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Temporal and Spatial Variations of Nutrients in Baiyangdian Lake, North China

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ABSTRACT. Baiyangdian Lake is the largest shallow freshwater body in the North China Plain. In this study, the spatial and temporal variations of nutrients have been studied based on the monthly data of eight state monitoring stations from 2000 to 2009. The results showed that: (1) Total phosphorus and total nitrogen were major pollutants in Baiyangdian Lake. The synthesized trophic state index indicated that the lake was in eutrophic or supereutrophic state. (2) Total phosphorus concentrations were higher in summer and autumn, and total nitrogen concentrations were higher in autumn and winter for most years from 2000 to 2009. Inter-annual water quality analysis showed that Baiyangdian Lake was seriously polluted in 2006, and the water quality in 2009 was the best in recent decade. (3) The water quality in the west of the lake was worse than that in eastern section, which caused by the point source pollution. In addition, nitrogen and phosphorus from non-point source might enter the lake through domestic sewage, the wastes and animal husbandry from the villages in the lake. (4) Variations of water level were influenced by both precipitation and water recharges. Total phosphorus concentrations in the lake were negatively correlated with water levels for most years, inferring that the dilution effects of water recharges could relieve water pollution in Baiyangdian Lake. This study suggested that the integrated management of water resources should focus on both pollution source control and water recharge regulations.

Keywords: Baiyangdian lake, eutrophication, hydrological condition, nutrients, water quality

1. Introduction

Both nitrogen and phosphorus were required to support aquatic plant growth and were the key limiting nutrients in most aquatic ecosystems (Conley et al., 2009). However, excessive nutrients will lead to water eutrophication. Therefore, nitrogen and phosphorus in natural waters have been studied extensively. Xia et al. (2004, 2009) examined the mechanism regarding the effects of suspended solids on nitrification in freshwater systems, the Yellow River with high solid contents. Zhang et al. (2008) have reported the temporal and spatial dynamics of nitrogen in lake and interstitial water of Chaohu Lake, China. The results showed that strong oxidative nutrient regeneration occurred near the sediment-water interface, and the sediment-water diffusive fluxes of ammonium caused a higher biomass of the phytoplankton. Neal et al. (2008) discussed the Nutrient Water Framework Directive issues of water quality management in terms of higher concentrations of nitrate and soluble reactive phosphorus in most rivers. Gardner and McCarthy (2009) also examined nitrogen dynamics at the sediment-water interface in Florida Bay. It was found that dissimilatory nitrate reduction to ammonium and dissimilatory nitrate reduction to nitrite were important mechanisms for retaining bioavailable fixed N as NH_4^+ or NO_2^- in Florida Bay, especially in summer. Wagner (2010) calculated the loading of nitrogen and phosphorus from various pollution sources and provided feasible measures to reduce nutrient contents in Lake Waco. In addition, several evaluation methods have been used to assess lake eutrophication, such as ecological risk assessment method (Wang et al., 2008), the synthesized trophic state index model (Yu et al., 2010) etc.

Baiyangdian Lake, the largest shallow freshwater body in the North China Plain, is of great importance in providing water resources, controlling floods, and regulating regional climate for the basin (Liu et al., 2006). Prior to the 1950s, Baiyangdian Lake was well known for its scenic beauty and richness of aquatic organisms. But since that time, the water quality has continuously worsened as a result of increasing pressures from the population expansion and economic development. Eutrophication has been considered as the major problem of Baiyangdian Lake since the 1980s. Thus, it is imperative to have reliable information on water quality for effective water pollution control and water resource management.

With regard to Baiyangdian Lake, several researchers have presented information regarding hydrological conditions (Cui et al., 2010; Moiwo et al., 2010), risk assessments of organic pollutants (Liu et al., 2010; Hu et al., 2010a; Hu et al., 2010b), and bioaccumulations of heavy metals (Chen et al., 2008). However, the study on spatial and temporal variation

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of nutrients in Baiyangdian Lake was scarce, which often made it difficult to identify water quality information and the pollution sources. Besides that, water recharges were important for water balance in shallow Baiyangdian Lake. In this case, the research questions of this study mainly focused on two parts: (1) the distribution characteristics of water nutrient concentrations in Baiyangdian Lake; (2) the effects of water recharge on water quality in Baiyangdian Lake.

