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Diatom records in sediments for eutrophication process of lake Xian'nv, China since the mid-20th century

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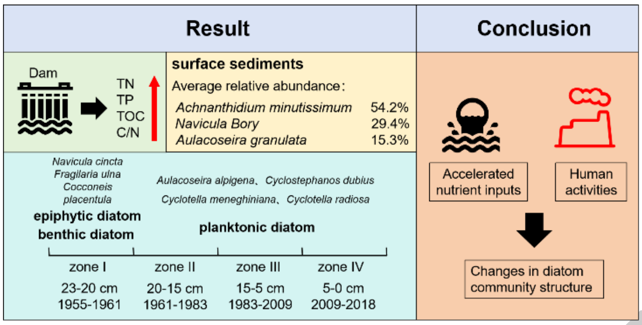
Graphical abstract



Abstract

To well understand the eutrophication process for inland lakes where more lands had been used for agriculture and industry without adequate environmental protections, 9 surface sediments and 1 core sediment in Lake Xian'nv which was located in the middle of Jiangxi Province were chosen. Combined with ^{210}Pb and ^{137}Cs geochronology, nutrient index including total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), Carbon nitrogen ratio (C/N), diatoms assembles and TDI index of eutrophic diatoms were compared quantitatively and conducted to elucidate the eutrophication process using statistical methods. The results showed a total of 155 years from 1863 to 2018 were recorded from the entire sediment core. The nutrient level in 23 centimeters below the surface of the sediment core where was synchronized with reservoir construction indicated TN, TP, TOC, and Carbon nitrogen ratio had been gradually increased since the construction of Dam. In surface sediments, the three diatoms with higher average relative abundance were *Achnanthidium minutissimum*, *Navicula Bory,* and *Aulacoseira granulata* with a value of 54.2 %, 29.4 %, and 15.3 % respectively. Significant changes of the diatom communities from 1955 to2009 had been recorded, where diatom communities could be classified into four distinct periods. In the first few years after the reservoir was built, the dominant diatoms were epiphytic and benthic diatom communities represented by *Navicula cincta*, *Fragilaria ulna,* and *Cocconeis placentula* in zone I on the bottom floor covered from 1955 to 1961. However, planktonic diatom communities were dominant after 1983 which were mainly constituted by *Aulacoseira alpigena*, *Cyclostephanos dubius, Cyclotella meneghiniana,* and *Cyclotella radiosa*. Both TDI index of eutrophic diatoms and Principal Component Analysis (PCA) revealed the succession from benthic diatoms to planktonic diatoms and changes in nutrient levels.

Keywords: Diatom community, sediments, nutrient levels, eutrophication process, lake Xian'nv

1. Introduction

As one of the most important ecosystems, lake could provide various valuable ecological services for local economic and social development, including drinking water, agriculture, fisheries, climate regulation, and flooding control, and also serve for biodiversity providing aesthetic and economic benefits (Dearing *et al.* 2012; Liu et al. 2012; Laj *et al.* 2022). In recent decades, a large number of artificial lakes have been formed along rivers due to the construction of dams, which were aimed at using water energy resources for power generation, navigation, and irrigation (Zhang *et al.* 2021; Serafim-Júnior *et al.* 2016; Etourneau *et al.* 2013). However, urban artificial lakes which were used as urban water resources and characterized by stagnant water bodies, fragile ecosystems, and irregular shapes were more easily affected by interference and rapid urbanization from human activities (Yang *et al.* 2021; Wang *et al.* 2013). These days, many artificial lakes were deteriorating as ecological system degradation, area shrinking, pollution, and eutrophication due to excessive input of sediment, nutrients, heavy metals, and organic pollutants (Huang *et al.* 2020; Wang *et al.* 2012).

Input of nitrogen (N) and phosphorus (P) could also cause a significant increase in algal blooms resulting in eutrophication of the water body (Ly *et al.* 2021; Noges *et al.* 2020; Rast and Thornton 2015). Water eutrophication caused by superfluous nutrient contamination has become one of the most prominent environmental problems on a global scale and poses a health risk for aquatic ecosystems and humans (Zolitschka *et al.* 2015; Jeppesen *et al.* 2010; Cardinale *et al.* 2012). Algal biomass and communities in sediments have been widely used to determine the potential level and source nutrients from agricultural, industrial, and urban discharges. The impact of hydrological conditions and climate changes on the level of algae biomass has also been receiving more attention (Mihaljević *et al.* 2010; Zepernick *et al.* 2023). Long-term environmental monitoring for total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), and algal assembles at the water and sediment was critical for exploring the underlying mechanism of the eutrophication process during different decomposition (Fontana *et al.* 2014).

