DIATOM COMMUNITY SUCCESSION AND NUTRIENT EVOLUTION RECORDED FROM A SEDIMENT CORE OF THE LONGGAN LAKE, A LARGE SHALLOW LAKE IN EAST CHINA

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Abstract: The Longgan Lake is a shallow mesotrophic macrophyte-dominated lake. According to the high-resolution diatom research from its sediment core, the diatom community succession was built, and the total phosphorus (TP) and chlorophyll-a (Chl-a) concentration were quantitatively reconstructed for the past 2000 years, based on the diatom-TP and diatom-Chla transfer functions. The shifts of diatom assemblages also mirrored the developments of aquatic plant, reflecting the characters of aquatic ecosystem evolution. The inferred epilimnetic TP concentration fluctuated within a small range of 36 to 62μg/L, indicating the lake remained a relative stable mesotrophic status in the long historical period. The periodical variations of the diatom assemblage and trophic status suggest a mitigating function of shallow macrophyte-dominated lakes to nutrient input. The changes of lakes' trophic status don't linearly respond to the human disturbance in the catchment. The dynamics mechanism of phosphorus in macrophyte-dominated lakes, as inferred from diatoms, will provide a scientific foundation for the prediction of trophic status change in a shallow lake, as well as the lake ecological restoration and management decisions.

Key words: Diatom assemblage; Nutrient; Quantitative reconstruction; Aquatic macrophyte; Longgan Lake

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The importance of aquatic vegetation to the ecological restoration has been recognized commonly by limnologists and lake managements[1-4]. As to the ecological restoration in eutrophicated lakes, it is of great significance to know the dynamic process of the ecosystem evolution in a macrophyte-dominated lake under the human impacts in historical period, to make it clear whether the community structure and ecological function would be affected by the extension of the vegetation growth, to find a solution to remain steady benign ecosystem after the recovery. Lacking of the long-term monitoring data about the ecological status and water quality, it is difficult to set realistic goals for restoration and management decisions[5-7], as well as to evaluate and predict the long expected effect after remedy. Aiming at those questions mentioned above it is necessary to develop the paleolimnologic study on shallow macrophyte-dominated lakes. In recent years the researches on the paleoecology, particularly on the environment reconstruction based on the sediment biomarker such as diatom have made rapid progress[7-10]. So far the diatom based nutrient reconstructions in shallow lakes mainly are limited to the algae-dominated lakes with eutrophic condition[8,11,12], only a few reports concerned the macrophyte-dominated lakes[13]. Lakes in the middle and lower reaches of the Yangtze River are large and shallow. Most of them are developed from the flood plain with long history[14]. That area is also high-density populated. Recently some important lakes such as the Taihu Lake and the Chaohu Lake have become algae-dominated and resulted in the deterioration of water quality due to strong human disturbance. Many other lakes also encounter the potential eutrophication. Fortunately there still exist some macrophyte-dominated lakes in the region, providing a perfect place for the researches about the relationship between aquatic vegetation ecology and the nutrition dynamics under human dis-

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turbance. The aims of this study are (1) to reconstruct the historic nutrient baseline through the high-resolution diatom research from a sediment core of Longgan Lake. (2) to discuss the relationship between aquatic ecosystem and trophic state, in order to provide scientific background information for the prediction of lake environmental change and for the ecological management.

The Longgan Lake (29°52′—30°05′N, 115°19′—116°17′E) is called "Leichi" in ancient time, located in the north coast of the Yangtze River and in the border of Hubei and Anhui provinces (Fig. 1). Its area was 578.95km^2 originally 40 years ago, with broad area of wetland around it, but now it shrinks to 316.2km^2 due to human reclamation. The wetland vegetation almost disappears, reduced by farming land. The Longgan Lake is a shallow and outlet lake, with the inflow from Huangmei, Hualiangting and Jingzhu in the south of the Dabie Mountain area. The outflows converge into the Yangtze River through two branch rivers. Currently the Longgan Lake is a mesotrophic macrophyte-dominated lake with abundant aquatic plant[15,16]. According to the result of successive seasonal investigation from 2000 to 2003, the concentration of total phosphorus (TP) in surface water was 51 μg/L, with total nitrogen of 774μg/L, chlorophyll-a (Chl-a) of 3.7μg/L, chemical oxygen demanded of 4067μg/L. The maximum and mean depth was 4.58m and 3.78m, respectively. The ratio of the catchment's area to the lake' area was about 17.4[14].

