

Variation of Water Quality and Nutrient Load Limits in Lake Baiyangdian, North China

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Abstract: We used Vollenweider mass balance model that can predict maximum allowable nutrient loading rates or load limits (LM) for prediction of trophic status in Lake Baiyangdian's fresh waters. The average annual hydraulic inflow rate (Q_i) and nutrient input concentration (C_{Pi}) explained most of the variation in LM for guiding the lake management. We found such a single model for total phosphorus (TP) could provide a reasonable fit to trophic status in Lake Baiyangdian. The total phosphorus tolerance input value should not exceed 1.0×10^7 g/year, and the tolerance range C_{Pi} could be limited in less than 0.108 g/m^3 . The research results can facilitate the development of total maximum loads for water diversion from reservoirs and may have broader regional utility. They may also aid the development of nutrient concentration criteria.

Keywords: Total phosphorus; water quality; trophic state; mass balance model; Lake Baiyangdian

1. Introduction

Lake Baiyangdian, situated centrally in the North China Plain, plays important roles in water supply, aquaculture, tourism, and recreation, as well as being of great conservation value for wildlife and wetland vegetation. The lake was well known as "the pearl of North China" due to its beautiful scenery, convenient transportation facilities, and biodiversity, including species such as fish, shrimp, crabs, mussels, turtles, and economically important aquatic plants. In last century, heavy pollution and consecutive droughts led to a decrease in biodiversity. Chemical plants, paper mills, and oil chemical plants poured much wastes into the Lake Baiyangdian. The water quality in the lake is degraded, mainly caused by agricultural runoff and wastewater discharge from Boading City, while the reduction of the surface area and depth of the lake due to the global climate changes, even worsen the eutrophic situation^[1].

As well as the rest of the nation, Lake Baiyangdian is seriously challenged by the increasingly complex problems stemming from anthropogenic effects on its natural aquatic systems. Cultural eutrophication of freshwater systems and estuaries, as a consequence of nutrient enrichment, is one such effect that has heightened public concern, giving rise to many academic and governmental programs whose collective goal is to improve their trophic status and restore designated uses. The need to reduce anthropogenic nutrient inputs to aquatic ecosystems in order to protect drinking-water supplies and to reduce eutrophication, has been widely recognized^[2]. However, the costs of doing this are substantial; hence, developing the appropriate nutrient management strategy is very important^[3].

Work over the last 10 yr and well into the foreseeable future is focused on applying a large and growing body

of information on the relationships between nutrient loads and trophic status toward the development of nutrient criteria intended to reverse or prevent cultural eutrophication of Lake Baiyangdian's water bodies. Many demonstrations of successful phosphorus (P)-only control in lakes are found in the literature^[4]. The concept of nutrient loading as a factor controlling lake productivity or trophic state has been one of the most productive theories in limnology and has stimulated much discussion and research^[5]. Originally proposed by Vollenweider^[6] and later refined^[7], this concept has had a great impact on all subsequent eutrophication research and lake management. The basic assumption behind the nutrient loading concept is that there is a dependence of lake trophic state either directly on the nutrient supply rate (loading) or, more commonly, on the nutrient concentration in the water.

Models built on this concept often assume steady state conditions and rely on empirical relations between nutrient loading, sediment retention, lake water concentration and phytoplankton biomass and production. The theoretical background is normally the continuously stirred tank reactor principle adopted from chemical engineering. Another class of models is the theoretical, dynamic models building on a detailed description of the different processes and representing a technique borrowed from engineering and control theory^[4]. There are many review articles on different types of eutrophication models, such as several types of models by StraSkraba^[8] and Kamp-Nielsen^[9], dynamic eutrophication models by Scavia & Chapra^[10] and phosphorus-chlorophyll models by Nicholls & Dillon^[11]. These models are potentially powerful tools in eutrophication research and management. However, considering the P concentrations for the upper and lower bounds of the eutrophic status, as well as the data available, we select Vollenweider mass bal-

Supported by the National Water Pollution Control Major Project of China (No.2008ZX07209-009)

ance model as the optimum.

The purpose of this paper is to analyze and discuss some trophic parameters (residence time, phosphorus loading and the average annual input TP concentration) of the present state of the art in modeling lake trophic state as a function of phosphorus loading aiding by Vollenweider mass balance model.

2. Study area

Lake Baiyangdian, the largest natural freshwater body in the North China Plain, is located 130 km south of Beijing (48°43'–39°02' N and 115°38'–116°07' E). The lake consists of more than 100 small and shallow lakes linked to each other by thousands of ditches with a surface area of 366 km² and a catchment of 31,200 m² and lake depth varies according to the hydrologic conditions (Figure 1), but is usually less than 2.0 m [12].