Fortunately, lake sediments could provide valuable information to elucidate catchment variation and processes, which might reflect lake development and help to reconstruct ecosystems (Costa-Böddeker *et al.* 2012; Yu *et al.* 2022). In paleolimnology, lacustrine sediments preserved information in previous lacustrine periods has been used as an efficient way to reconstruct the environment changes of lake ecosystems lacking long-term historical records by using the stable isotopes and sedimentary bio information (Smol and Caraballo 2008; Gell *et al.* 2005; McGowan *et al.* 2005; Hess *et al.* 2023). Data before area development identified by stable isotopes technology could trace background threshold values and provide a statistical basis for estimating current chemical and physical activities derived from anthropogenic sources (Zhang *et al.* 2018; Liu *et al.* 2012). The sediment deposition rate could also effectively record the erosion intensity and hydrodynamic conditions of the basins (Zhang *et al.* 2018). Diatom communities were particularly sensitive to a range of environmental factors including nutrient status, hydrology, and water quality, which has been used to trace and evaluate historical ecological conditions for lake (Grundell *et al.* 2012; Bhattacharya *et al.* 2016). Therefore, multi-proxy analyses based on lacustrine sedimentary stratigraphy had been increasingly accepted to research and explore the environmental and ecological conditions of lakes (Pillsbury *et al.*2021; Lan *et al.*2018).

Since the 1950s, a great number of reservoirs have been constructed in Jiangxi Province to provide valuable clear fresh water, clean energy, and ecological services for downstream (Huang *et al.* 2017). Located in the northwest of Jiangxi Province, Lake Xian'nv also known as Jiang'kou Reservoir served as a water source for City Xin'yu and a famous scenic spot was appeared through dam construction on the River Yuan in 1958 (Ouyang *et al.* 2018; Zhang *et al.* 2015). However, rapid population growth and economic development in recent decades had exposed the lake ecosystem to a higher risk, including the decline of water quality, eutrophication risk, as well as biodiversity degradation, and water ecological security (Ji *et al.* 2020; Li *et al.* 2022). In order to identify underlying processes and mechanisms, it was necessary to trace the ecological process for both nature and humans in hydrological regimes. However, the lack of long-term monitoring data made it difficult to understand the current state of lake ecology (Zhang *et al.* 2018).

Combined with ^{210}Pb and ^{137}Cs geochronology, stratigraphic records of sedimentary nutrients loading, diatom assemblages, and TDI index of eutrophic diatoms, this paper aimed to identify the eutrophication process synchronized with anthropogenic nutrient loading. The work purposed to (1) establish a high-resolution record of nutrient level; (2) record the diatom assembles shift since reservoir construction; (3) distinguish the stress of four distinct periods on the diatom succession.

2. Materials and methods

2.1. Study area

As illustrated in Figure 1, Lake Xian'nv composed of Qian'yang (upstream) and Wu'long (downstream) and connected by Zhong'shan Gorge was built in 1958 with a surface area of 50 km^2. It was a large subtropical mountain lake reservoir in south China and the second largest reservoir in Jiangxi Province. Originated from Mountain Wugongshan at the western boundary of Jiangxi, River Yuan was a tributary of River Ganjiang, passed through Pingxiang and Yichun cities, and finally entered River Ganjiang from lotus pavilion in Zhangshu City after leaving Longweizhou, Xinxi Township, and Yushui District. The average annual runoff and sand from April to September were 110.94 m^3/s and 450,000 tons respectively, accounting for 68.5% and 84% of annual runoff and sand (Zhang *et al.* 2015). As an important gene pool of subtropical plants, this basin had higher water quality, high species diversity, rich plant species, high forest coverage rate, and good vegetation protection. However, local water quality deterioration and eutrophication have occurred in the reservoir area, as well as abnormal ecosystem security problems in recent years.

2.2. Sediment sampling

Based on the collected data and investigation, 9 benthic diatoms sampling sites (S1-S9) and 1 deposition sampling site (C) were sampled in mid-March 2018. Among them, S1-S5 was collected from the upstream of Lake Qian'yang, and S6-S9 was sampled from Lake Wulong in the downstream. Meanwhile, a 37-cm long sediment core was collected from the northern part of Lake Qian'yang (Figure 1) using a handheld cylindrical gravity corer with an outer diameter of 90 mm (Nanjing Institute of Geography and Limnology, ZZC-90, China). The sampling site of sedimentary columnar samples should meet the following requirements: (1) near the lake center with little interference; (2) avoid disturbance to sediments. The core was immediately sliced into 1cm sections on the shore and all samples were packaged in a self-sealing plastic bag with a serial number predefined by the depth and sites of the samples. After all samples were taken back to the laboratory, they were immediately stored in a refrigerator at -20 °C for further analysis.

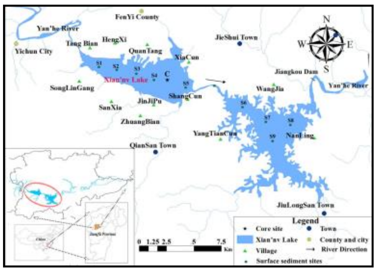


Figure 1. Sampling sites for surface and core sediments from Lake Xian'nv, Jiangxi Province

2.3. Sediment chronology

Pre-processing of samples: (1) 7mL sample tubes were marked according to the samples to be tested, then these tubes were weighed; (2) samples after screening with 100 mesh sieve were then loaded into the tube, and the total weight were weighed; (3) sample mass was equal to the subtraction between total weight and tube weight. Determination of specific activities: the specific activities of ^{210}Pb and ^{137}Cs in the sediments were measured using a Gamma spectrometer (GWL-120-15, ORTEC Corporation, USA). The analytical test was entrusted to the State Key Laboratory of Environment at the Nanjing Institute of Geography and Limnology, Jiangsu province, China. The ^{210}Pb chronologies were calculated using the constant rate of supply (CRS) model, and verified by the highest ^{137}Cs activity in 1963 (Lan *et al.* 2018; Zhang *et al.* 2018).

