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Spatial distribution characteristics of phosphorus in the overlying water, interstitial and sediment of Lihu Lake, China

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ABSTRACT

The levels and spatial distributions of phosphorus in the overlying water, interstitial water and sediments in Lihu Lake were investigated in April 2012. In the overlying water, the total phosphorus (TP) concentrations ranged from 0.024 to 0.306 mg/L with an average value of 0.064 mg/L. The lake was divided into four zones, and the spatial distribution trends of TP and dissolved inorganic phosphorus (DIP) levels in the overlying water were both as follows: Zone A < Zone < B < Zone C < Zone D. The spatial distribution trends of dissolved total phosphorus (DTP) and inorganic phosphorus levels in the interstitial water were consistent with those of TP and DIP levels in the overlying water. The average DTP concentration of the interstitial water (0.134 mg/L) was evidently higher than that of the overlying water (0.025 mg/L), indicating the potential release of the bio-available phosphorus. The TP concentrations in the surface sediments were at the range of 321.77–1,062.08 mg/kg. The DTP levels in the interstitial water had a positive correlation with TP levels in the surface sediments. Changes of environmental conditions could make the sediments continue to release phosphorus to the overlying water. The TP levels of the overlying water showed a decreasing trend from 2002 to 2012. The results showed that the artificial ecological projects and environmental treatment projects for endogenous pollution sources had effectively improved the water quality since 2003.

Keywords: Eutrophication; Phosphorus; Spatial distribution; Lihu Lake

1. Introduction

In recent years, most of Chinese lakes have experienced the process of eutrophication and accordingly they have reached mesotrophic or eutrophic level [1–3]. Accelerated eutrophication of lakes has become one of the serious problems on surface water environment in China. Serious eutrophication can lead to the explosive growth of plankton and the sharp deterioration of water quality in a lake, threatening the safety of drinking water and aquatic ecosystem [4,5]. Human activities introduce massive plant nutrients into lakes so that ecological balance of the water bodies are altered and destroyed [6]. Excessive discharge of plant nutrients to freshwater bodies increases the risk of lake eutrophication. The two key factors influencing lake eutrophication are input of plant nutrients from industrial, agricultural and municipal wastewater and endogenous release of plant nutrients from lake sediment. As more and more stringent water quality standards have been implemented, the pollution from point sources around lakes has been largely reduced and the delivery of plant nutrients into freshwater bodies has been strictly controlled [7]. Thus, the release of plant nutrients from lake sediment has been the main problem of lake pollution control and has gained more and more attentions from researchers at home and abroad in the field of lake research [8].

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Lake eutrophication has a close relationship with the status of plant nutrients (e.g., nitrogen and phosphorus) in water, such as species, levels and the ratios of nitrogen to phosphorus. Plant nutrients can be accumulated in sediments on the bottom of a lake by absorption, complexation, flocculation and sedimentation [9–11]. The nutrients can be also released from these sediments. Moreover, the releasing processes are diverse and mainly involved three approaches: (1) the nutrients are re-released from lake sediment to the pore water by mineralization and desorption; (2) the nutrients released from the sediment are re-absorbed or combined by the loose and suspended particles in lakes; (3) the nutrients are also released to the overlying water by ion exchange, molecular diffusion and biological disturbance. Since most of external pollution sources were under controlled, lake sediments have become one of the key factors influencing water quality of a lake [12,13].

Lake sediments are recognized as the major reservoir of phosphorus in aquatic environment of a lake and are also considered to be the main source of endogenous phosphorus [14,15]. Transformations of stable phosphorus to active phosphorus may elevate the phosphorus level in the overlying water and further accelerate lake eutrophication [16,17]. Thus, as an important limiting nutrient, phosphorus exchange between the overlying water and sediments of a lake could influence the eutrophication process. Phosphorus, widely distributed in water environments, is present in various forms in lakes. These forms of phosphorus in lake sediments act as primary participants of phosphorus cycling in water environments and influence phosphorus balance in them. Simultaneously, the levels and spatial distributions of phosphorus in overlying water, interstitial water and sediments can reflect improvement performance of the water quality for local waters, especially for the lake environments under long-term artificial ecological reconstruction. However, there are limited previous researches on applying distribution characteristics of phosphorus to evaluate the improvement performance of a lake by environmental engineering projects.