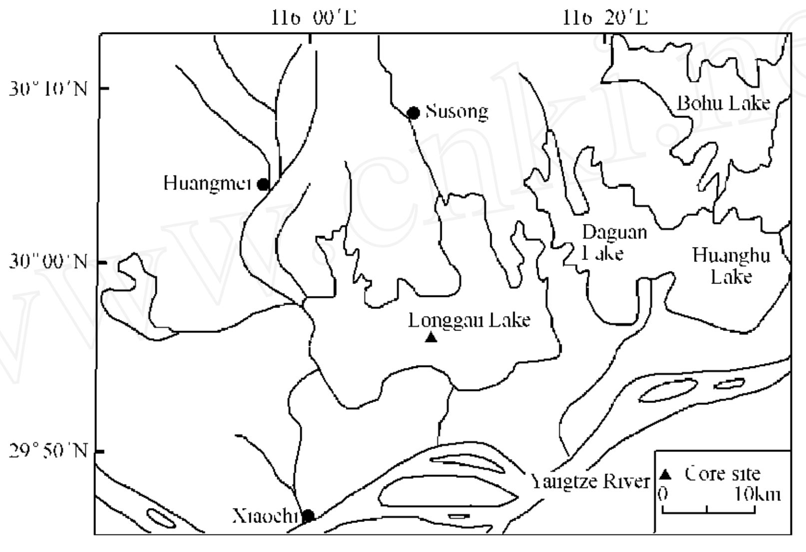

Fig. 1 The Longgan Lake geography and core site

1 Methods

The core, with a length of 123cm, is located at the center of the Longgan Lake under a water depth of 3.5m. The lithology of the profile from bottom to top is as follows: 123-62.5cm, greyish green mud; 62.5-42cm, greenish grey mud with more organic remains; 42-25cm, slight grayish dark mud with some banding of yellow mud; 25-14cm, grey mud; top 14cm, greyish dark mud. Samples were sliced in the field at 1cm interval. Subsamples were treated with standard method, namely the HCl (10%) and H_2O_2 method[17]. After the diatom samples mounted on glass slides, species were identified and counted using a Leica microscope (oil immersion objective, magnification 10 ×100). Diatom taxonomy followed Krammer and Lange-Bertalot[18]. At least 300 valves were counted for each sample. Species abundance was expressed as percentage.

The sediment chronology of the above 25cm section was provided by ^{210}Pb dating. The chronology of the 42—62.5cm section was inferred from the comparison between the sediment proxy and the historical events recorded in the literature. The detail description refers to Yang et al. (2002)[19]. Since the sediments are solid grayish-green mud below the 62.5cm, it is impossible to infer the chronology below this depth due to changed sediment accumulation rate. According to published literature[20,21], a ^{14}C data of bulk organic matter at the depth of 123cm in another core, which was taken near to our core, is 1892 ±73 a BP (calibrated age is 136 AD). The ages for some key layers are shown in Fig. 3 and Fig. 4.