Therefore, this study firstly elaborated the characteristics of eutrophication and nutrients in Baiyangdian Lake. The temporal and spatial variation trends of water quality were explored based on the monthly water quality data, including total nitrogen (TN), total phosphorus (TP), dissolved oxygen (DO), chemical oxygen demand (COD_{Mn}) and biological oxygen demand (BOD) at eight state monitoring stations from 2000 to 2009. The synthesized trophic state index was applied to evaluate the trophic state. Then, the relationship between variations of water quality parameters and hydrological conditions were investigated. In addition, the pollution sources were analyzed.

2. Materials and Methods

2.1. Study Area

Baiyangdian Lake, located in the North China Plain (115º45’ ~ 116º07’E, 38º43’ ~ 39º02′N), is a major part of Daqinghe River water system, which belongs to Haihe River basin (Figure 1). It is consisted of 143 small and shallow lakes linked by thousands of ditches, with a mean surface area of 366km^2 and a water depth of less than 2 meters (Xu et al., 1998). Major rivers, such as Zhulonghe River, Xiaoyi River, Tanghe River (including Qingshuihe River), Fuhe River, Caohe River, Puhe River, Pinghe River and Baigouyinhe River converge to form Baiyangdian Lake at Anxin County. Of all these rivers, Fuhe River is an important pollution source for the lake, as it receives almost all the agricultural runoffs, domestic and industrial sewages from Baoding City. There are 156 reservoirs in Baiyangdian basin, with a total capacity of 3.64 × 10^{9}m^3, in which Angezhuang Reservoir, Wangkuai Reservoir and Xidayang Reservoir are three major reservoirs for water supplement of Baiyangdian Lake.

2.2. Data Sources

Water samples were collected monthly from eight state monitoring stations. As shown in Figure 1, Nanliuzhuang village is the only entrance for Fuhe River flows into Baiyangdian Lake. Wangjiazhai village, located in the lake, which is referred as “overpopulated village zone” and “recreation center area”. Duancun village, the entrance of Wangkuai Reservoir discharges into the lake, is near the wastewater reservoir of Tanghe River. Shaochedian village, the entrance of Angezhuang Reservoir discharging into Baiyangdian Lake, lies in the northernmost region. Zaolinzhuang village is the outflow of the lake. Quantou and Guangdianzhangzhuang villages are located in the center of the lake, in which the former is protection zone of fish habitat for its relatively better water quality. Caiputai village is in the east that far from the Fuhe River.

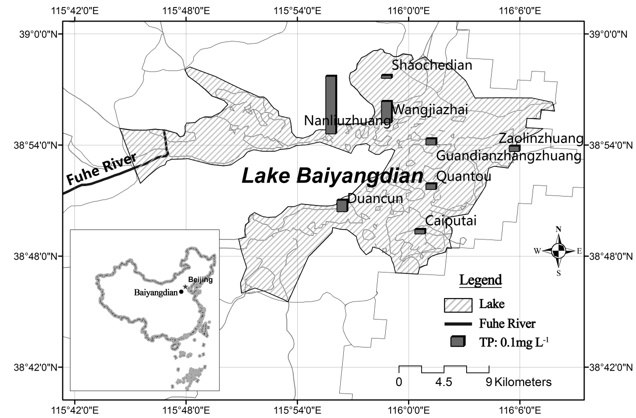

Figure 1. Locations and eight sampling sites in Baiyangdian Lake.

Water samples were collected at 0.5 m depth (representative of the mixed water columns) of the lake. The monitoring water quality parameters included TN, TP, DO, BOD, *chla*, COD_{Mn} and secchi disk depth (SD) from 2000 to 2009. The analytic methods used were based on the “State criteria of the People's Republic of China, water quality criteria” raised by State Environmental Protection Administration of China (State Environmental Protection Administration of China, 2002). Ammonium molybdate spectrophotometric method and alkaline potassium persulfate digestion-UV spectrophotometic method were applied to total phosphorus and total nitrogen concentrations analysis. The electrochemical probe method and dilution and seeding method were used to analyze the concentrations of dissolved oxygen and biological oxygen demand, respectively. The spectrophotometric method and permanganate oxidation method were used to measure the *chla* and COD_{Mn} concentrations. The secchi disk was used to measure secchi disk depth. The water quality data (TN, TP, BOD, COD_{Mn}, DO, SD and *chla*) and hydrological data (precipitation, evaporation and water levels) were all obtained from the Agency of Environmental Protection of Anxin County, Hebei Province.