This study aims to investigate the levels and spatial distributions of phosphorus in the overlying water, interstitial water and sediments in Lihu Lake, and to preliminarily evaluate the water quality of the lake and the effect of environmental controlling measures on the lake environment. Lihu Lake is taken as the research object. The lake is a sub-lake of Taihu Lake located in Wuxi City of China and is a typical shallow lake. For two decades before 2000, with the increase of population and the rapid industrialization, the lake was frequently disturbed and polluted due to human activities so that its ecological functions were dramatically weakened. The most serious case was that the degraded water quality was once lower than the fifth class of the national surface water environmental quality standard. The water environment of Lihu Lake has drew attentions from local and central governments and a variety of engineering techniques have been implemented in the lake for more than a decade. The study can provide more information for the prevention and control of eutrophication in the urban landscape lakes.

2. Materials and methods

2.1. Study area

The study area is located in Lihu Lake (31°29′54″ N–31°32′50″ N, 119°13′12″ E–119°17′11″ E), which is a freshwater lake in Binhu District of Wuxi City, Jiangsu Province (Fig. 1). Lihu Lake is a part of Taihu Lake, stretching to urban area of Wuxi City. Lihu Lake has become a relatively independent urban landscape lake. Baojie Bridge divided the lake into two parts known as "East Lihu" and "West Lihu". The east–west width of Lihu Lake is 0.3–1.8 km and the south–north length is about 6 km. In the case of normal water level, the shoreline of this lake is 21 km long and the total surface area is about 8.6 km^2. Lihu Lake is located in the humid north subtropical monsoon climate zone with southeast wind in summer and more northerly wind in winter, where spring and autumn are the wind-direction transition seasons. In the lake district, the annual average temperature was 15.4°C, the extreme maximum temperature was 37.7°C and the extreme minimum temperature was –8°C. The average annual precipitation days are 125 days, the annual amount of precipitation is about 1,112 mm and that of evaporation is 920 mm. The temporal distributions of the annual precipitation and evaporation are uneven. The perennial water level and the average water depth are 3.07 and 1.80 m, respectively. The control gates are set up on the connecting channels including inflow and outflow rivers. The channels in the north of Lihu Lake are mainly inflow lakes, while the channels in the southeast of the lake are mainly outflow lakes. These rivers usually have a very low water flow velocity. When there is a rainstorm and flood, the drainage from Lihu Lake to Taihu Lake can be done by the graduating valves and pump stations. In the case of water shortage in Lihu Lake, water can be diverted from Taihu Lake.

2.2. Sampling positions and sampling procedure

As was shown in Fig. 1, Lihu Lake was divided into four zones (Zone A, B, C and D) with three boundaries: Li dyke, Baojie Bridge and Lihu Bridge. In Zone A, the eutrophication problem was serious because there were once a lot of fish ponds. But in the last decade, fishery industry in this zone has been prohibited and aquatic vegetation has been restored. Zone A belongs to Cancelling Fishery and Restoring Lake zone. For Zone B, aquatic vegetation reconstruction project has

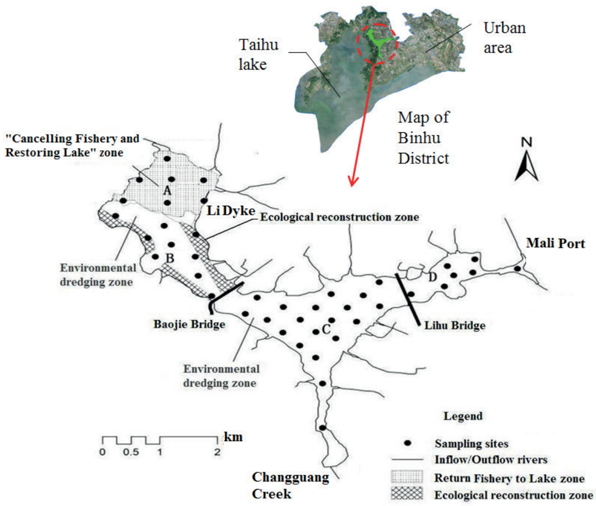

Fig. 1. Location map of sampling positions in Lihu Lake.

been carried out around the coast and environmental dredging has been done in the northwest waters. Improvement projects have also been done at the coast of Zone C, such as the constructed wetland of Changguang Creek. In Zone D, the water eutrophication pollution is serious because of pollutants emission from intensive residential buildings around the zone. So Zone D is a key zone for improvement of Lihu Lake.