The corresponding calculation formula was as follows:

$$I_x = I \times e^{-\lambda t}$$

Where, I_x was the accumulation specific activities of ^{210}Pb above depth x ($Bq \cdot cm^{-2}$); I was the total storage volume of ^{210}Pb ($Bq \cdot cm^{-2}$); λ was the decay constant ($0.03114 \cdot a^{-1}$).

The deposition rate of each layer of sediment could be concluded based on the above equation:

$$t = -\frac{1}{\lambda}\ln\left(1 - \frac{I_{x1}}{I}\right)$$

Where, t was the deposition time of each layer (a); I_{x1} was the accumulation specific activities of ^{210}Pb above depth X1 ($Bq \cdot cm^{-2}$); I was the total storage volume of ^{210}Pb ($Bq \cdot cm^{-2}$); λ was the decay constant ($0.03114 \cdot a^{-1}$).

2.4. Chemistry analysis

TOC was determined by potassium dichromate oxidation-spectrophotometry (HJ 615-2011) (Liao *et al.* 2017). Potassium dichromate standard solution and concentrated sulfuric acid were added with 0.3g sieving sample, shaken evenly, put in an oil, and bathed at 185-190℃. After that, an o-phenline indicator was added and then titrated with 0.2mol /L ferrous sulfate solution. TN was determined by the Kay method (HJ 717-2014), in which 0.5g sieving soil sample was dissolved with concentrated sulfuric acid, distillated by an automatic Kjeldahl nitrogen analyzer (K9840, Hanon, China), and titrated with 0.02 mol/L hydrochloric acid standard solution. TP was determined by alkali fusion Molybdenum-antimony anti-spectrophotometry (HJ 632-2011), in which 0.5g sieving soil sample was dissolved with concentrated sulfuric acid and perchloric acid, transferred to 100mL volumetric bottle, and measured by UV-vis spectrophotometer (TU-1950, Persee, China) at 700nm wavelength.

2.5. Diatom identification

Methods mentioned in Battarbee (ECRC) standard diatom treatment methods were used for the pretreatment and preparation of diatom samples: (1) sampling: 0.5g of sediment sample screened with 100 mesh sieve were weighed and put into a 50ml centrifuge test tube; (2): the samples were added hydrochloric acid (HCL) and placed in a 90℃ water bath until no bubbles were reacted; (3) 30% hydrogen peroxide (H_2O_2) was added until the organic matter was removed by heating in the water bath; (4) cleaned with distilled water and centrifuged (2500 RPM /min, 5min each) 3 times; (5) 100μL sample was soaked and dropped on clean slide, covered with gum drop and finally dried into a permanent piece for microscope observation; (6) diatoms were identified and counted using Olympus microscope (CX31) under 100x10x oil lens.

2.6. Data analysis

2.7.1 Diatom index

(1) Relative abundance

At least 300 diatoms were counted in each sample, and the relative abundance P of diatom species was calculated as follows:

$$P = N_{sp} \times 100\% \quad (2\text{-}1)$$

Where, N_{sp} was the total number of diatom species, and N was the total number of diatom species in each sample.

(2) Dominant species

Generally, diatom species account for more than 2% of all diatoms were defined as the dominant species, and the calculation formula was as follows:

$$P_{SP} = \frac{n_{sp}}{n} \times 100\% \quad (2\text{-}2)$$

(3) Diatom abundance

Abundance index D was used to describe the distribution of diatom diversity in the sediment, and the calculation formula was as follows:

$$D = \frac{S-1}{\log_2 N} \quad (2\text{-}3)$$

Where: N was the number of diatom species in the sample, and S was the number of diatom species in the sample.

2.7.2 Statistical methods

Multivariate statistical analysis methods including Hierarchical clustering, principal components analysis (PCA), and Redundancy analysis (RDA) were used to determine the diatom communities, and identify the main drivers of diatom community change. In this research, Excel 2013, SPSS 23.0, Canoco 5.0, Origion 8.5, and Photoshop CS6 were used to process the experimental data and draw graphics. The diatom index TDI was calculated by Omnidia7.5.

3. Results

3.1. Physicochemical properties of sediments

Based on the determination results of sedimentary column C, the vertical profile distribution of specific activity of $^{210}Pb_{ex}$ and ^{137}Cs was shown in Figure 2(A). It could be confirmed from the figure that the $^{210}Pb_{ex}$ specific activity with a value ranging from 52.53 to 229.93 $Bq \cdot kg^{-1}$ presented an irregular zigzag distribution pattern with the increase of depth, indicating significant human activities and the ^{137}Cs profile of activities ranged from 0 to 5.27 $Bq \cdot kg^{-1}$. Labeled with ^{137}Cs, the chronological sequence of the corresponding sedimentary layer identified by the CRS model is shown in Figure 2(B). It could be found from the figure that ^{137}Cs began to appear at a depth of 5cm, and an obvious peak was recorded at a depth of 19cm which was corresponding to 1963. Using the location of the ^{137}Cs accumulation peak to calculate the sediment deposition rate, the measured age of the column sample was 155 years in total, corresponding to 1863-2018, and the sediment deposition rate ranged from 0.03 to 0.58 g·cm·yr^{-1} with an average value of 0.12 g·cm·yr^{-1}.