2.3. Statistical and Assessment Methods

Correlations of water quality parameters and water levels were analyzed by using Statistical Package for Social Scientists (SPSS) 13th version. The trophic state index (TSI) method was used to evaluate trophic state in the lake.

The trophic state index (TSI) proposed by Carlson (1977, 1991), also presented by Kratzer and Brezonik (1981) and Havens (1995), is an acceptable method to evaluate lake trophycation, as it provides a continuous numerical class of lake trophic state and a reliable method for quantitative studies of eutrophication mechanism (Yu et al., 2010). The improved Carlson’s trophic state index was investigated by the research group of the lake and reservoir eutrophication in China that selecting *chla*, TP, TN, COD_{Mn}, and SD as the evaluating variables (Jin et al., 1995). Then China National Environmental Monitoring Centre carried out the synthesized trophic state index (STSI) based on the improved Carlson's equations to classify lake trophic states. In this study, the STSI was applied to evaluate the eutrophic state in Baiyangdian Lake. The detail of the evaluation method was given below (Wang et al., 2002):

The improved Carlson's equations for single trophic state index (TSI) are defined as:

$$\begin{cases} TSI(chla) = 10 \times \left[2.5 + 1.086 ln(chla)\right] \\ TSI(TP) = 10 \times \left[9.436 + 1.624 ln(TP)\right] \\ TSI(TN) = 10 \times \left[5.453 + 1.694 ln(TN)\right] \\ TSI(SD) = 10 \times \left[5.118 - 1.94 ln(SD)\right] \\ TSI(COD) = 10 \times \left[0.109 + 2.661 ln(COD)\right] \end{cases} \quad (1)$$

where *chl*a, TP, TN, COD_{Mn} are the concentrations in water body, and SD is the secchi transparency of water.

Next, the weight coefficient W_j of the *j*th trophic state index (TSI_j) can be calculated by taking the *chl*a as basic index, and the formula is:

$$W_j = \frac{r_{ij}^2}{\sum_{j=1}^{m} r_{ij}^2} \quad (2)$$

where r_{ij} is the relative coefficient between the *j*th index and *chl*a, and it is from the computing results based on the investigation data of 26 typical lakes in China including shallow and macrophyte-dominated lakes, which was suitable for Baiyangdian Lake (Table 1), r_{ij}^2 is the square of r_{ij}, and *m* is the number of variables.

Then, the STSI was obtained as:

$$STSI = TSI(\Sigma) = \sum_{j=1}^{m} \left[w_j \times TSI_j \right] \quad (3)$$

where w_j is the weight of the *j*th index that is shown in Equation 2, TSI_j is the *j*th trophic state index shown in Equation 1. At last, the values of STSI could be used to classify the trophic state of the lake (Table 2).

3. Results and Discussion

3.1. The Hydrological Condition of Baiyangdian Lake

Figure 2 showed the variations of the averaged water levels, precipitation and evaporation in Baiyangdian Lake. There were two peaks for the water level curve. The first was influenced by artificial water supply from reservoirs; and the second was influenced by the arrival of the rainy season, which was similar to the variation of the difference between precipitation and evaporation. Thus, both water recharges and precipitation influenced the variations of water levels in shallow Baiyangdian Lake. This hydrological condition in Baiyangdian Lake was different from that in other lakes such as the Taihu Lake, where high water levels occurred in rainy season and low water levels ha- ppened in dry season (Yang and Liu, 2010).

Table 1. Correlation Coefficients between Water Quality Index and *chl*a (Wang et al., 2002)

Parameters	chla	TP	TN	SD	COD_{Mn}
r_{ij}	1.0000	0.84	0.82	-0.83	0.83
r^2_{ij}	1.0000	0.7056	0.6724	0.6889	0.6889

Table 2. Correlations between Synthesized Trophic State Index and the Level of Lake Water Quality (Wang et al., 2002)

Trophic state	Synthesized trophic state index	Water quality
Oligotrophic	$0 < STSI \leq 30$	Excellence
Mesotrophic	$30 < STSI \leq 50$	Good
Eutrophic	$50 < STSI \leq 60$	Polluted
Supereutrophic	$60 < STSI \leq 70$	Superpolluted
Hypereutrophic	$70 < STSI \leq 100$	Hyperpolluted