The quantitive reconstructions for the past epilimnetic TP and Chl-a concentration were based on the diatom data in a sediment core and with the diatom-based TP and Chl-a transfer functions which derived from the 49 lakes in the middle and lower reaches of the Yangtze River (Yang, 2004)[22]. The current TP and Chl-a concentrations in the Longgan Lake are within the arranged gradient bounds (the gradient of TP and Chl-a are 30—560μg/L and 2.14—77.02μg/L, respectively; Dong et al, 2004[16]), suitable for the reconstruction of the two environment indicators. The establishment of the transfer functions was according the CCA (Canonical Correspondence Analysis) result from the diatom-water quality dataset, where TP, followed by Chl-a, are the most important variables, explaining most of the diatom data[22]. The diatom-TP transfer function was achieved using the weighted-average (WA) model due to TP gradient length (2.59 standard deviation), while the partial-least-square (PLS) model[23] was selected to generate diatom-Chl-a transfer function (Chl-a gradient length is 1.9 standard deviation). The TP model showed its high predictive power ($R^2_{jack} = 0.75$), low predictive error ($RMSEP_{jack} = 0.17$) and good correlation between observed and diatom inferred TP. However, Chla model had a relatively poor predictive ability with $R^2_{jack} = 0.68$, and higher predictive error with $RMSEP_{jack} = 0.24$[22]. The reconstructions were performed using the program CALIBRATE version 7.0[24].

2 Results

The diatoms are very abundant, dominated with epiphytic, facultative planktonic and benthic taxa, and the planktonic taxa are seldom found in the whole sediment core. The facultative planktonic species are mainly *Aulacoseira granulata*, with few *A. alpigena*, *A. ambigua*, *Synedra ulna* and *E. pectinalis*. The benthic species mainly include *Fragilaria construens* var. *venter*, following with some other small *Fragilaria* types such as *F. brevistriata*, *F. pinnata* and some *Navicula*. Lots of epiphytic species are seen successingly in the core. Among them *Achnanthes minutissima*, *Cocconeis placentula*, *Epithemia adnata*, *Cymbella affinis* have relatively high percentage. As a whole, when *A. granulata* or *Fragilaria construens* var. *venter* become the single dominant species, the diatom diversity measured by Hill's N2 value[25] is lowest. And when the epiphytic species become the dominant assemblage, the diversity is very high, which is most obvious at the top of the core (above 10cm. ! Fig. 2).

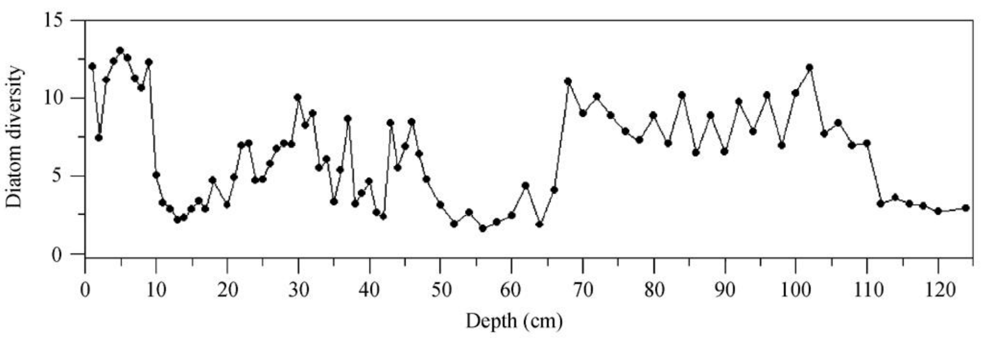

Fig. 2 The diatom diversity of the sediment core

According to the changes of the diatom percentages the core can be divided into 8 Zones as follows (Fig. 3):

Zone Ⅰ(120-109cm): *A. granulata* is the single dominant species in the basal zone. *F. construens* var. *venter* shows an increasing trend. Other species such as *Gyrosigma acuminatum*, *Gomphonema parvulum*, *Eunotia pectinalis* and *Amphora libyca* occur frequently with lower percentages. The species diversity of this zone is relatively lower than Zone Ⅱ

Zone Ⅱ(109-76cm): This zone, with a higher diversity, is characterized by both *A. granulata* and *F. construens* var. *venter*. Some species such as *G. acuminatum*, *G. parvulum*, *Fragilaria capucina*, *A. libyca*, *C. affinis* increase in percentages.

