Sustainable environmental flow management based on lake quality protection: The case of Baiyangdian Lake, China

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Abstract

Water shortages and quality deterioration are serious dilemmas for lake managers as both problems sharply decrease the ecosystem services and functions provided by a lake. In this paper, using WASP as a tool, we have established and calibrated a water quality simulation model for Baiyangdian Lake and then analyzed water quality variations in scenarios with different pollution load reductions and different environmental flow releases into the lake and discovered the sustainable schemes for environmental flow management. From the results, in the scenarios of 30%, 50%, and 90% pollutant load reduction, the sustainable environmental flows are 3.52, 3.13, and 2.12 m³/s, and the corresponding lake levels could attain 7.45 m, 7.35 m, and 7.05 m from the initial 6.0 m. The obtained results indicated that water release could improve the lake volume and quality simultaneously.

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Keywords: Environmental flows; pollutant load reduction; WASP; Baiyangdian Lake

1. Introduction

Lake water which is allocated and made available for maintaining ecological processes and particular ecological characteristics in a desirable state is referred to as the environmental flows for a lake [1, 2]. Environmental flow is one of the important components in water resources planning, management and allocation, and sustainable environmental flow benefits the health and maintenance of the aquatic ecosystem. Based on this previous research, the water balance, ecological water level, relative curve, and functional methods are typically used to assess the environmental flows of lakes and have recently been

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adopted for use in China [3]. Most of the research on environmental flows has focused on water quantity but has neglected water quality [4]. Amount of water could affect its water quality due to the self-purification of a lake. Although nature has an ability to maintain its balance and self-recovery, it still has limitations. As a result of industrial and urban development, large quantities of sewage are discharged into lakes, thereby degrading the water quality. Water quality problems, and especially eutrophication, are becoming increasingly important challenges in the management of lake water [5]. How the environmental flow will be under the water degradation? Islam et al. [6] predicted water quality improvement in environmental flow releasing to the Buriganga River. Cha et al. [7] describes a management scheme to control river water quality using additional water discharges from upstream dams, which results in an increase environmental flow followed by an enhancement of water quality in a target river, and they attempts to have an insight into the environmental flow under the environmental water degradation.

The main goal of this study was to analyze water quality variations in scenarios with different pollution load reductions and environmental flow releases into the lake to reveal sustainable schemes for environmental flow management.

2. Material and methods

2.1. Study area

Baiyangdian Lake (38°43'N to 39°02'N, 115°45'E to 116°07'E) is the largest shallow freshwater lake in northern China. It is located in Anxin County of Hebei province (Figure 1). The lake consists of more than 100 small and shallow lakes linked to each other by thousands of ditches, covering a total surface area of 362.8 km² when the water depth is 10 m.
Before the 1950s, nine tributaries in the upstream inflowing to the lake maintained the lake level above 7.5 m. However, succeeding construction of dams and reservoirs upstream of the lake, aimed toward economic and social water users, has profoundly changed its natural hydrologic regime [8]. The annual reservoir outflow is now wholly inadequate to meet the lake's e-flow requirements and restore ecosystem health, and the lake has become a semi-closed water body with no natural outflows.

At present, only water from the Fu River flows into Baiyangdian Lake, and before the water enters the lake, it runs through a detention and treatment pond to reduce the pollutant load. Nitrogen and phosphorus also enter the lake from the surrounding villages. This includes a total of 39 villages in raised fields and 84 other villages, with a population totaling 271,000 t/a. Domestic sewage, excrement, livestock wastewater, and aquaculture waste flows into the lake, which leads to severe eutrophication [4].

In the environmental flows deficit and pollutants squeeze, the values of ammonia nitrogen (NH$_3$-N), total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) mostly fail to meet the requirements for class III water quality, which is the requirements of the environmental functional domain for Baiyangdian Lake. Releasing some water to the lake could raise the water level and improve the water quality, but it is necessary to cut some pollutants down to save water as much as possible.

2.2. Approach framework

In this paper, we try to balance the environmental flow management and water quality protection. Increasing the environmental flows from the reservoir to the lake could relieve water quality but could also aggravate the competition with the domestic, agricultural and industrial water sectors; while purely pollutant load treatment by establishing wastewater treatment plants (WWTP) would vastly increase the lake protection cost. So we analyze the spatial responses of water quality in the lake with the boundary of different environmental flows and pollutant load reduction by using water quality simulation modeling and find out the suitable environmental flows in different pollutant load management (See Figure 2).

![Fig. 2 Schematic representation of the simplified approach framework](image-url)

2.3. Water quality modeling

A water quality model, WASP (version, WASP 7.4), was applied to simulate and evaluate the mechanistic relationships between external nutrient loading and water quality of Baiyangdian Lake. This model helps users interpret and predict water quality responses to natural phenomena and man-made...
pollution for various pollution management decisions [9]. The model idealizes the real water body by computational segments. Supply of the fresh water to the lake is provided from the Xidayang Reservoir. Outflow from a hypothetical WWTP enters into the lake from segment 1.