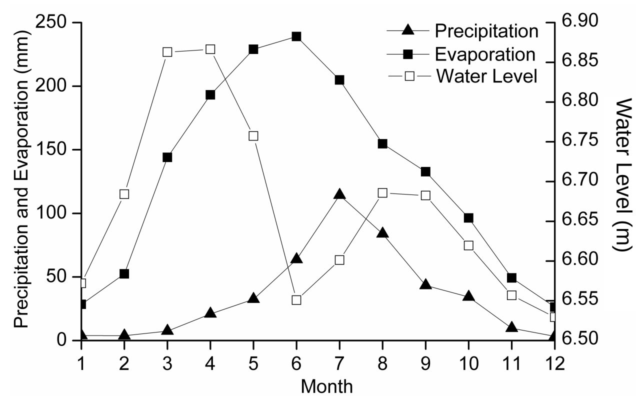

Figure 2. Monthly variations of averaged water levels, precipitations and evaporations in Baiyangdian Lake (2000-2009).

3.2. Temporal Variations of Nutrients in Baiyangdian Lake

Nutrient concentrations in Baiyangdian Lake were relatively higher compared to other lakes. Monthly averaged TN concentrations in Baiyangdian Lake varied from 2.56 to 5.6 mg/L (2000 ~ 2009), which were higher than that in Lake Okeechobee (1.2 ~ 2 mg/L during the period of 1999 ~ 2003), a shallow and eutrophic lake in USA. In Lake Taihu, the third largest freshwater lake in China, the averaged TN concentrations occurred in a similar range (2 ~ 5 mg/L in the period of 2001 ~ 2005) as observed in Baiyangdian Lake. Monthly averaged TP concentrations in Baiyangdian Lake were from 0.08 to 0.61 mg/L (2000 ~ 2009), which were higher than that in Lake Okeechobee and Lake Taihu, with the concentration ranges of 0.05 ~ 0.2mg/L (1999 ~ 2003) and 0.07 ~ 0.16 mg/L (2001 ~ 2005), respectively (James et al., 2009).

The monthly variation of TP concentrations was analyzed for each year from 2000 to 2009 in the lake, and the results

Table 3. Conditions of Water Recharges and Comparisons of TP Concentrations between the Reservoirs and Baiyangdian Lake (2000 - 2009)

Period of water recharge	Reservoir	WD out of the reservoir (10^4 m^3)	WR flow into the lake (10^4 m^3)	TP in the reservoir (mg/L)	TP in the lake (mg/L)
2000.7	Angezhuang	3111	1800	0.07	0.5
2000.12. - 2001.1.	Wangkuai	7902	4060	0.015	0.105
2001.2. - 2001.3.	Angezhuang	3287	2164	0.01	0.35
2001.6. - 2001.7.	Wangkuai	9079	4513	0.055	0.24
2002.2. - 2002.3.	Xidayang	5015	3501	0.06	0.35
2002.4. - 2002.5.	Xidayang	3873	1974	0.015	0.205
2002.7. - 2002.8.	Wangkuai	6108	3104	0.05	0.305
2003.1. - 2003.3.	Wangkuai	20000	11634	0.18	0.37
2004.2. - 2004.6.	Yuecheng	39000	16000	0.025	0.19
2005.3. - 2005.4.	Angezhuang	5863	4251	0.025	0.19
2006.3.	Angezhuang	3200	828	0.05	0.3
2006.3. - 2006.4.	Wangkuai	9000	4844	0.03	0.27
2006.11. - 2007.3.	The Yellow River	20000	10010	0.10	0.15
2008.1. - 2008.6.	The Yellow River	31200	15660	0.10	0.25
2009.6. - 2009.7.	Angezhuang	6974	1725	0.045	0.135
2009.11.	The Yellow River	20000	10000	0.10	0.27

Notes: WD = water discharge; WR = water recharge; TP = total phosphorus; Min = minimum.

showed that TP concentrations varied seasonally with the higher values occurring in summer and autumn, and the lower values occurring in spring and winter for most years. As shown in Table 3, water recharges usually occurred in spring and winter, and the averaged TP concentrations of eight monitoring stations in the lake were higher than that in the reservoirs (2000 ~ 2009), with the values of 0.11 ~ 0.37 mg/L for the lake and 0.01 ~ 0.18 mg/L for the reservoirs, respectively. Besides that, TP concentrations were negatively correlated with water levels in eight years of 2000 ~ 2009, and the correlations were significant in 2000, 2007 and 2009 ($P < 0.05$). Thus, water recharges from the reservoirs mainly relieve water pollution with dilution effect in Baiyangdian Lake. Taking 2007 for example, the maximum of mean TP concentrations of the eight stations (0.66 mg/L) occurred in August and the minimum (0.05 mg/L) occurred in March (Figure 3). That the maximum of TP in Baiyangdian Lake occurred in summer may be linked to the significantly negative correlation with lower water levels ($P < 0.05$), inputs of the industry wastewater and domestic sewage, as well as the precipitations during the rainy season.