Zone Ⅲ(76-65cm): The species *F. construens* var. *venter* is in an overwhelming high percentage in this zone.

A. granulata and other species, as well as the diversity, obviously decrease. The epiphytic species reach to the lowest value in this interval.

Zone Ⅳ(65-49cm): *A. granulata* again become dominant species. *E. pectinalis*, *G. acuminatum* also experience a slight increase. In individual layer *E. pectinalis* increases suddenly and reaches up to 30%. Other species in the zone had very low percentages. The diatom diversity increases in some extent in the lower layers but declines again in the upper part of this zone.

Zone Ⅴ(49-42cm): Zone Ⅴ is characterized by high percentages for epiphytic taxa, i.e. *E. adnata*, *C. placentula*, *A. minutissima* and *C. affinis*. The diversity and the species number increases obviously. The small types of *Fragilaria* and *A. granulata* decrease or disappear rapidly. Moreover *Aulacoseira alpigena* and some facultative plankton species such as *Nitzschia amphibia* show a slight increase in this stage.

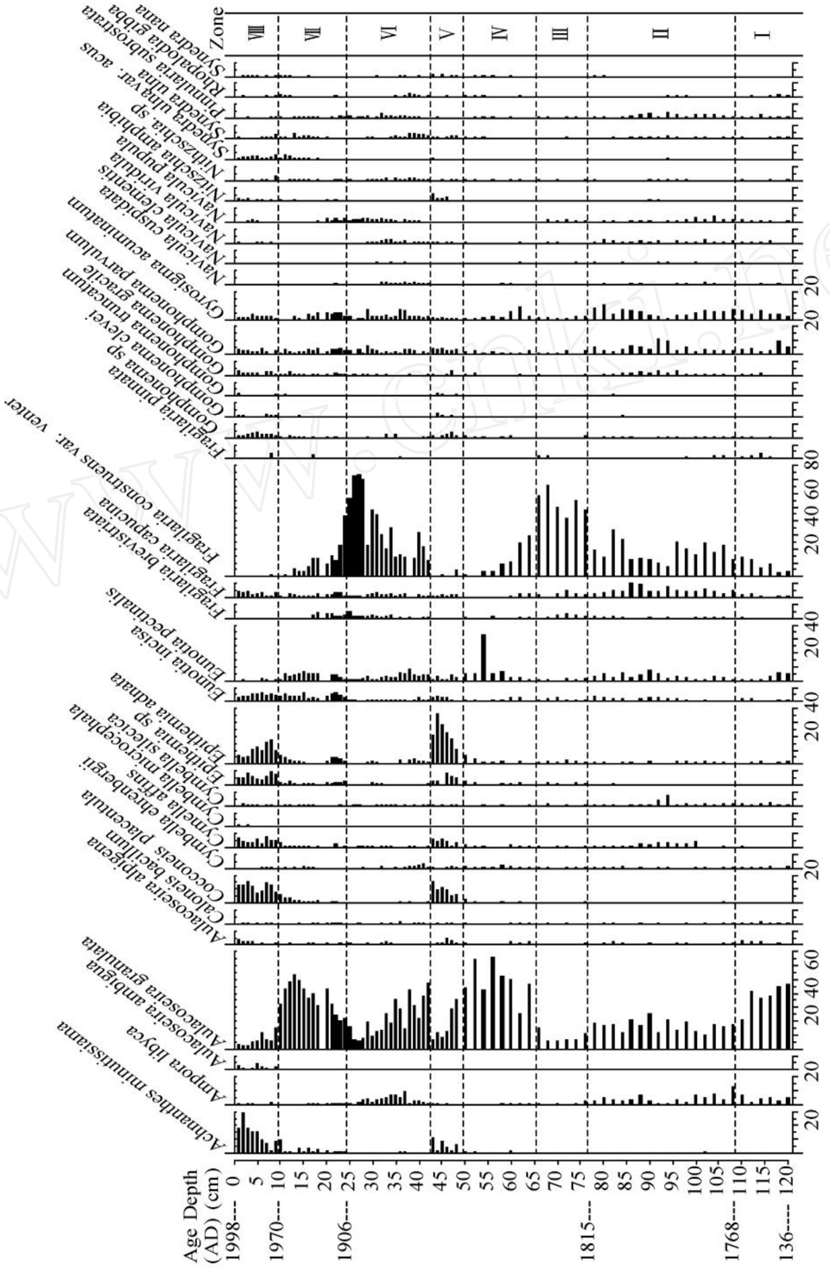

Fig.3 Relative percentage of total diatom numbers from the Longgan Lake sediment core

Zone Ⅵ(25-42cm): The lower part of this zone is dominated by *A. granulata*., followed by *Fragilaria construens* var. *venter* in the upper part. Except for *G. acuminatum*, most epiphytic species decrease in the population. Small amount of benthic species also occurred frequently. The diatom diversity changes greatly and drops to the lowest value at the depth of 28-25cm, coinciding to the highest value of *Fragilaria construens* var. *venter*.

Zone Ⅶ(25-10cm): Again the species *A. granulata* become dominat. *Eunotia* increases while the benthic species decrease. The diatom diversity shows a declining trend in this zone.

Zone Ⅷ(The top 10cm): The diatom assemblage resembles the zone Ⅵ and is characterized by a marked increase in epiphytic percentage and the diversity. *A. minutissima*, *E. adnata*, *C. placentula*, *C. affinis*, *Cymbella microcephala* increase significantly, forming the dominant species.