During years 2000 to 2009 water quality was measured monthly in eight sampling sites of the lake by national Departments (Table 1). The sewerage system collects all the urban sewage and transfers them to the water treatment plant, which is situated west of the lake (near Nanliuzhuang sampling site). The sewerage system is separated: wastewater goes to the water treatment plant but rain water goes into the lake.

Table 1 Yearly average temperature, pH values and total phosphorous for the eight sampling sites of Lake Baiyangdian (2000-2009)

Sample point	Average temperature(°C)	Average Ph	Average TP(g/m ³)
Shaochedian	15.92	8.10	0.06
Wangjiazhai	17.24	8.16	0.31
Quantou	17.80	8.19	0.09
Zaolinzhuang	17.51	8.27	0.09
Caiputai	16.77	8.34	0.06
Guangdianzhangzhuang	18.51	8.15	0.11
Duancun	16.52	8.55	0.19
Nanliuzhuang	17.40	7.99	1.06
Total Average	17.21	8.22	0.24

3. Materials and Methods

Samples were collected during 2000-2009 from eight national sampling sites on Lake Baiyangdian (Figure 1).

Assuming that long-term effects can be approximated by average annual values in a well mixed lake, a mass balance can be written for the nutrient of interest. The scheme of a simple model for this case is presented in figure 2. The phosphorous, as the limiting element of

Lake Baiyangdian, has been recognized by many limnologists [13].

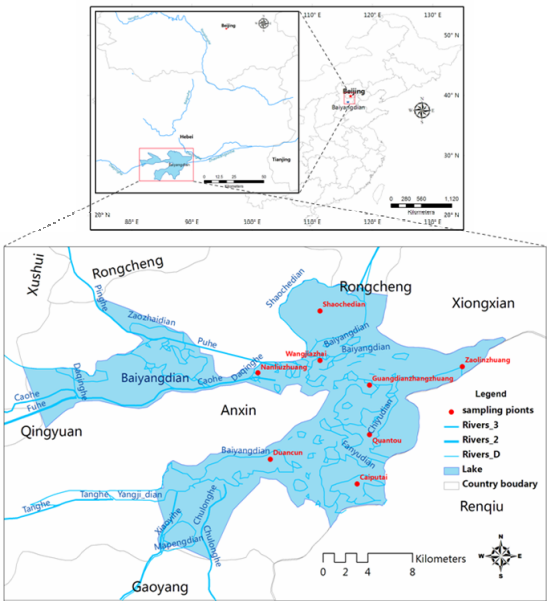


Figure 1 Location of Lake Baiyangdian for the study (red dots represent national sampling sites)

3. Materials and Methods

Samples were collected during 2000-2009 from eight national sampling sites on Lake Baiyangdian (Figure 1).

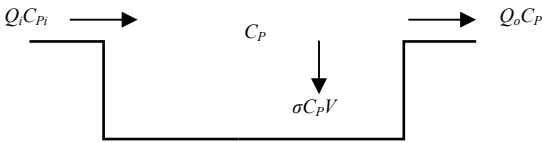


Figure 2 Scheme of the mass balance model

The rate of change in concentration with time is given by:

$$V \frac{dC_P}{dt} = Q_i C_{Pi} - \sigma C_P V - Q_o C_P \tag{1}$$

where Q_i is the average annual hydraulic inflow rate from all sources (m³/year), C_{Pi} is average annual input TP concentration (g/m³), C_P is TP concentration in the lake (g/m³), σ is first-order rate coefficient for TP loss from the lake (1/year), Q_o is average annual outflow (m³/year), V is lake volume (m³), t is residence time (year), M is the average annual TP input rate (g/year), and obviously M can be formulated by:

$$M = Q_i C_{Pi} \tag{2}$$

Integration of Eq. (1) C_{P0} from at time zero to C_{Pi} at time t yields:

$$C_p = (C_{p0} - \frac{Q_i C_{pi}}{V\sigma + Q_0}) \times e^{-(\sigma + \frac{Q_0}{V})t} + \frac{Q_i C_{pi}}{V\sigma + Q_0} \quad (3)$$

where C_{p0} is TP concentration at time zero.

Eq. (2) describes the concentration of TP in the water as a function of time, as a result of changing the TP input concentration (C_{pi}) and the average annual hydraulic inflow rate (Q_i). The model can be used to analyze the response of Lake Baiyangdian when the phosphorus loading rate changes.

4. Results

The most recent available data (2000-2009) are used to analyze trophic parameters of Lake Baiyangdian, including residence time, phosphorus loading and average annual input TP concentration.

4.1 Residence Time

The residence time (t) and TP concentration (C_p) in Lake Baiyangdian is shown in Figure 3. The residence time (t) and TP concentration (C_p) in Lake Baiyangdian can be represented by a rapid decline during the first twelve years followed by an almost steady-state condition (Figure 3).