The monthly variation of TN concentrations for each year from 2000 to 2009 was similar in eight years. The results showed that TN concentrations were lower in spring and summer (from May to August) than that in autumn and winter. In 2007, the maximum of TN concentrations in Baiyangdian Lake was 7.13 mg/L in December and minimum of 1.17 mg/L in May (Figure 3). The TN concentrations declined in spring and summer, which was mainly related to seasonally increased denitrification. It was reported that the proportion of TN removal by denitrification was typically 60 ~ 95% in wetland (Lee et al., 2009). Zimmerman and Benner (1994) presented that the maximal rates of denitrification generally occurring in the summer, and variation in water temperature accounted for 52% of the variability associated with denitrification rates. Similarly, Senga et al. (2010) found that the denitrifying activity increased in

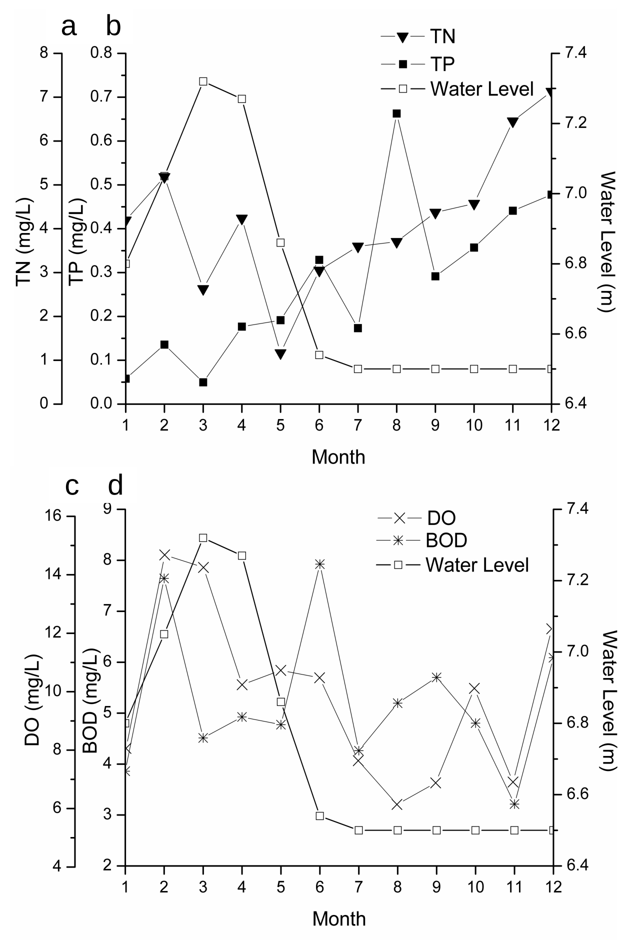

Figure 3. Monthly variations for averaged concentrations of water quality parameters and water levels in Baiyangdian Lake in 2007: (a) TP, (b) TN, (c) BOD, (d) DO.

Table 4. Annual Variation of Synthesized Trophic State Index in Baiyangdian Lake from 2000 to 2009

Year	TSI_{chla}	TSI_{TP}	TSI_{TN}	TSI_{CODMn}	TSI_{SD}	STSI	TS*
2000	55.34	74.69	77.51	61.49	73.16	67	SE
2001	56.72	71.14	77.50	60.35	73.62	67	SE
2002	53.65	70.21	78.23	62.65	77.03	67	SE
2003	56.31	74.74	86.21	58.69	75.97	69	SE
2004	61.43	68.75	78.12	61.31	77.63	69	SE
2005	52.09	65.62	80.19	61.53	67.63	64	SE
2006	63.15	68.82	81.65	61.44	75.66	70	SE
2007	63.83	73.60	78.80	61.97	69.67	69	SE
2008	59.91	70.70	79.02	57.84	65.62	66	SE
2009	45.56	63.63	75.75	59.21	64.84	60	ET

* TS: Trophic State; SE: Supereutrophic; ET: Eutrophic.

summer and was positively correlated with the temperature of the overlying water, with partial correlation coefficients from 0.64 to 0.88 ($P < 0.05$). For the Baiyangdian Lake, the water temperature increases significantly from May and declines from September, so the denitrifying activity is higher during May and August.