There are altogether 43 sampling points in the study area. Water and sediment samples were collected from these sampling points in April 2012. The overlying water samples were collected by a water sampler while the surface sediments at the depth of 10 cm were collected by a cylindrical sampler (04.23 Beeker, Eijkelkamp, Netherland, Φ = 12 cm). For each sampling points, four parallel samples of the surface sediments were collected and fully mixed. The sediment samples were centrifuged at 7,200 rpm and the supernatant is the interstitial water. After the supernatant is decanted and collected, the sediment samples were sealed in polyethylene bags. The sediment samples were stored at 2°C–8°C by a cooler with ice and were analyzed and tested within 48 h.

2.3. Analytical methods

The samples of overlying water, interstitial water and sediment were included in this study. The overlying water samples were used for the analysis of total phosphorus (TP), dissolved inorganic phosphorus (DIP) and dissolved total phosphorus (DTP), while the interstitial water samples were used for the analysis of DIP and DTP. The surface sediments were used for the analysis of TP. TP, DIP and DTP were determined by the molybdate colorimetric method [12,18]. The water samples for TP analysis were digested at 121°C for 30 min after $K_2S_2O_8$ was added, and then were added by 10% ascorbic acid. TP concentrations of the treated samples were measured by the molybdenum-blue spectrophotometric method with an ultraviolet–visible spectrophotometer (DR5000, Hach, USA). DIP and DTP were determined with the same method for TP determination, except that the water samples were not digested and were filtered with a 0.45 μm cellulose acetate membrane for DIP analysis while the samples were filtered with a 0.45 μm cellulose acetate membrane for DTP analysis. Phosphorus fractions in the sediment samples were analyzed by the method developed by the Standards Measurements and Testing Program of the European Commission (SMT method) [19]. The reagents have been purchased from Sinopharm Group Co., Ltd. in China. The data analysis of phosphorus in the sediments is based on dry weight.

2.4. Data analysis and graphing

The data calculation was performed with Excel 2010 and the statistical analysis was conducted with Origin 8.0. The contour maps of Lihu Lake and sampling points were conducted by ArcGIS software. The spatial distributions of phosphorus in the overlying water, interstitial water and sediment of Lihu Lake were mapped by Surfer 10.0.

3. Results and discussion

3.1. Spatial distribution of phosphorus in the overlying water

The nutrient levels in the overlying water directly affect eutrophication process of lakes [20–22]. As a typical plant nutrient, phosphorus is a key factor influencing the lake eutrophication [17]. To better understand the variations of phosphorus in a lake ecosystem, it is of great significance to analyze the DP, DTP, DIP and their contents of the overlying water. The concentration distributions of various phosphorus species in Lihu Lake and the estuaries surrounding the lake are shown in Fig. 2.

