Investigation of water pollution in Baiyangdian Lake, China

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Abstract

To delineate the water quality of Baiyangdian Lake, North China, a ten-year analysis (2000-2009) of the variations on water quality parameters were conducted in the lake. The results showed that the variation of pollution indexes for TP, TN and NH$_4^+$ took a larger fluctuation and two “pollution peaks” appeared in 2000 and 2006 in the comprehensive pollution index curve. A simple model was subsequently used to analyze the response of Baiyangdian Lake when the nutrients loading rates were changed. This model described the variations of lake parameters related with nutrients concentrations. It also suggested that maximum tolerance discharges of total phosphorus and nitrogen to Baiyangdian Lake is 10 tons/year and 437.5 tons/year, respectively.

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Keywords: water pollution; human activity; Baiyangdian Lake; nutrients; water environment

1. Introduction

In the industrialized world, eutrophication is a common problem in fresh water ecosystems. It is also an important issue of water environment that has been attracted by many countries in the worldwide (Carpenter et al, 1998[1]; Wang et al, 2008[2]). Lakes have important functions, such as the sources of drinking water, irrigation, shipping, fishery, landscape entertainment and energy production. However, all these functions depend on the water quality which should be based on a well-balanced environment in terms of its physical, chemical and biological variables (Yu et al, 2010[3]). Many freshwater lakes undergo eutrophication with the increasing input of nutrients (Zhang et al, 2008[4]). Certain chemicals, such as nitrogen, phosphorus, can distort and disrupt aquatic ecosystems by overfeeding. In most of the lakes of China, the severe eutrophication, degeneration of ecosystems and deterioration of water quality has resulted in uncontrolled nutrient inputs to water bodies and their proximity to agriculture and use in aquaculture (Chen et al, 2008[5]).

Conley (2009) [6] showed that a focus on only P Schindler (1977) [7] or N (Elser et al. 1990[8]; Downing and McCauley 1992[9]) reduction should not be considered unless there is clear evidence or strong reasoning that a focus on only one nutrient is justified in that ecosystem and will not harm downstream ecosystems. Therefore, understanding the variations of N and P concentrations are both of key important for water environment improvement.

Baiyangdian Lake, the only largest freshwater body in the North China Plain, plays an important role in providing water resources, controlling floods, and regulating regional climate (Liu et al, 2006[10]). Baiyangdian Lake is of great importance with respect to drinking, fishing, tourism and energy generation. In recent decades, the aquatic environment of Baiyangdian Lake has changed
drastically and come into exacerbated trend because of domestic wastewater inputs, the influent of upstream rivers of through runoff in flood seasons, the release of endogenesis sediment and the pollutants of tourism.

Many researchers have studied on Baiyangdian Lake pollution. Li et al. (2006) [11] evaluated current water quality of Baiyangdian Lake by using multi-variate analysis. Li et al. (2007) [12] applied the improved principal component analysis method to estimate water quality in Baiyangdian Lake. Wang and Yin (2008) [13] suggested that the boundary filtration effect of reed-bed wetlands is important for improving the water quality of inland waters, and this effect should be considered in regulating and managing lake water levels. Wang et al. (2009) [14] analyzed water quality balance and developed water quality model based on BP structure of artificial neutral network. Zhang et al. (2010) [15] investigate the spatial-temporal variation of the water quality and the main factors affecting the quality by using grey clustering comprehensive pollution index and single factor pollution indexes. However, little is known about the lake conditions when the nutrient loading changes. And this is necessary for forecasting the water environment in the future, which is also useful for water quality improvement.

Several predictive models have been developed to evaluate the effect of nutrients loads on the in-lake nutrient concentration, in which the input-output or mass-balance approach is the most common method. Reckhow (1988) [16] developed a phosphorus input-output model that incorporated data from lakes and reservoirs in the southeastern U.S. This model is accurate for the in-lake phosphorus concentration in Swift Creek Reservoir and Occoquan Reservoir. Arman (2009) [17] used this model the response of Lake Sapanca when the phosphorus loading rate was changed. And the variation of different parameters with respect to phosphorus concentration was studied to identify effects and results.

In this paper, we use comprehensive pollution index method to identity the current pollution condition of Baiyangdian Lake. In the next section, a simple model is developed based upon the ideas of mass-balance approach developed by Reckhow (1988) [16]. Through this model, the variation of different parameters (time, mass flow, net specific rate of loss to sediment, lake volume and surface area) with respect to nitrogen or phosphorus concentration (C) were studied to identify the effects and results water eutrophication. Finally, the threshold values of input rates of nutrients concentrations are calculated and the measures to protect the lake are discussed.