The BOD concentrations in Baiyangdian Lake varied from 3.21 in November to 7.92 mg/L in June (Figure 3). The maximum of DO concentrations occurred in February and the minimum was in August, with the values of 14.68 and 6.14 mg/L, respectively (Figure 3). It may be related with the high loads of organic nutrients in the lake and its decomposition by microorganisms, which consumes dissolved oxygen in the water. The more organic nutrients decomposed by microorganisms, the more oxygen be used, leading to the higher BOD value (Solanki et al., 2010).

3.3. Trophic State of the Baiyangdian Lake

Annual synthesized trophic state index ranged from 60 to 70 during the period of 2000 ~ 2009, with the minimum in 2009 and the maximum in 2006, respectively (Table 4). It was observed that water quality was the best in 2009, which was related to the highest water level in this year of recent decade. In 2006, a large quantity of industrial and domestic sewage from Baoding city illegally discharged into Baiyangdian Lake without any treatment. So water body was seriously polluted and "Dead Fish Event" occurred in the lake. In addition, STSI displayed a seasonal change that was similar to TP variation. Table 5 represented the monthly variations of trophic state in Baiyangdian Lake in 2007. The high value of STSI occurred in August that belonged to hypereutrophic state, and the minimum of STSI occurred in March when the lake was in eutrophic state.

3.4. Spatial Variations of Nutrients in Baiyangdian Lake

Figure 4 represented the spatial variation of water quality in eight monitoring stations in Baiyangdian Lake based on the analysis of annual average values of water quality parameters in the recent ten years (2000 ~ 2009). Figure 4a indicated that TP concentrations in Nanliuzhuang and Wangjiazhai villages

Table 5. Monthly Variations of Synthesized Trophic State Index in Baiyangdian Lake in 2007

Month	TSI_{CODMn}	TSI_{TP}	TSI_{TN}	TSI_{chla}	TSI_{SD}	STSI	TS
Jan.	10.37	9.03	14.11	15.22	11.13	60	ET
Feb.	10.96	11.63	14.75	14.99	16.76	69	SE
Mar.	9.99	8.56	12.69	13.57	10.44	55	ET
Apr.	10.72	12.44	14.14	13.51	10.59	61	SE
May	10.88	12.68	10.23	15.17	12.33	61	SE
June	12.00	14.34	13.14	16.44	13.53	69	SE
July	11.76	12.38	13.65	17.91	14.60	70	HE
Aug.	11.91	16.47	13.73	17.45	15.23	75	HE
Sep.	11.62	13.97	14.24	18.75	13.88	72	HE
Oct.	11.74	14.58	14.37	18.40	14.53	74	HE
Nov.	11.98	15.23	15.42	16.25	12.89	72	HE
Dec.	11.39	15.47	15.72	13.99	13.00	70	SE

* TS: Trophic State; ET: Eutrophic; SE: Supereutrophic; HE: Hyper-eutrophic.

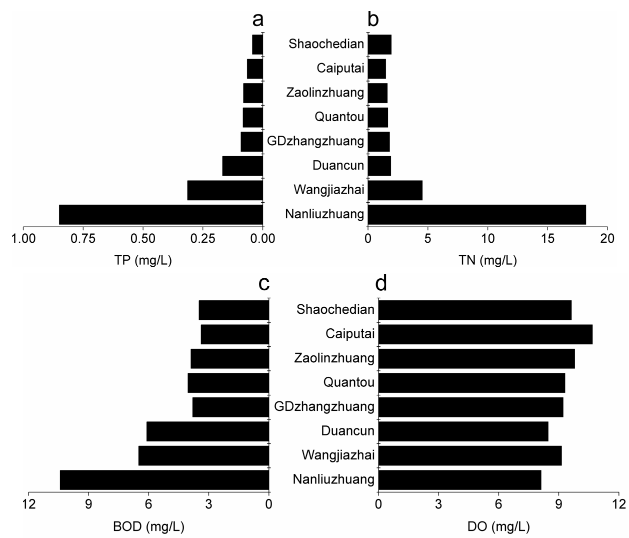

Figure 4. Spatial variations of water quality parameters in eight monitoring stations of Baiyangdian Lake (2000 - 2009): (a) TP, (b) TN, (c) BOD, (d) DO (GDzhangzhuang indicates Guangdianzhangzhuang).