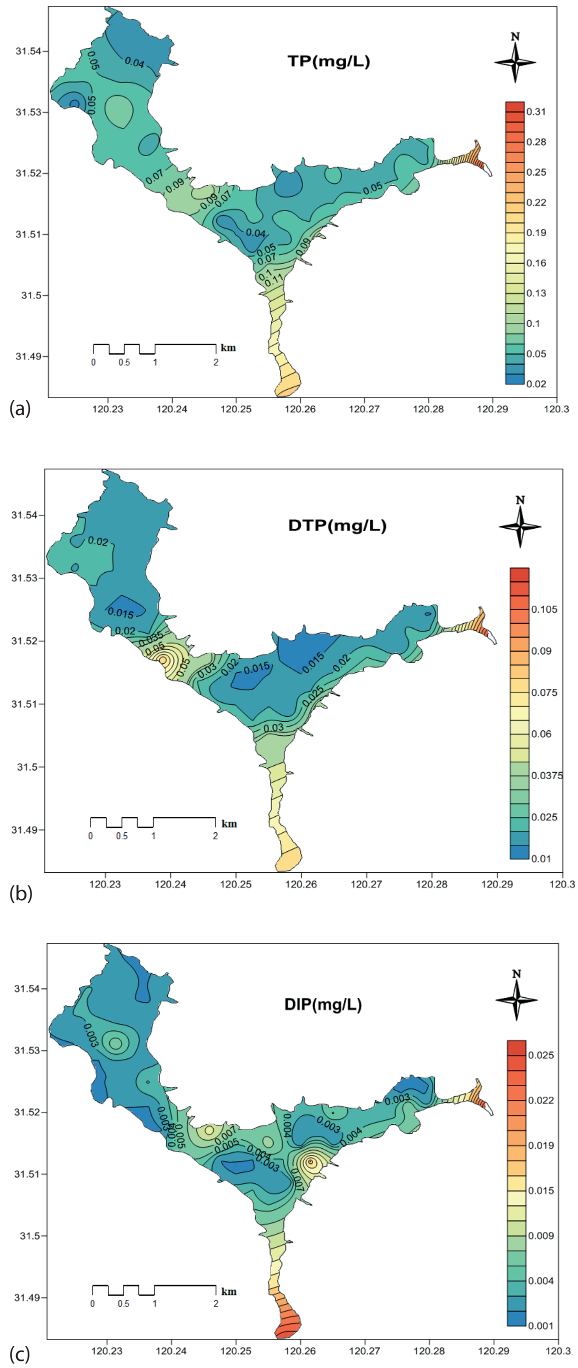

Fig. 2. Spatial distribution of phosphorus in the overlying water of Lihu Lake: (a) spatial distribution of TP in the overlying water; (b) spatial distribution of DTP in the overlying water and (c) spatial distribution of DIP in the overlying water.

In the overlying water, TP concentrations ranged from 0.024 to 0.306 mg/L and its average value reached 0.064 mg/L (Fig. 2(a)). TP concentrations varied greatly among the lake zones. The water quality situation corresponded to each lake zone. The water quality of Zone A was the best and the TP concentration was 0.04 mg/L. The trend of the TP concentrations in the overlying water of all lake zones was: Zone A < Zone < B < Zone C < Zone D. For the overlying water, the spatial distribution trend of DIP was similar to that of TP, and the concentrations of DIP were 0.002–0.025 mg/L (Fig. 2(c)). The DTP concentrations of the overlying water in the lake body were between 0.015 and 0.112 mg/L with an average value of 0.025 mg/L (Fig. 2(b)).

The TP concentrations of the overlying water in each lake zone were lower than those in the estuaries. From the west to the east, the concentrations of phosphorus in the estuaries increased. The TP concentrations in the estuaries of Zone A and B were 0.08 and 0.07 mg/L, respectively, while those in the estuaries of Zone C and D were 0.17 and 0.21 mg/L, respectively. Moreover, the TP contents in the lake estuaries of Zone A and B were lower than those of Zone C and D.

In Lihu Lake, the spatial distribution characteristics of phosphorus in the overlying water had relationship with the conditions of the surrounding environment and the inflow estuaries. For Zone A and B, the lake areas were both isolated by the artificial dyke and were in a semi-closed state. As the external pollution sources were significantly reduced, the phosphorus pollution was preliminarily controlled. What's more, the strategy of "Cancelling Fishery and Restoring Lake" for Zone A benefited the aquatic ecological restoration, and the engineering of environmental dredging for Zone A and B and the project of vegetation restoration for Zone B evidently reduced the pollution from endogenous phosphorus. However, many residential areas were located around Zone C and D, and a substantial proportion of phosphorus pollutants were came from domestic wastewater and discharged into the lake zones before the control of the external pollution source. It is supposed that phosphorus could be accumulated in the sediment and would be released from them. This presumption is supported by the results of phosphorus in the interstitial water and the sediments, which is shown as follows. So the phosphorus pollution was more serious in Zone C and D. Especially in the lake area around Mali port, the TP concentration of the overlying water was more than 0.21 mg/L.