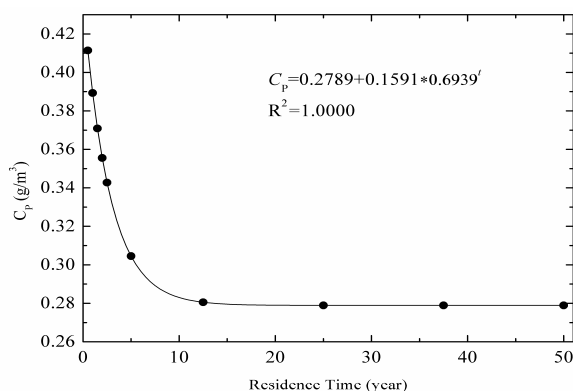


Figure 3 Variation of residence time (t) and TP concentration (C_p) in Lake Baiyangdian

4.2 Phosphorus loading

The effect of the average annual TP input rate (M) on variation of residence time (t) and TP concentration (C_p) in Lake Baiyangdian can be examined in two categories. The decline categories represent TP input rate gradient region from 2.0×10^6 — 1.0×10^7 g/year, and the increase categories represent TP input rate gradient region from 1.25×10^7 — 2.0×10^7 g/year. The effect of TP input rate on the variation of residence time and phosphorus concentration indicates a turning point where the decline occurs at about $C_p = 0.417$ g/m³ and the incre-

ment appears around $C_p = 0.451$ g/m³. In both cases, a steady-state condition is reached after twelve years. TP concentration of Lake Baiyangdian should be no more than 0.434 g/m³ and the maximum tolerance TP input rate should be limited less than 1.0×10^7 g/year (Figure 4).

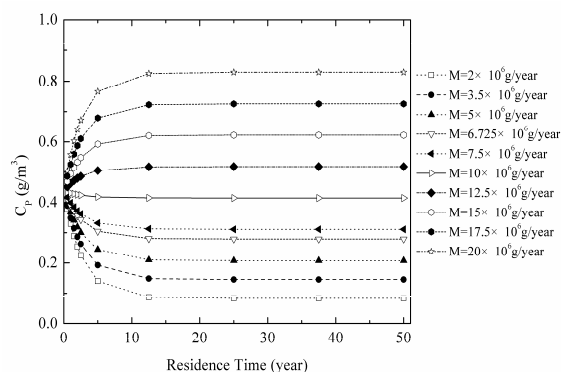


Figure 4 Effect of TP input rate (M) on variation of residence time (t) and TP concentration (C_p) in Lake Baiyangdian

4.3 The Average Annual input TP concentration

The effect of average annual input TP concentration (C_{pi}) on variation of residence time (t) and TP concentration (C_p) can also be examined in two categories, and indicates a turning point where the decline occurs at about $C_p = 0.417$ g/m³ and the increment appears around $C_p = 0.451$ g/m³. Similarly, the decline categories represent average annual input TP concentration (C_{pi}) gradient region from 0.015—0.084 g/m³, and the increase categories represent average annual input TP concentration (C_{pi}) gradient region from 0.131—0.200 g/m³. A steady-state condition is also reached after twelve years. The maximum average annual tolerance inputting TP concentration (C_{pi}) should be less than 0.108 g/m³ (Figure 5).

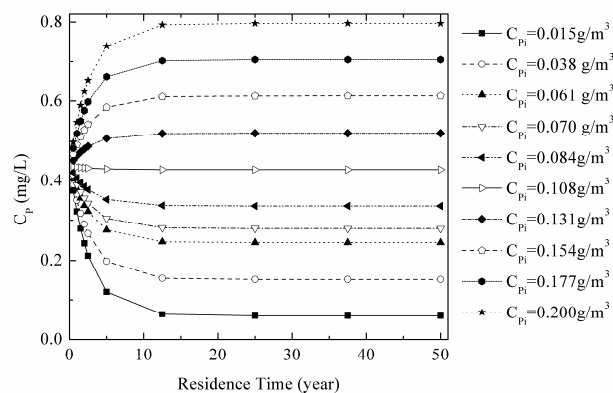


Figure 5 Effect of average annual input TP concentration (C_{pi}) on variation of residence time (t) and TP concentration (C_p) in Lake Baiyangdian

So, the average annual TP input rate (M) and the average annual inputting TP concentration (C_{Pi}) are two critical values. The maximum tolerance values of the critical values are 10 tons or 1.0×10^7 g/year and 0.108 g/m^3 . For this reason, it provides a theoretical basis for river and reservoir management. Especially, the nutrient concentration should be paying more attentions in Water Diversion Project.

5. Conclusion

The average annual hydraulic inflow rate and the average annual input TP concentrations on eight sampling sites in Lake Baiyangdian are determined. The values of loading, discharge and accumulation amounts of phosphorous causing eutrophication were calculated and the trophic state of the lake was determined. According to the results and analysis using Vollenweider mass balance model, management strategies should be taken such as water diversion regulations and processes. Furthermore, nutrient input rate and the nutrient concentration should be paying more attentions in practice.

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