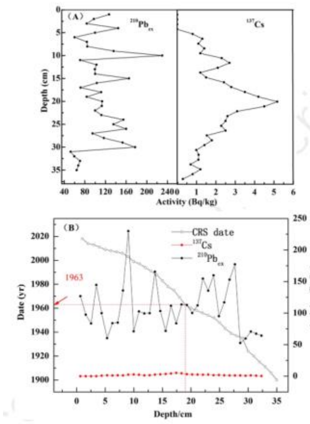


Figure 2. Activities of 210Pb and 137Cs along the depth of sediment core from Lake Xian'nv (A), time scale of sediment core of Lake Xian'nv inverted by 210Pb and 137Cs (B)

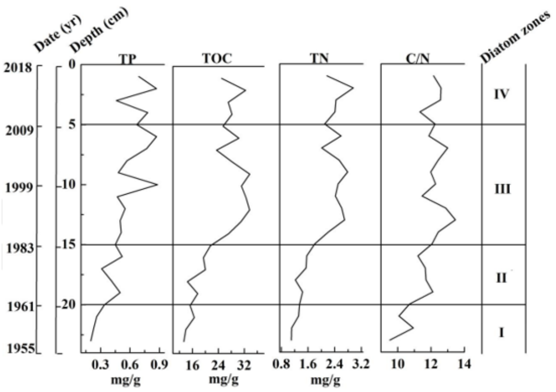


Figure 3. Stratigraphic plots of geochemical and physical parameters of TP, TOC, TN, and C/N in the Xian'nv Lake

The average values of nutrient indexes including TP, TOC, and TN in surface sediments were 0.52, 25.43, and 2.76 mg·g^{-1}. These indexes in sediment column C are illustrated in Figure 3. Along the vertical section of the sedimentary column, the indexes showed similar trends and gradually increased from bottom to top. Of these, the content of TP was varied from 0.31 to 0.88 mg·g^{-1} with an average of 0.56 mg·g^{-1}. The TOC content ranged from 13.37 to 33.65 mg·g^{-1}, and the TN content ranged from 1.1 to 2.96 mg·g^{-1}. The average values of TOC and TN were 24.41 mg·g^{-1} and 2.04 mg·g^{-1} respectively. The C/N ratios fluctuated between 9.53 and 13.46 with an average value of 11.86. Combined with the clustering of diatoms and the distribution characteristics of nutrient indexes, the nutrient indexes of the sediment column from bottom to top were divided into four assemblage zones, including zone I (23-20 cm, 1955-1961), zone II (20-15 cm,1961-1983), zone III (15-5 cm, 1983-2009) and surface zone IV (5-0 cm, 2009-2018).

Generally, TP, TOC, and TN contents in Zone I were the lowest, and the average C/N ratio was 10.32. After that, TP, TOC, and TN in Zone II with the depth among 20 to 15cm from bottom to top showed a fluctuating upward trend, and maintained at a low level on a whole. The average value of C/N in this period was 11.74, which was higher than that in combination zone I. However, the contents of TOC, TN, and TP in Zone III with a depth from 15 to 5 cm reached the maximum value in the sediment core, and the C/N ratio was also recorded at the highest level with an average ratio of 12.37. Compared with Zone III, the level of nutrient indexes in Zone IV decreased slightly and the C/N ratio of this belt was lower than that of the down belt with an average value of 12.18.

3.2. Diatom community characteristics in surface sediments

Based on the analysis of benthic diatom communities from surface sediments S1-S9, 68 species, 16 genera, 9 families, 5 orders, and 2 classes were identified, as listed in Table 1. Diatoms were mainly composed of *Centricae* and *Pennatae*, of which *Centricae* has 11 species, 4 genera, 1 family, and 1 order, belonging to *Coscinodiscaceae*. There were 4 orders, 8 families, 12 genera, and 57 species of *Pennatae*, including *Araphidiales*, *Raphidionales*, *Monoraphidales* and *Aulonoraphidinales*. According to the classification and statistics of diatoms, the species of *Raphidionales* were the most, reaching 38 species, followed by 11 species of *Coscinodiscaceae*, 7 species of *Araphidiales*, 6 species of *Aulonoraphidinales* and 6 species of *Monoraphidales*. Among all families, *Naviculaceae* had the largest number of species, reaching 29 species, followed by 11 species of *Coscinodicaceae* and 7 species of *Fragilariaceae*, accounting for 42.6%, 16.2%, and 10.3% of the total respectively. Among all genera, *Navicula Bory* had the largest number of species, accounting for 20 species, followed by 5 species of *Pinnularia Ehrenberg* and 4 species of *Cyclotella Kutzing*, accounting for 29.4%, 7.4% and 5.9% of the total respectively.