were higher, which were almost twenty times larger than that in Shaochedian village. TN concentrations were also much higher in Nanliuzhuang and Wangjiazhai villages, but the minimum was found in Caiputai village that nearly one tenth of the maximum (Figure 4b). The water quality of the sampling sites closed to pollution sources in the west of the lake was worse than that in the east of the lake. Nanliuzhuang village, the entrance of Fuhe River flowing into Baiyangdian Lake, was located in the west of the lake. Fuhe River received almost all the domestic sewages and some industrial wastewater from Baoding City. It was indicated that the average TN and TP concentrations in Fuhe River were 30.33 and 2.27 mg/L from 2003 to 2008, respectively (Wang et al., 2010), which were much higher than that in Nanliuzhuang village, with the average values of 18.19 mg/L for TN concentration and 0.85 mg/L for TP concentration from 2000 to 2009. As in the case of shallow tropical water body in Andhra Pradesh State, India (Solanki et al., 2010), the lakes in towns and cities increasingly serve as sinks for domestic sewage, municipal, and industrial wastes. Wangjiazhai village, located in the lake, is an "overpopulated village zone" and "recreation center area", so a large quantity of domestic sewages, garbage and animal husbandry discharged into the lake directly without any treatment. The average TN and TP concentrations in Wangjiazhai village were 4.54 and 0.31 mg/L in ten years. Thus, non-point source pollution was also alarming.

Similar to distribution of nutrients concentrations, the maximum BOD concentrations were observed in Nanliuzhuang and Wangjiazhai villages, and the minimum values were in Guangdianzhangzhuang and Caiputai villages (Figure 4c). However, the distributions of DO concentrations were exactly the opposite, the averaged maximum occurred in Caiputai village and minimum occurred in Nanliuzhuang village (Figure 4d). BOD concentrations were positively correlated with TP and TN concentrations, with the correlation coefficients were 0.97 ($P < 0.01$) and 0.92 ($P < 0.01$), respectively. In contrast to spatial variation of nutrients, DO contents were significant negatively correlated with TP and TN concentrations ($P < 0.05$). Much higher nutrient concentrations in Nanliuzhuang and Wangjiazhai villages resulted in high oxygen consumption by microorganisms, which leads to higher biological oxygen demand and less dissolved oxygen in water.

3.5. Proposed Management Plan for Water Pollution

The temporal variation characteristics of nutrient concentrations in Baiyangdian Lake showed that TP concentrations were higher in summer and autumn, and TN concentrations were higher in autumn and winter. TP concentrations were negatively correlated with water levels in Baiyangdian Lake for most years. The spatial distribution of nutrients indicated that Nanliuzhuang and Wangjiazhai villages were most seriously polluted areas in the lake. Based on the obtained results, we proposed to strengthen water recharge regulations for the lake. Besides that, it was necessary to take measures to remediate Fuhe River pollution and strengthen non-point pollution controls in the lake. For examples, it proposed to build sewage treatment plants and domestic waste treatment stations to reduce the nutrient inputs to the lake.

4. Conclusions

This investigation revealed that Baiyangdian Lake was characterized by remarkable spatial and seasonal heterogeneity regarding water quality. TP concentrations were higher in summer and autumn, and TN concentrations were higher in autumn and winter. It was indicated that the minimum STSI occurred in 2009 and the maximum occurred in 2006. Thus, water quality was best in 2009 and worst in 2006 accordingly. The TP concentrations in the lake was negatively correlated with water levels ($P < 0.05$) for most years from 2000 to 2009, which indicated that the water recharges from the reservoirs could relieve water quality pollution in Baiyangdian Lake. Spatial analysis of water quality presented that Nanliuzhuang and Wangjiazhai villages influenced by domestic and Industrial pollutants from Fuhe River had the highest levels of nutrients in water body, while the lowest nutrient concentrations occurred in Caiputai and Shaochedian villages that were far from the pollution sources. Besides that, domestic sewages and the wastes and animal husbandry from the villages were also major reasons for higher nutrient concentrations in the lake. This study suggested that great efforts should be made on controlling pollution sources in the lake and the Fuhe River, as well as strengthening water recharge regulations for Baiyangdian Lake.

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