The diatom diagram shows that the interior change of each zone is relatively stable. At the interval of 42-25cm (Zone Ⅵ) the diatom assemblage shift from *Aulacoseira granulate* to *Fragilaria construens* var. *venter* gradually, resembling the change at the depth of 120-65cm (Zone Ⅰ—Ⅲ). The time span in the latter one is much longer. It is obvious that if we don't take the time span into account, there exist two succession cycles in diatom evolutions which correspond with the depth of 120-41cm and 41-0cm respectively. In each succession, diatom developments experience 4 stages changing from facultative planktonic to facultative planktonic plus benthic, again to facultative planktonic, and finally to epiphytic dominant communities.

Total 61 diatom taxa in sediment core, representing 71% of surface diatoms in modern data set, are used for the reconstruction of TP and Chl-a in the past. Fig. 4 shows the changes of the inferred TP. DI-TP and Chl-a for the nearly past 2000 years based on diatom transfer functions and sediment diatom data. Because of the lack of long-term monitoring water quality data in recent decades we can't make a comparison between the inferred TP and Chla and monitoring data. However, the inferred TP concentration (50.99μg/L) from the surface sediment collected in 2002 is in good agreement with the measured TP value (51μg/L, 2002—2003; Dong et al, 2004[16]), while the measured Chla value (3.71μg/L) is much different with the inferred concentration (6.5μg/L), suggesting a lower reliability of Chla reconstruction. The error of inferred Chla may relate to its relatively low importance in explanation of diatom data in CCA and its lower predictive power (see above description). For caution's sake, we mainly use the TP result for the discussion below. The trend of Chla curve can be used to reveal the changes of algae biomass in historical period.

The inferred lake TP concentration fluctuates within a short range of 36—62μg/L. According to the fixed TP parameter in trophic classification system in China (Tab.1, Jin et al, 1994[26]), the lake trophic status switched within the upper-limit of the mesotrophic and the lower-limit of the meso-eutrophic conditions in the nearly past 2000 years. But according to the OECD[34] criterion (Tab.1), the trophic states of the lake always changed in the mid-lower-level of eutrophic conditions. In order to facilitate the discussion below, the China's criterion is used in this paper. Detailed changes of TP and Chla in each stage are illustrated in Tab.1:

During 136—1768 AD (corresponding to the depth of 120-65cm), the epilimnetic TP concentration increased slowly within 46-60μg/L. TP concentration fluctuated about 50μg/L in the earlier and middle period (the depth of 120-76cm) and increased to 58—60μg/L in the later period (the depth of 76-65cm).

