard *et al.*, 1996). Upcore increases in the TP concentrations of lake sediment profiles may reflect increasing phosphor-rus loading through time. Alternatively, higher TP concentrations in very recent deposits of some lakes may have been attributed to diagenetic factors. Higher TP in uppermost deposits is, in part, a consequence of high concentrations of temporarily stored, organic-bound phosphorus (OP) and given time these high TP concentrations will decline as nutrients are released to overlying waters (Sondergaard *et al.*, 1996). It was found that OP concentrations generally increased with decreasing depth in hundreds of cores from Taihu Lake (Yao, 2007). The ratio of OP to TP was less than 35%, and it showed an upcore increase tendency. Average TP accumulation rates after the early 1980s are 0.97 and 0.92 times higher than those from the 1950s to the 1980s in ZS and THS cores, respectively (Fig. 5). Higher TP contents in recent deposits of Taihu Lake result from both diagenetic factors and human activities.

Generally, there was no significant difference in average sediment accumulation rates between the 1950s and the mid 1980s and hereafter in the two cores. Thus the organic matter and nutrients enrichment from the mid 1980s was not due to high sediment loading to the lake, though high bulk sediment accumulation rates were responsible for high rates of nutrient and organic matter accumulation in some periods. Temporal shifts in organic sediment and nutrient accumulation in Taihu Lake are probably attributable to a suite of human-induced watershed modifications. Anthropogenic nutrient inputs to Taihu Lake increased due to population explosion and hence enhanced human activities in the watershed since the 1950s (Hu, 2003), while the change was slight from the 1950s to the 1970s, and inputs were agricultural and household wastes (Chang, 1996). The rapid development since the 1970s probably increased lake eutrophication in the mid 1980s via delivery of nutrient-rich waters from urban storm water runoff and rural septic tanks, so the water quality of Taihu Lake was degraded from the 1970s to the 1990s. Furthermore, agriculture around the lake is likely sources of nutrient-rich runoff within the catchment. Previous studies showed that industrial wastewater contributed 16% of total nitrogen to eutrophication of Taihu Lake, while agricultural non-point source accounted for 59% (Li and Yang, 2004).

Investigation of Taihu Lake from the 1960s showed an increasing tendency of nutrients in surface sediment (Hu, 2003), and the historical changes of nutrients recorded in the two cores were consistent with monitoring data. Trolle *et al.* (2008) found that TP concentrations in surficial sediment were significantly correlated with TP, TN and Chlorophyll *a* concentrations of water column in Taihu Lake. This indicates that nutrients especially TP in the sediment of such a shallow lake can record valuable information of past trophic status.

5 Conclusions

General increase in total organic carbon and nutrient concentrations with decreasing depth in the sediment occurs in recent time in Taihu Lake. The sedimentation accumulation rates in ZS and THS cores ranging from 0.10 g/(cm^2•yr) to 0.76 g/(cm^2•yr) show no trend of recent increase. However, there is remarkable increase in nutrients and organic matter accumulation rates since the mid-1980s in Taihu Lake dated cores. The TP accumulation rates after the early 1980s are 0.97 and 0.92 times higher than those from the 1950s to the 1980s in ZS and THS cores, respectively. Increased delivery of organic matter and nutrient to the lake system can be responsible for the nutrient enrichments in the lake bottom sediment. The upward trend of organic matter and nutrients enriched in the cores indicates that Taihu Lake has become eutrophicated since the mid 1980s. In addition, human activities have exerted great influence on environmental changes of the lake in the last decades. The changes in the organic matter and nutrients in the cores can be used to trace the history of eutrophication and provide insights into pre-disturbance conditions in the lake ecosystem, and assist in environment restoration of lake.

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