2. Materials and Methods

2.1 Description of Study Area

Baiyangdian Lake is one of the biggest lakes in the North China Plain, with an area of 366km² that located in the range of 115°45′–116°07′E and 38°43′–39°02′N. It is consisted of 143 small and shallow lakes linked by thousands of ditches at a water level of 5.5-6.5m above the sea level (Dagu Height). In the recent 50 years, the water depth varies between 5.2m and 9.26m. When the water depth is less than 5.5m, the lake is drying. In the basin, there are 156 reservoirs, with a total capacity of 3.64 ×10⁹m³, in which Angezhuang Reservoir, Wangkuai Reservoir and Xidayang Reservoir are three major reservoirs for water diversion of Baiyangdian Lake.

2.2 Sampling.

In order to assess water pollution of Baiyangdian Lake, eight state controlling sampling sites (Guangdianzhang Zhuang, Quan Tou, Caipu Tai, Duan Cun, Shaoche Dian, Zaolin Zhuang, Wangjia Zhai, Nanliu Zhaug) were collected around the lake (Fig. 1). The related water quality parameters, such as total nitrogen (TN), total phosphorus (TP), dissolved oxygen (DO), pH, BOD₅, COD from 2000 to 2009 were analyzed. These data were monitored every other month in each year. All the hydrological and water quality data were obtained from Anxin Environmental Protection Bureau.
3. Results and Discussion

3.1 In situ parameters

Annual average water discharge (m$^3$), temperature (°C), pH, dissolved oxygen (mg/L) for Baiyangdian Lake from 2000-2009 were given in Table 1. During the time period of ten years, the highest temperature was 19.8 °C in 2001, and the minimum value was 15.8°C in 2007. The average pH was about 8, almost with no difference. But the variations of average dissolved oxygen and water discharge values were relatively large, ranged 0.18-1.07×10$^8$m$^3$ and 5.8-10.7mg/L, respectively. Many factors could affect DO values, such as water temperature, intensity of photosynthesis, lake hydrodynamism, oxygen consumption of chemical and biological metabolism etc (Zhang et al, 2007[18]).

Table 1. Annual average water discharge, temperature, pH and DO values for Baiyangdian Lake (2000–2009)
### Table 1. Average water discharge, Temperature, pH and DO from 2000 to 2009

| Year | Average water discharge ($10^8$ m$^3$) | Temperature (°C) | pH | DO (mg/L) |
|------|--------------------------------------|----------------|----|-----------|
| 2000 | 0.50                                 | 16.1           | 8.8 | 10.0      |
| 2001 | 0.38                                 | 19.8           | 8.3 | 8.9       |
| 2002 | 0.18                                 | 16.9           | 8.3 | 10.7      |
| 2003 | 0.50                                 | 16.2           | 8.1 | 7.8       |
| 2004 | 0.85                                 | 16.5           | 8.1 | 9.0       |
| 2005 | 1.07                                 | 18.1           | 8.2 | 5.8       |
| 2006 | 0.65                                 | 17.7           | 8.2 | 9.1       |
| 2007 | 0.58                                 | 15.8           | 8.1 | 10.0      |
| 2008 | 0.95                                 | 17.4           | 8.0 | 8.1       |
| 2009 | 0.95                                 | 17.5           | 8.1 | 8.6       |

#### 3.2 Comprehensive evaluation of water quality of Baiyangdian Lake

By comparing the standard limited values ("Environmental quality standards for surface water"—Chinese standard GB 3838-2002) of water quality with the annual average water quality parameters from 2000 to 2009, the results showed that volatile phenol, cyanide, mercury, arsenic, chromium VI and heavy metals were minor pollutants that their mean values were lower than Standard Level III. Thus, seven representative indicators, including pH, DO, permanganate index, BOD$_5$, TP, TN and NH$_4^+$ were chosen as the estimation parameters, and the comprehensive pollution index method was used to analyze the water quality changes of Baiyangdian Lake. The integrated pollution value ($P$) is given by:

$$ P = \frac{1}{n} \sum_{i=1}^{n} \frac{C_i}{S_i} $$

where $P$ is comprehensive pollution index, $P_i = C_i / S_i$ is single pollution index for one pollutant, $C_i$ is the annual average concentration of the measured pollution index (mg/L), $S_i$ is the standard values of Chinese standard GB 3838-2002, Level III (mg/L), respectively.