The Chla concentration kept the same trend of TP, but increased obviously during the later period.

During 1768—1815 AD (corresponding to the depth of 42-25cm), TP concentration slightly decreased in the earlier period with a little fluctuation, followed by a rapid decline from 45μg/L to 39μg/L (50-42cm interval). Chla concentration was very low in this stage.

During 1815—1906 AD (corresponding to the depth of 42-25cm) TP concentration increased again and reached to the highest value of 62μg/L before 1906AD. The Chla concentration experienced a slight increase at earlier time but increased quickly afterwards, coinciding to the high TP concentration.

After 1906AD, TP concentration changed back to the value about 50μg/L, the concentration dropped further to the lowest value (36—41μg/L) since 1970s. Chla showed the same trajectory as TP. The water quality investigated, however, showed that the epilimnetic TP concentration has returned to 51μg/L since 1998.

The changes of the inferred TP concentration were consistent with those of the diatom assemblage. The high percentage of *Fragilaria construens* var. *venter* usually occurred in relatively high trophic condition meso-eutrophic status with higher TP and Chla concentrations. The diatom assemblage dominated with epiphytic *E. adnata*, *C. placentula*, *A. minutissima*, *C. affinis* corresponded to the lowest TP and the Chla concentration in mesotrophic condition. When *A. granulata* or both *A. granulata* and *Fragilaria construens* var. *venter* become dominant in sediment, TP concentration changed slightly with the medium value between above. Just as diatom evolution, changes of TP concentration also showed the periodicity with two similar trends from low to high, to lower, and finally to lowest concentration.

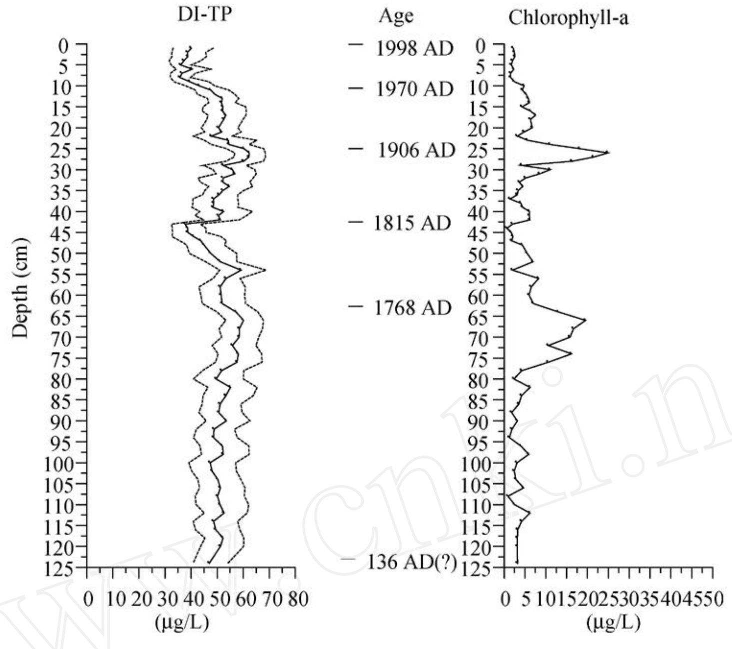

Fig. 4　Changes of diatom-inferred TP and Chla (DI-TP) concentrations in the Longgan Lake in the past 2000 years (dash line presents the range of TP changes)

Tab. 1　Comparison of trophic category based on the water quality index[26, 34]

Trophic Category (China)	Oligotrophic	Oligo-mesotrophic	Mesotrophic	Meso-eutrophic	Eutrophic	Hypertrophic
TP(μg/L)	<5	5—10	10—50	50—100	100—1300	>1300
Chl-a(μg/L)	<1	1—2	2—10	10—26	26—1000	>1000
Trophic Category (OECD)	Oligotrophic		Mesotrophic		Eutrophic	Hypertrophic
TP (μg/L)	<10		10—35		35—100	>100
Chl-a (μg/L)	<2.5		2.5—8		8—25	>25