3.2. Spatial distribution of phosphorus in the interstitial water

As a bond of overlying water and sediment, interstitial water plays an important role in maintaining dynamic equilibrium of chemical substances and affecting pollutant transportation on water–sediment interface [23]. Fig. 3 presented the spatial distribution of DTP and DIP of the interstitial water in Lihu Lake and the coastal estuaries. The spatial distribution trends of DTP and DIP in the interstitial water were similar: Zone A < Zone < B < Zone C < Zone D. DIP concentrations of the interstitial water ranged from 0.02 to 0.09 mg/L with an average concentration of 0.037 mg/L. DTP concentrations of the interstitial water varied at the range of 0.085–0.195 mg/L, and the average concentration (0.134 mg/L) was 4.36 times higher than that of the overlying water (0.025 mg/L) (Fig. 3(a)). Among these four zones, DTP in Zone A was at the lowest level (0.09 mg/L) but DTP in Zone C and D was higher than 0.12 mg/L (Fig. 3(b)). The comparison of phosphorus levels of the interstitial with those of the overlying water indicated that the sediments acted as a source of phosphorus in Lihu Lake and continuously released the bio-available phosphorus in the overlying water so as to keep the eutrophic level of the water body.

3.3. Spatial distribution of phosphorus in the sediments

Nutrients exchange of sediment–water interface could influence the water quality of a lake. Nutrients released from sediments are also considered to be a key factor that caused the lake eutrophication, especially when exogenous pollution sources are largely reduced [24,25]. Phosphorus is mainly accumulated in the lake sediments. On one hand, phosphorus from external pollution sources can be directly accumulated in the lake sediments by a series of process such as absorption, complexation, flocculation and sedimentation

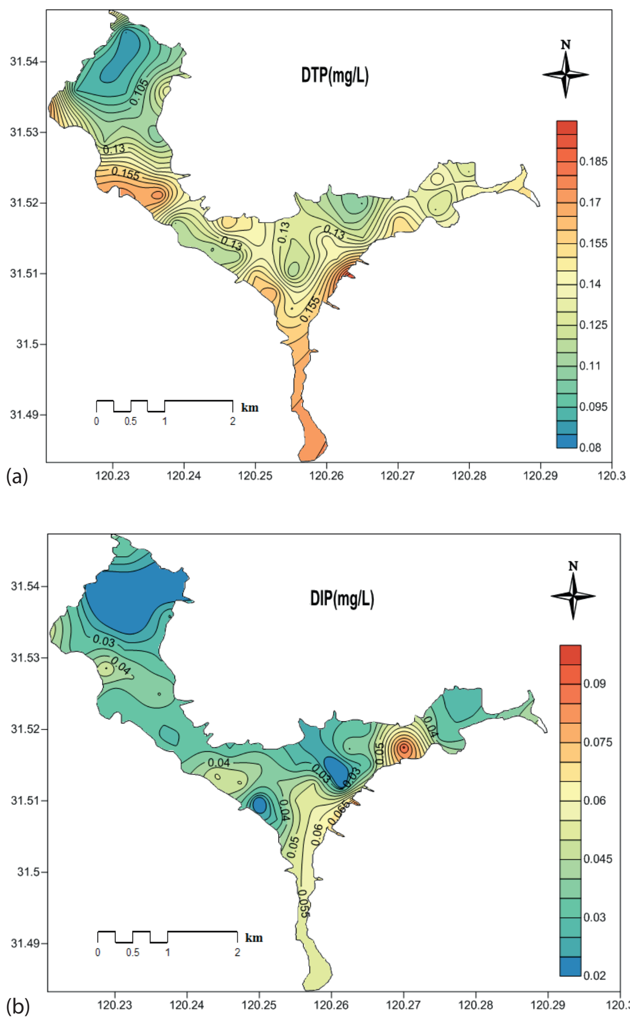

Fig. 3. Spatial distribution of phosphorus in the interstitial water of Lihu Lake: (a) spatial distribution of DTP in the interstitial water and (b) spatial distribution of DIP in the interstitial water.