In general, the relationship between comprehensive pollution index $P$ and water quality level is presented as follows:

| $P$   | Water quality level |
|-------|---------------------|
| ≤0.20 | I Cleanness         |
| 0.21-0.40 | II Sub-cleanness    |
| 0.41-1.00 | III Slight pollution|
| 1.01-2.00 | IV Moderate pollution|
| ≥2.01 | V Severe pollution  |

The results showed that the variation of single pollution indexes for TP, TN and NH$_4^+$ took a larger fluctuation (Fig. 2). From 2000 to 2009, the annual average pollution index of TP was largest except 2005 and 2006. And the variation trends of TN and NH$_4^+$ were similar. The maximum contamination values of these two water quality parameters were 5.21 and 3.52 in 2005. The minimum values were 2.60 in 2002 for TN and 0.19 in 2001 for NH$_4^+$, respectively. The variations of pollution indexes for other parameters were relatively stable, but their water quality levels were still in Level IV or V.
With the rapid development of economy and improvement of living standard, the untreated waste water from industry and living flowed into Baiyangdian Lake, which exacerbated pollution of water environment. In China, the fisheries production mainly from freshwater culture in ponds, reservoirs, lakes, and river channels (Zhong and Power, 1997[19]; Liu and Diamond, 2005[20]). In most cases, these water bodies are extremely eutrophic that receiving nutrients from both agricultural runoff, human waste and the aquaculture itself. Besides that, as fishery is a major industry for local resident, it is reported that only 13.9% N and 25.4% P of the baits could be utilized, the remains sank into sediment or water environment, which caused the serious pollution of nitrogen and phosphorus (Xu et al, 1998[21]).

The comprehensive pollution index was increasing with fluctuation (Fig. 3). Two “pollution peaks” appeared in 2000 and 2006, as the “died fish event” of large areas happened in the time period as the result of water level decline and water quality deterioration. After that, the government took measures to close the enterprises that were not up to standard and start to dispatch of water quantity of reservoir quickly. Then the water environment degradation was alleviated and the comprehensive pollution index decreased. From 2000 to 2002, the comprehensive pollution declined from 3.00 to 1.93. In the period of 2003-2005, this value was about 2.3. During 2007-2009, the contamination index was reduced to 1.92, the minimum of ten years.

### 3.3 A simple eutrophication model applied to Baiyangdian Lake

Assuming that long-term effects of water pollution can be evaluated by yearly average nutrients concentrations in a well-mixed lake, a mass balance equation could be developed for the nutrients in the lake. The scheme of a simple model for this case is described in Fig. 4.
So the rate of change in concentration with time is given as follows:

\[
\frac{dC}{dt} = \frac{M}{V} \cdot \frac{CQ}{V} \cdot \frac{KCA}{V} \tag{2}
\]

where \(M\) is mass flow from all sources (g/year), \(C\) is the average annual nutrient concentration (mg/L), \(K\) is net specific rate of loss to sediments (m/year), \(Q\) is average annual outflow (m\(^3\)/year), \(V\) is lake volume (m\(^3\)), \(A\) is surface area (m\(^2\)) and \(t\) is residence time (year) respectively. The expression of \(C\) with respect to \(C_0\) (g/m\(^3\)) at time zero from Eq. (2) is defined as:

\[
C = \frac{M}{Q + KA} \left( 1 - e^{-\frac{QK}{V}} \right) + C_0 e^{-\frac{QK}{V}} \tag{3}
\]

Eq. (3) described the nutrient concentration in water body as a function of time, as a result of changing the nutrient input rate, \(M\). This model can be used to analyze the response of Baiyangdian Lake when the nutrient loading rate changes. Table 3 shows the data used in the model. The model was developed on the annual average data of ten years (from 2000-2009). \(C_0\) was the mean concentration of nutrients in 2000.

Table 3. The parameters used in the model for Baiyangdian Lake

| Parameter                     | Unit | Real value | Range of simulated values |
|-------------------------------|------|------------|---------------------------|
| Total phosphorus              |      | Total nitrogen | Total phosphorus | Total nitrogen |
| Surface Area, A               | m\(^2\) | 83441700   | 83441700                  | 5x10\(^5\)-12x10\(^5\)  |
| Volume, V                     | m\(^3\) | 660000000  | 660000000                 | 2x10\(^7\)-10x10\(^7\)  |
| Net specific rate of loss to sediment, K | m/year | 0.289     | 1.102                     | 0-1.4                     | 0.25-2               |
| Nutrients input rate, M       | g/year | 6725748    | 262121622                 | 4x10\(^5\)-200x10\(^5\) | 7x10\(^5\)-70x10\(^5\) |
| Initial nutrients concentration, C0 | g/m\(^3\) | 0.244   | 3.938                     | 0.100-0.400              | 2.600-5.200         |
| Out flowrate, Q               | m\(^3\)/year | 0        | 0                        | 0                         |

3.4 Variations of lake parameters related with nutrients concentrations in Baiyangdian Lake

Variation of residence time and phosphorus concentration in the lake can be represented by a rapid decrease during the first ten years followed by an almost steady-state condition (Fig. 5). In Fig.6, the nitrogen concentration took the similar variation trend with time as that in Fig. 5.