3　Discussion

The diatom assemblage evolution in the Longgan Lake in the past 2000 years reveals some important information about the aquatic ecosystem. Generally epiphytic species can be linked to the aquatic macrophytes[13]. The dominant epiphytic diatoms in the core reveal the good growth and long lifespan of aquatic plants. The increase of the facultative planktonic species suggests that there are relatively abundant macrophytes in waters but their lifespan is perhaps not very long, and they only provide attached body for the piece of growth period. The benthic species can reflect the ability of the light penetration[27]. In shallow lakes with the moderate trophic status, the increase of benthic species and decreased coverage of aquatic plants may reflect the higher water turbidity. The benthic diatom taxa have been shown to have specific affinities to substrate, plant leaves or stems[13,28]. The succession of the epiphytic species recorded in the sediment core indicates that the development of macrophytes with different degree kept going on in the past 2000 years. In zone Ⅰ, zone Ⅳ, the bottom of zone Ⅵ and zone Ⅶ, the facultative planktonic *A. granulata* and a few amount of epiphytic species indicate the relatively low abundance of macrophytes during these intervals. In Zone Ⅲ and the top of zone Ⅵ, the increase of benthic species is relative to the reduce of production in macrophytes. The epiphyte-dominated assemblage in the Zone Ⅴ and Zone Ⅷ, characterize the littoral diatom community, indicates the thriving aquatic plants during the two intervals.

The growth extent of the macrophyte reflects the water cleanness[13]. The increasing macrophyte abundance have their ability to compete for nutrition and light, to reduce resuspension of nutrient-rich sediment effectively, and to suppress algal biomass[29,30]. The reduction of macrophyte revealed by the increase of the small type of *Fragilaria* in zone Ⅲ and on the upper part of zone Ⅵ, indicated that the water is possibly disturbed to some extent. Also, in great shallow lakes, the reduction of macrophyte would strengthen the stormy waves, resulting in the increase of water turbidity. During the period of 136—1768 AD and 1815—1906 AD, *Aulacoseira*-dominated assemblage was replaced by *Fragilaria*-dominated community, coinciding to the raise of water phosphorus concentration and the algae biomass, the reduction of the macrophyte coverage and the increase of the water turbidity. On the contrary, the shift from *Fragilaria*-dominated to *Aulacoseira*-dominated and finally to epiphytic diatom assemblages (during the period of 1768—1815 AD and the last 100 years) illustrates the gradual expansion of macrophyte and the increase of water transparence.

The dry weight of the phosphorus in the sediment can reach 0.01—10g/kg[31], far higher than the epilmnetic phosphorus. For such a high concentration it is seemingly reasonable to infer the waterbody phosphorus change through the sediment phosphorus measurement by the means of geochemistry[7]. However, through the comparison between the sedimentary phosphorus and the epilimnetic phosphorus from deep and small shallow eutrophic lakes, Anderson (1993)[32] and Bennion et al. (1995)[27] concluded that sediment phosphorus could not mirror the surface water phosphorus, and the diserepancy mainly came from the factors such as changes of oxidation-reduction potential at sediment-water interface, the transference and resuspension of the sedimentary phosphorus[7,33]. Despite there is only a few reports about TP reconstruction in macrophyte-dominated lakes[13], the diserepancy between sediment and water phosphorus can also seen in such a lake from the study of Longgan Lake core (Fig. 5). The sediment phosphorus concentration during 1768—1815 AD and the last 100 years in the core was