In benthic diatoms, *Achnathidium minutissimum* was the absolute dominant species with the highest relative abundance of 67.2% and the average relative abundance of 54.2%. *Aulacoseira granulata* was another dominant species with the average relative abundance of 15.3%. Besides, there were dominant genera and species, including *Navicula Bory* with an average relative abundance of 29.4%. The average relative abundances of the other common generas, including *Pinnularia Ehrenberg*, *Gomphonema Ehrenberg*, *Nitzschia Hassall,* and *Fragilaria Lyngbye*, were less than 10%. The dominant species of benthic diatoms were *Achnathidium minutissimum*, *Aulacoseira granulata*, *Cyclostephanos dubius*, *Cyclotella meneghiniana* and *Cyclotella radiosa*.

3.3. Diatom community characteristics in sediment core

Consistent with the species of diatoms in surface sediments, 129 species of diatoms belonging to 22 genera, 10 families, 5 orders, and 2 classes were identified in the effective depth within 23 cm of columnar samples. Among them, there are 67 species of *Raphidionales*, followed by 25 species of *Aulonoraphidales*, 18 species of *Coscinodiaceae*, 10 species of *Araphidiales,* and 9 species of *Monoraphidales*. Among them, *Naviculaceae* has the largest number of species with 46 species, followed by 18 species of *Coccinodiscaceae*, 13 species of *Nitzschiaceae,* and 11 species of *Cymbellaceae*, accounting for 35.7%, 14%, 10.1%, and 8.5% of the total respectively. Among all genera, *Navicula Bory* has the largest number of species with 30 species, followed by *Cyclotella Kutzing* with 9 species, and *Gomphonema Ehrenberg* with 8 species, accounting for 23.3%, 7%, and 6.2% respectively. The 9 dominant species and genera were *Aulacoseira apigena*, *Aulacoseira granulata*, *Cyclotephanos dubius*, *Cyclotella meneghiniana*, *Cyclotella radiosa*, *Coconeis placendula*, *Fragilaria ulna*, *Achnathidium minutissimum*, accounting for 3.59%, 9.46%, 6.52%, 3.85%, 4.53%, 2.42% and 2.08% of diatoms respectively.

Table 1. Statistics of species and genera for benthic diatom in surface sediments

Class	Order	family	genus	Total diatom
Centricae	Coscinodiscaels	Coscinodiscaceae	Cyclotella Kutzing	4
			Melosira Agardh	2
			Stephanodiscus Ehrenberg	1
			Aulacoseira Thwaites	4
Pennatae	Araphidiales	Fragilariaceae	Fragilaria Lyngbye	4
			Synedra Ehrenberg	3
	Raphidionales	Eunotiaceae	Eunotia Ehrenbery	4
	Biraphidinales	Naviculaceae	Gyrosigma Hassall	20
			Navicula Bory	5
			Pinnularia Ehrenberg	5
		Cymbellaceae	Cymbella Agardh	4
		Gomphonemaceae	Gomphonema Ehrenberg	3
	Monoraphidales	Achnanthaceae	Cocconeis Ehrenberg	3
			Achnanthes Bory	3
	Aulonoraphidinales	Nitzschiaceae	Nitzschia Hassall	4
		Surirellaceae	Surirella Turpin	2

As shown in Figure 4, there were 25 species with relative abundance ≥ 1% in the sample, accounting for 96.32% of the total number of diatoms. Among them, there were 5 kinds of planktonic diatoms. Below 20 cm of the core sediment, the proportion of *Aulacoseira granulata* was the highest with its relative abundance ranging between 3.58% and 26.29% and the average value of 14.94%, and it was recorded in 23 samples at the same time. Other planktonic diatoms such as *Cyclostephanos dubius*, *Cyclotella radiosa*, *Cyclotella meneghiniana*, *Cyclotella radiosa,* and *Aulacoseira apigena* were also recorded. The species of epiphytic and benthic diatoms accounted for up to 70%, mainly including *Achnanthes minutissima*, *Cocconeis placentula*, *Stephanodiscus minutulus*, *Navicula minima*, *Navicula cincta*, *Gomphonema gracile*, *Synedra ulna*, etc.

The diatom assemblage data could be divided into four assemblage zones by constrained cluster analysis. The combination I belt was located between 23 - 20 cm with corresponding age ranging from 1955 to 1961, in which benthic diatoms were dominated with the highest abundance of 62% and the main dominant species were *Navicula cincta*, *Fragilaria ulna*, and *Cocconeis placentula*. Meanwhile, *Aulacoseira granulata* occupied an absolute advantage with the relative abundance fluctuating between 30% and 37%, showing a downward trend from bottom to top. In combination II with a depth of 20-15cm, the planktonic diatom species *Aulacoseira granulata* was still the dominant species with the relative abundance fluctuating from 22% to 26%. Nutrient-tolerant species such as *Cyclostephanos dubius*, *Cyclotella meneghiniana*, *Achnathidium minutissimum* began to appear and showed an upward trend in this belt. In combination III zone, the content of *Cyclostephanos dubius*, *Cyclotella meneghiniana,* and *Achnathidium minutissimum* reached the maximum. In combination IV zone, the content of planktonic species *Cyclotella radiosa* increased significantly. Nutrient-tolerant species began to decrease, and the contents of benthic diatom species *Navicula oligotraphenta* and *Nitzschia solgensis* increased.