[9–11]. On the other hand, a portion of phosphorus can be utilized by aquatic organisms and accumulated in these organisms and the phosphorus is ultimately released from the biological residue. In this case, the phosphorus can also indirectly accumulate in the lake sediments. For these reasons, the sediments have a close relationship with phosphorus cycle and aquatic ecosystem of a lake.

In Lihu Lake, the spatial distributions of TP in the surface sediments showed a trend of significant spatial heterogeneity (Fig. 4). TP level in the surface sediment of "East Lihu" was relatively higher than that of "West Lihu". The possible reason was that there was less water pollution controlling projects implemented in "East Lihu". The TP concentrations in the surface sediments of Lihu Lake ranged from 321.77 to 1,062.08 mg/kg with an average concentration of 593.75 mg/kg. The TP levels in the surface sediments in Zone D and the east part of Zone C reached 949.18 and 1,062.08 mg/kg, which were higher than other parts of Lihu Lake. The TP levels in surface sediments of the lake estuaries were at the range of 321.77–916.41 mg/kg and the average level was 575.53 mg/kg. The TP levels in surface sediments of the lake estuaries were still high even though the delivery of plant nutrients into the lake had been controlled. The results indicated that the rapid processes of industrialization and urbanization had led to the discharge of a large amount of municipal, industrial and agricultural sewage and had further led to the accumulation of phosphorus in the sediments of the estuaries in Lihu Lake before the external pollution sources were controlled.

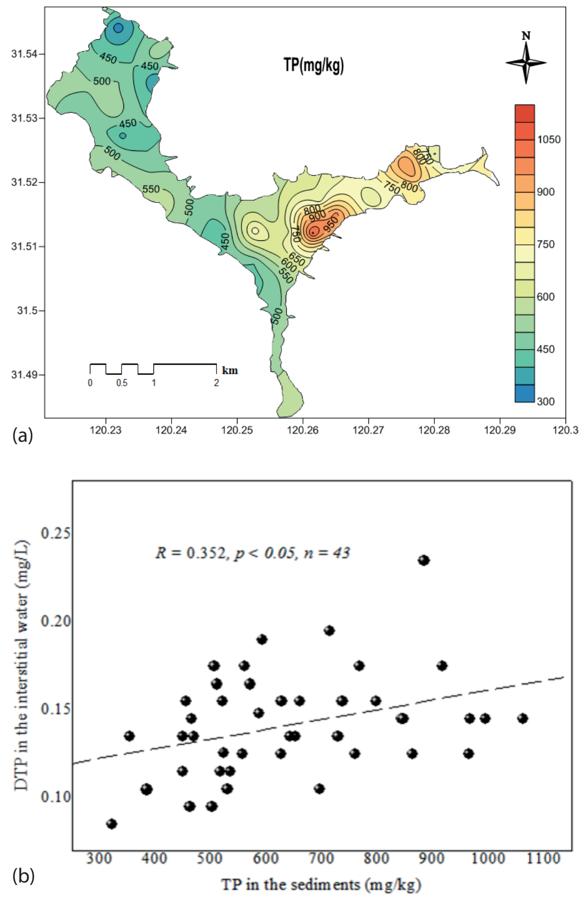

Fig. 4. Spatial distribution of phosphorus in the sediments of Lihu Lake and the relationship between TP in the sediments and DTP in the interstitial water: (a) spatial distribution of TP in the sediments and (b) the relationship between TP in the sediments and DTP in the interstitial water.

Understanding the relationship of DTP levels in interstitial water and those in surface sediments in a lake can provide reliable scientific basis for the control and management of the lake eutrophication in future. As was shown in Fig. 4(b), the DTP levels (Y, mg/L) in interstitial water had a positive correlation with the TP levels (X, mg/kg) in surface sediments. The positive correlation relationship could be expressed as an equation: $Y = 0.10589 + 5.54482 \times 10^{-5}X$. The results implied that the phosphorus release from the sediments had an important influence on the phosphorus level of Lihu Lake. It has been confirmed that the changes of physical and chemical conditions or biological process of a lake could cause the nutrient release from the sediments so as to influence the nutrient level in the overlying water [14,26,27]. It has been also proven that the shear stress generated by lake currents and waves led to the surface sediments re-suspension and promoted the nutrient release from the sediments [25]. Since phosphorus contents in the lake sediments were still high, it could be deduced that wind waves disturbance and environmental conditions change could make the sediments continue to release phosphorus to the overlying water.