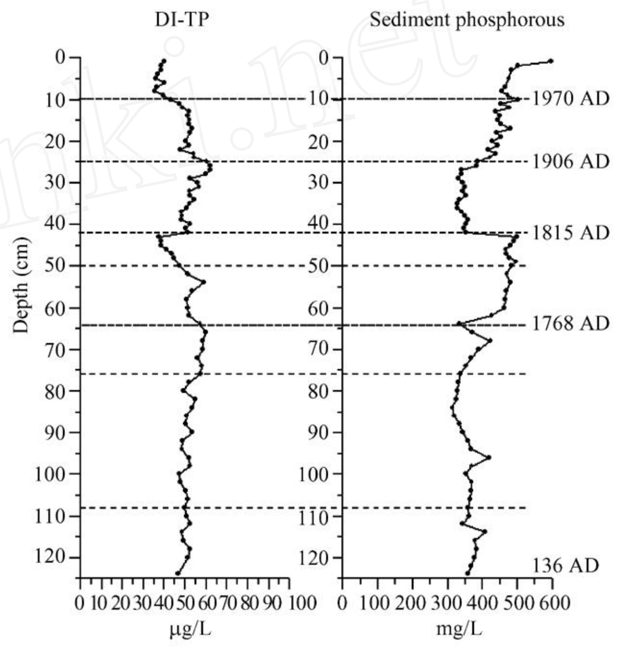

Fig.5 Comparison between inferred epilimnetic TP asediment phosphorus

high and kept an increasing trend, contrary to the inferred surface water phosphorus. The increased sediment phosphorus also reflects the enhanced human activity during the two stages[19]. It is clear that the TP concentration in macrophyte-dominated lakes doesn't directly response to the change of ecosystem in catchment by human disturbance and the sediment phosphorus can't stand for the epilimnetic total phosphorus. Different from the other algae-dominated shallow lakes and deep lakes, however, the TP change in macrophyte-dominated lake is affected by the growth extent of aquatic plants rather than the release of the sediment. From the above, we consider that there exist a self-purification function and buffering mechanism in the aquatic ecosystem of the large shallow, macrophyte-dominated lake.

The diatom research from the core reveals the periodical pattern of environmental evolution in the Longgan Lake, a macrophyte-dominated lake. Nevertheless, the periodicity in macrophyte-dominated lakes hasn't been reported yet in other regions, more researches should be done in other shallow lakes to support our conclusion. The periodical changes of diatom assemblage and water TP concentration provide evidence for the forecast of trophic change in the Longgan Lake and the useful information for environment management. From the latest water quality monitoring data in the Longgan Lake, the epilimnetic TP inclined to meso-eutrophic state again (about 51μg/L). Accordingly, the dominant species *A. granulata* appeared again in the surface sediment diatom (sampled in 2002), perhaps hinting the beginning of another environment evolution cycle. It is plausible that if human activity remains unchanged, or properly cut down the nutrient input from the catchment, the water quality of the Longgan Lake will keep a relatively good condition in a long time, based on the nutrient background in historical period. However, the extensive fish culture, as well as excessive sewage effluent from the catchment, would break the current stable aquatic ecosystem of macrophyte-dominated lake, leading to the disappearance of aquatic plants and appearance of planktonic diatom taxa in waterbody, and finally to the eutrophication problems just like the Taihu lake and the Chaohu lake in east China.

4 Conclusions

(1) The sequence of diatom evolution in the past 2000 years is established from a sediment core of the Longgan Lake. The diatom record reveals the obvious periodical pattern of environment evolution in macrophyte-dominated lakes.

(2) The changes of historical epilimnetic total phosphorus and chlorophyll-a concentration are quantitively reconstructed based on the modern diatom transfer function and sediment diatom flora. The inferred surface water TP concentration fluctuates from 36 to 62μg/L, indicating the Longgan Lake has been at a middle trophic condition over a long historical period.

(3) The relationship between nutrient evolution, diatoms and macrophyte ecology are discussed in this paper. It indicates that water TP concentration in macrophyte-dominated lake does not respond directly to the human activities in the catchment. There exists a self-purification function and buffering mechanism in the aquatic ecosystem of the large shallow, macrophyte-dominant lake.

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