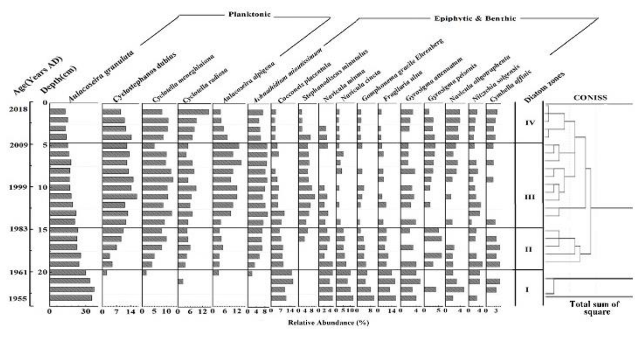


Figure 4. Stratigraphic plots of dominant diatom species, percentage of planktonic, epiphytic, and benthic diatoms in sediment core from Lake Xian'nv

4. Discussion

^{137}Cs was an artificial radionuclide generated by atmospheric nuclear tests in the 1950s and 1970s that flowed gradually into the water body with atmospheric subsidence and surface runoff (Saniewski *et al.* 2020). As shown in Figure 2, a well-defined ^{137}Cs peak was observed at 19 cm depth which could mark the 1963 when the testing of nuclear weapons was concentrated in this period (Lan *et al.* 2020). Lake Xian'nv was formed for water storage after a dam was built in 1958 and completed in 1960, by which the corresponding depth for this period verified by ^{210}Pb dates was recorded about 22-23cm. Therefore, the sedimentary samples within the effective depth of 23 cm from the surface were used for analysis.

As indicated in Figure 3, nutrients in sediments had been gradually accumulated since the construction of the dam which usually led to worse of hydrodynamic conditions (Wu *et al.* 2019). After 1961, the values of TP, TOC, TN, and C/N ratios were slightly increased until 1983, and then a significant increase was recorded from 1983 to 2009. After that, the nutrient contents were maintained at a stable level. The continuous increase of nutrients might indicate that the nutrient sources in Lake Xian'nv Lake continued to increase. Meanwhile, the average deposition rate based CRS model revealed that the intensity of all kinds of interference continues to rise. It had been reported that TN and TP contents in Lake Xian'nv increased continuously before 2009, and subsequently were gradually effectively controlled (Luo 2017).

The input of nutrients played a key role in the evolution of the ecological environment of Lake Xian'nv (Zou 2015). Since the 1950s, the development of industry, large-scale urbanization, and the large-scale development of agriculture had led to a rapid increase in the urban population and the use of chemical fertilizers around Lake Xian'nv (Liao *et al.* 2008). The data shows that the nutrients and water quality of Lake Xian'nv was mainly determined by the following two factors (Zhang *et al.* 2015). The first source was the discharge of industrial and domestic sewage which increased rapidly with the rapid economic development, and the water quality of the lake continued to deteriorate. On the other hand, cage culture had been developed rapidly since the early 1980s. In 2006, the number of cages used for fish farming was estimated at 15,000, which finally caused nutrients continuously accumulate in sediments (Luo 2017).

Besides, nutrient enrichment in the Lake Xian'nv recently was also consistent with the continuous intensification of human activities, including urbanization and fertilizer usage, which were also important sources of phosphorus and nitrogen for lakes (Chen *et al.* 2013). A significant effect of numerous human activities on diatom succession, species composition, abundance, and seasonal dynamics had been revealed (Kim *et al.* 2018). Due to the limitation of data collection around the basin, this analysis was based on the population and fertilizer use of Jiangxi Province, as shown in Figure 5. In recent decades, the population and fertilizer used in Jiangxi Province had been continuously soared, especially after the 1980s. From 1950 to 1959, the population of Jiangxi Province was less than 20 million, and the population growth rate was also maintained at a low level. However, the population was in a rapid growth stage from 1959 to 1999, and maintained a steady slight growth trend after 2000. In 2017, the total population of Jiangxi Province reached up to 46.22 million. At the same time, the use of chemical fertilizer in Jiangxi Province has increased since the 1980s.

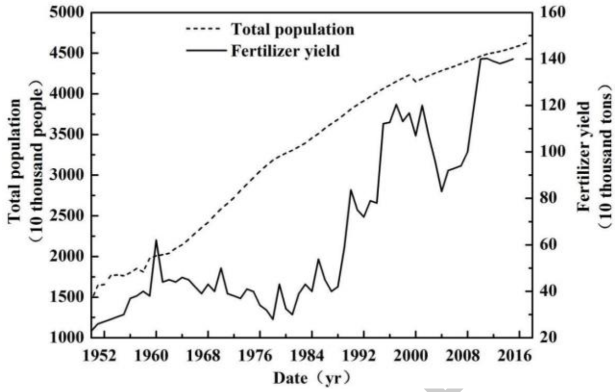


Figure 5. Trend of total population and fertilizer usage in Jiangxi Province since 1950

Lakes ecosystems were connected with the surrounding environment wherein materials and energy could be exchanged frequently (Vlaičevića *et al.* 2021). These nutrients could be absorbed by primary producers and consumers, and released after death (Sen and Mallick 2021). The average C/N ratio in Lake Xian'nv at the early stage was 10.32, indicating that the organic matter in the sediment in this period mainly came from both endogenous plankton and terrestrial organic matter.Before 1983, the C/N ratios in Lake Xian'nv had been maintained at 12 with a relatively low level. However, a higher value of the C/N ratio at the third stage indicated that the lake might be significantly affected by human activities. Generally, the value of C/N ratio with 10-12 meant that organic matter derived from phytoplankton, while the value of the C/N ratio over 20 meant that mixtures of algae and higher plants (Lei *et al.* 2018).