![Figure 5. Variation of residence time and phosphorus concentration in Baiyangdian Lake](image-url)
Fig. 6 illustrates the change of nutrient input rate (M) and phosphorus concentration. When the phosphorus input rate increased, the phosphorus concentration in Baiyangdian Lake decreased. However, the nitrogen concentration increased linearly with the increment of nitrogen input rate (Fig. 8).

Fig. 7. Variation of phosphorus input rate and phosphorus concentration in Baiyangdian Lake

Fig. 8. Variation of nitrogen input rate and nitrogen concentration in Baiyangdian Lake
Figs. 9 and 10 give the variation of specific rate of loss to sediments and nitrogen concentration in Baiyangdian Lake. This variation was obtained by using Equation (3). The figures revealed that when the net specific rate loss to sediment enhanced, both the phosphorus and nitrogen concentrations declined exponentially.

![Graph showing variation of specific rate of loss to sediments and phosphorus concentration in Baiyangdian Lake](image)

Figure 9. Variation of specific rate of loss to sediments and phosphorus concentration in Baiyangdian Lake

![Graph showing variation of specific rate of loss to sediments and nitrogen concentration in Baiyangdian Lake](image)

Figure 10. Variation of specific rate of loss to sediments and nitrogen concentration in Baiyangdian Lake

The volume variation and nutrients concentrations in Baiyangdian Lake are presented in Fig. 11 and Fig. 12. With the volume of the lake becoming large, the phosphorus and nitrogen concentrations reduced non-linearly, but the nitrogen concentration declined relative rapidly when the lake volume less than $3 \times 10^7$.

![Graph showing volume variation and phosphorus concentration in Baiyangdian Lake](image)

Figure 11. Volume variation and phosphorus concentration in Baiyangdian Lake
Figure 12. Volume variation and nitrogen concentration in Baiyangdian Lake
From Fig. 13, we can conclude that when the lake surface area increased, the phosphorus concentration firstly increased then decreased, in which the turning point is $8.5 \times 10^7$ m$^2$. Fig. 14 shows that when the surface area of the lake increased, the nitrogen concentration decreased.

**3.5 Nutrients input rates on variation of residence time and nutrients concentration in Baiyangdian Lake**

Fig. 15 denotes that the effect of nutrient input rate on variation of residence time and phosphorus concentration in Lake Baiyangdian. Two categories curves were found in this figure. It indicates that when the phosphorus input rate is bigger than 10 tons/year, the phosphorus concentration in the lake will increase in the first thirteen years, and the phosphorus concentration will decline when the input rate is smaller than 10 tons/year conversely. Similarly, fig. 16 demonstrates that when the nitrogen input rate is bigger than 437.5 tons/year, the nitrogen concentration in the lake will increase, and conversely the nitrogen concentration will decline when the input rate is smaller than 437.5 tons/year. In both cases, a steady-state condition is reached after ten years.
Therefore, the nutrient input rate (M) is the critical value. The largest yearly tolerance of phosphorus and nitrogen in Baiyangdian Lake is 10 tons/year and 437.5 tons/year, respectively. For this reason, the discharge of domestic sewage to the lake should be diverted or be subjected to treatment when the nutrient loadings exceed the tolerance level of the lake.

4. Conclusions

The annual mean pH, DO, permanganate index, BOD5, TN, TP and NH4+ of water samples form eight state controlling points were determined. By perusing the results of pollution index of the chemical analyses and considering the polluters in the basin, this study shows that TP and TN are main pollutants, which impacts on the eutrophication in Baiyangdian Lake. And TP is first pollutant which impacts on the eutrophication in the lake. From 2000 to 2009, the pollution indexes of almost all the selected water quality parameters were in water quality class IV or worse than that.

An eutrophication model forecast the response of the lake when the nutrient loading rates were changed in the following 50 years. It indicates that the critical values of nutrient input rates are 10 tons/year for phosphorus and 437.5 tons/year for nitrogen, respectively. That is, as long as the nutrient input rates are less than the threshold values, the nutrients concentration in the lake will reduce gradually. And in the first five to thirteen years, the response of the lake to the nutrient input rates are relative obviously, and then a steady state condition is attained.

Generally, the lake is an important water resource for domestic and industrial water supply and recreation when its quality and clarity are good enough. However in the recent years, Baiyangdian Lake has become heavily polluted, and the pollution level is in relatively high. The reason for the pollution is the pollutants from the upstream river,
Fuhe River, where the domestic sewages from Baoding City flow in. As Baiyangdian Lake is of great importance for improving ecological environment of North China, it is obligatory to take measures against the pollutants.

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