3.4. The change trend of the average TP level of the overlying water

Urban shallow landscape lakes, such as the West Lake in Hangzhou City, the Ink Lake in Wuhan City and Xuanwu Lake in Nanjing City, are generally the static- or slow-flow water bodies. They are characterized by small water area, low transparency, small environmental capacity and weak self-purification capacity. These lakes are sensitive to human activities and vulnerable to nitrogen and phosphorus pollution so that the eutrophication processes are easy to occur in these lakes. Lihu Lake is just one of the typical urban landscape lakes in China. The industrialization and urbanization process in the area around Lihu Lake brought many kinds of point and non-point source pollutants into the lake. The total nitrogen and phosphorus contents of the lake once sharply increased and the water quality in the estuaries was even inferior to the fifth class of the national surface water environmental quality standard, and as a result Lihu Lake became one of the water areas of the worst environment quality in Taihu Lake. In order to avoid the further eutrophication of the lake and the continuing degradation of the water quality, the local government has extensively carried out the environmental dredging and ecological reconstruction projects since 2003. In this study (April 2012), the average TP concentration in the overlying water of 43 sampling points was 0.06 mg/L, which was significantly lower than the average TP concentrations from 1998 to 2002 (0.20–0.33 mg/L). As was described in Fig. 5, the average TP level in Lihu Lake showed a decreasing trend from 2002 to 2012. The results indicated that the environmental dredging and ecological reconstruction projects improved the water quality. The water quality

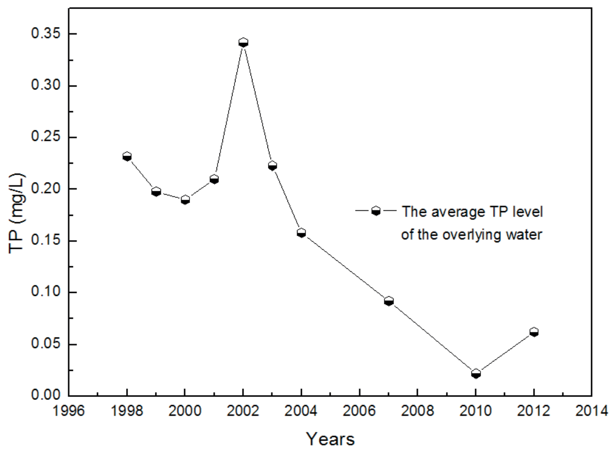

Fig. 5. The change trend of the average TP level in the overlying water of Lihu Lake.

had been returned to the fourth class of the national surface water environmental quality standard since 2007. The facts demonstrated that, under the strictly controlling of exogenous pollution sources, the environmental treatment projects and artificial ecological projects for endogenous pollution sources were an effective approach to improve the water quality of the eutrophic lake.

4. Conclusion

The levels and spatial distributions of phosphorus in the overlying water, interstitial water and sediments in Lihu Lake were investigated and the water quality of the lake was preliminarily evaluated. The TP concentrations in the overlying water ranged from 0.024 to 0.306 mg/L and the average value reached 0.064 mg/L. The spatial distribution trends of TP and DIP levels in the overlying water were both as follows: Zone A < Zone < B < Zone C < Zone D. The spatial distribution trends of DTP and inorganic phosphorus levels in the interstitial water were consistent with the ones of TP and DIP levels in the overlying water. The average DTP level of the interstitial water was 4.36 times higher than the one of the overlying water. The interstitial water could continuously release the bio-available phosphorus. The TP concentrations in the surface sediments were still high with an average concentration of 593.75 mg/kg. The DTP levels in the interstitial water had a positive correlation relationship with the TP levels in the sediments. Environmental conditions change could lead to the re-release of phosphorus from the sediments. Since 2003, the artificial ecological projects and environmental treatment projects could significantly reduce endogenous pollution sources and effectively improve the water quality of the eutrophic lake. As a result, the TP level of the overlying water showed a decreasing trend from 2002 to 2012.

Acknowledgements

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