Moreover, studies had also shown that rapid population growth and climate warming had also effectively accelerated the eutrophication of Lake Xian'nv (Liao *et al.* 2008), Fortunately, these problems have attracted enough concern from the Chinese government and some non-government organizations, and a series of comprehensive water protection measurements had been conducted to reduce the environmental impact of various behaviors (Zou, 2015). Among them, one of these representative measures was to completely ban cage fishing in 2012 (Luo 2017), which effectively reduced the nutrient content in Xian'nv Lake.

Consistent with the eutrophication trend, the diatom community in Lake Xian'nv was mainly composed of benthic diatoms and showed a regular community shift. The abundance of eutrophic species including *Cyclostephanos dubius*, *Cyclotella meneghiniana,* and *Achnathidium minutissimum* increased gradually since 1961. These species were common in some eutrophic lakes in Europe and North America due to higher nutrient level (Smol and Stoermer 2010; Yang *et al.* 2010; Lotrer *et al.* 1997). As illustrated in Figure 6(A), the main dominant species with relative abundance greater than 5% included *Achnathidium minutissimum* and *Cyclostephanos dubius* in the sediment core were also the dominant species of surface sediment diatoms. The TDI calculation results in Figure 6(B) also indicated that the TDI value of diatom community in surface sediment was significantly higher than that in combination zone I, combination zone II, and combination zone IV, and slightly lower than that in combination zone III, indicating that the water nutrient level in the lake area has been controlled after years of improvement. The abundance and species composition of diatoms in the sediment core showed obvious differences at different depths, which was consistent with the change trend of TDI index.

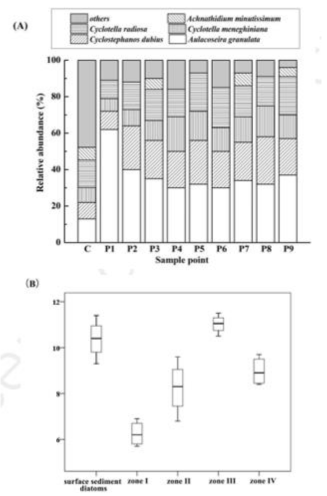


Figure 6. Distribution of dominant diatom species in surface sediments and sediment core (A); TDI Box diagram of diatom for surface sediment and four diatom sedimentary zones (B)

Before the construction of the dam from 1955 to 1961, phytoplankton was dominated by benthic diatoms and the quantity of diatoms was low with lower productivity. The TDI value in the same period was maintained at a low nutritional level. After the completion of the reservoir, the number of benthic diatoms suitable for flowing water decreased significantly, and the number of planktonic diatoms with easy growth in still water increased gradually. Diatom species increased significantly, and diatom productivity increased greatly. During this period, the TDI value increased, and nutrient-tolerant species appeared. *Aulacoseira granulata*, an indicator for clean water, gradually decreased after the construction of the dam, meaning a transfer of the ecosystem (Lei *et al.* 2021). Generally, *Aulacoseira granulata* was a siliceous genus with a higher sedimentation rate and a preference for disturbed currents (Chen *et al.* 2013; Schmieder 2009; Hötzel *et al.* 1996). *Aulacoseira granulata* has been associated with physical alterations, such as depth variation, turbulence, and mixing regime (Costa-Böddeker *et al.* 2012), and tended to be more pronounced under increased flow conditions in Jurumirim Reservoir (Nogueir *et al.* 2000).

At the initial stage of reservoir construction, nutrient indexes TP, TN, and TOC were maintained ata low level, diatoms were dominated by benthic communities including *Cocconeis placentula*, *Gomphonema gracile* and *Fragilaria ulna*, and planktonic diatom *Aurancoseira grannulata*. The study on the eutrophication process of lakes in the middle and lower reaches of the Yangtze River indicated that the content of *Aulancoseira grannulata* was maintained ata higher ratio when the lake nutrients were low and dominated by benthic diatoms (Chen *et al.* 2014). After the reservoir transferred from river to lake, the species and biomass of planktonic diatoms increased, while the epiphytic and benthic diatoms couldn't reproduce in large numbers in the deep-water environment (Wang， 2016). The contents of *Cyclostephanos dubius*, *Cyclotella meneghiniana*, *Aulacoseira alpigena* and *Achnathidium minutissimum* were gradually increased, and the TDI index value was also increased. A study on diatoms in 45 eutrophication lakes of the Yangtze River revealed that *Cyclotella meneghiniana*, *Achnathidium minutissimum*,and *Aulancoseira grannulata* were usually indicators for water eutrophication (Dong *et al.* 2006).

In order to more clearly understand the structural change characteristics of sedimentary diatoms, principal component analysis (PCA) was performed on diatom data with relative abundance greater than 2%, as shown in Figure 7. The results showed that the first axis could explain 74.1% of the changes in the diatom community, and the relationship was significant. The second axis only explained 6.9% of the changes in the diatom community, with little impact. There were significant differences between the two ends of main axis 1, in which the positive direction was mainly composed of benthic diatom species, such as *Navicula cincta*, *Stephanodiscus minutulus*, *Fragilaria ulna*, *Synedra ulna*,*Gomphonema gracile* and the negative direction was mainly composed of nutrient tolerant planktonic diatom species, such as *Cyclostephanos dubius*,*Cyclotella radiosa*,*Aulacoseira granulata*,*Cyclotella meneghiniana*. The change of diatom community could reflected in the transformation from the positive direction of main axis 1 to the negative direction, which was consistent with the succession from benthic diatom to planktonic diatom and the change of nutrient level.

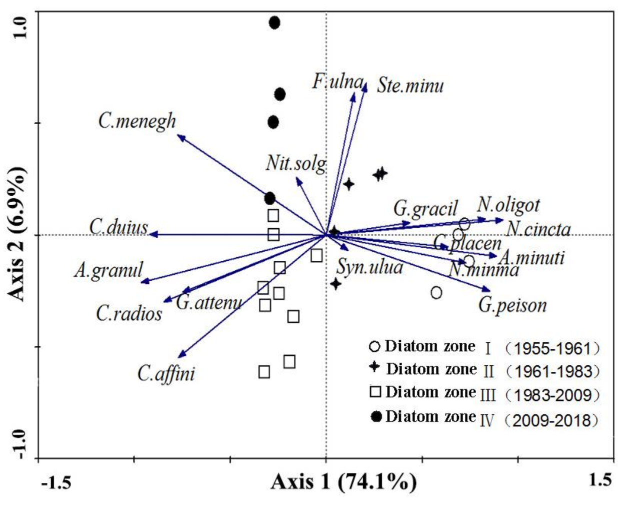


Figure 7. Ordination plot of diatom assemblage with principal component analysis for Lake Xian'nv

Nutrient indicators accumulation in the sediment usually corresponded to the eutrophication process of a lake (Zhang *et al.* 2018). The evolution process of nutrients in Lake Xian'nv was reconstructed by using diatom community combination and nutritional indicators in this research. The study revealed that the diatom communities wereconsistent with sedimentary nutrition TDI index records. For more than 60 years after the operation of the reservoir, the nutrient species including *Aulancoseira grannulata,Cyclotella meneghiniana*,*Achnathidium minutissimum*,*Cyclostephanos dubius*,*Aulacoseira alpigena* had been competed with the indicator species of clean water, and occupied a certain advantage between combination zone II to IV and an absolute advantage in combination zone III. Due to the intensification of human activities, such as cage fish culture, tourism, and domestic sewage discharge, the nutrients in water had been increased. However, the water nutrition level had also been decreased after the ban on cage fish culture in 2012.

5. Conclusion

The diatom community succession after the formation of reservoir Lake Xian'nv was reconstructed using multiple sediment biogeochemical proxies. Before the dam was built from 1955 to 1961, the phytoplankton were mainly benthic diatoms, and the number of diatoms was small. After the completion of the reservoir, the number of benthic diatoms suitable for flowing water decreased significantly, such as Aulacoseira granulata, and the number of planktonic diatoms easy growth in still water increased gradually, diatom species increased significantly.At the initial stage of reservoir construction, nutrient indexes TP, TN and TOC maintain in a low level, diatoms were dominated by benthic communities including Cocconeis placentula,Gomphonema gracile and Fragilaria ulna, and planktonic diatom Aurancoseira grannulata.After the reservoir transferred from river to lake, the species and biomass of planktonic diatoms increased, such as Cyclostephanos dubius,Cyclotella meneghiniana,Aulacoseira alpigena and Achnathidium minutissimum while the epiphytic and benthic diatoms couldn't reproduce in large numbers in deep-water environment.To sum up, the change of diatom community could reflected in the transformation from benthic diatom, such as Navicula cincta,Stephanodiscus minutulus,Fragilaria ulna,Synedra ulna,Gomphonema gracile, to nutrient tolerant planktonic diatom species, such as Cyclostephanos dubius,Cyclotella radiosa,Aulacoseira granulata,Cyclotella meneghiniana.

The acceleration of nutrient input had significantly increased the nutrient levels of the water body and mainly contributed to the continuous increase of algal biomass and shift of the diatom community structure. The hydrological dynamic conditions changed by the dam construction, and accelerated human activities synchronously enhanced the ecosystem changes. At the same time, the improvement of environmental protection management, prohibition of some human activities, and the construction of sewage plants after 2008 have effectively reduced the nutrient level of water. The supervision of industrial sewage discharge should be strengthen to help reduce the discharge of industrial sewage by relevant departments. In addition, it is essential to promote the concept of water conservation, which can minimize the impact of human activities on the lake.

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