Nash-Sutcliffe efficiency (NSE) has been used to indicate how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in equation (1) below [10].

$$Nash = 1 - \frac{\sum_{i=1}^{n} (q_i - \hat{q}_i)^2}{\sum_{i=1}^{n} (q_i - \bar{q})^2}$$

where $n$ is the total number of the sub-districts, $q_i$ is the monitored data in sub-district $i$, $\hat{q}_i$ is the simulated data from the WASP model in the sub-district $i$, and $\bar{q}$ is the mean of monitored data in the $n$ sub-districts. The values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance [11].

### 2.4. Water quality modeling

#### Pollutant load reduction

As shown in Figure 1, we assume that one WWTP would be established to reduce the pollutant load into the lake’s status quo. Traditionally, there are three wastewater treatment levels, including primary, secondary, and advanced treatment. Table 1 shows the treatment efficiency in the three treatment levels. So we set the three scenarios schemes, including 30%, 50% and 90% pollutant load reduction.

| WWTP                | COD   | BOD   |
|---------------------|-------|-------|
| Primary treatment   | 30-40 | 20 - 30 |
| Secondary treatment | 50-60 | 85-90 |
| Advanced treatment  | >90   | >99   |

#### Environmental flows into the lake

Based on the plans of “Integrated management for Xidayang Reservoir,” the releasing of available water in different hydrological years is shown in Table 2. Environmental flow rates to the lake range from 1.10 to 10.17 m$^3$/s, and we make the available water release discrete, which includes 1.50, 2.00, 2.50, 3.00, 3.50, 4.00 and 5.00 m$^3$/s of flow rates. The different flow rate would combine with the three pollutant load reductions, and consist of the simulated scenario.

| Hydrological year | In dry year | In normal year | In wet year |
|-------------------|-------------|----------------|-------------|
| Available water volume (10$^8$ m$^3$) | 0.37 | 1.14 | 3.21 |
| Outflow rate (m$^3$/s) | 1.10 | 3.60 | 10.17 |
3. Results and discussion

3.1. Water quality model calibration

These coefficients and monthly freshwater inflows were used to simulate four water quality variables. Model results were compared with measurements of spatially-averaged field data in each model segment from August to October 2009. Each sub-district was modeled by assuming complete mixing between the discharged water and the upstream flow.

Table 3. Values of the NSE derived from the model calibration

| Date         | NSE   | NH$_3$-N | Org-N | Org-P |
|--------------|-------|----------|-------|-------|
| August-2009  | 0.56  | 0.64     | 0.83  | 0.76  |
| September-2009 | 0.52 | 0.59     | 0.90  | 0.86  |
| October-2009 | 0.48  | 0.60     | 0.78  | 0.75  |

In Table 3 the values of the NSE were derived for the evaluation of the model parameters. The NSE ranges between 0.48 and 0.90, confirming the quality of fit between measured and simulated concentrations.

Fig. 3. Scatter plot of the monitored versus simulated DO, ammonia, organic nitrate and organic phosphorus.
3.2. Scenario 1: with 30% pollutant loading reduction

We have simulated water quality when the inflowing was 1.50, 2.00, 2.50, 3.00, 3.50, and 4.00 m$^3$/s, respectively. The simulated endpoints of the water quality in the different inflowing have been shown in Figure 4 and the fitting curves of between concentrations of water quality and inflowing shown as Table 4.

![Figure 4](image-url)  
Fig. 4. Relationships between concentrations of DO (a), ammonia (b), organic nitrate (c), and organic phosphorus (d) and inflowing.

| Relationship     | Fitting equations          | $R^2$   |
|------------------|----------------------------|---------|
| DO ($y$) ~ Inflowing($x$) | $y = -0.417x^2 + 1.284x + 5.392$ | 0.912   |
| NH$_3$-N ($y$) ~ Inflowing($x$) | $y = 0.062x^2 - 0.573x + 1.782$ | 0.997   |
| Org-N ($y$) ~ Inflowing($x$)  | $y = -0.08x + 0.330$      | 0.973   |
| Org-P ($y$) ~ Inflowing($x$)  | $y = -0.001x^2 - 0.006x + 0.070$ | 0.931   |

Table 4 the fitting curves of between concentrations of DO, ammonia, organic nitrate, and organic phosphorus and inflowing.

When the inflowing is over 2 m$^3$/s, the spatial-minimum concentration of DO is superior to the water quality standard of III class (5 mg/L), which might benefit from the lake reaeration by hydrodynamic force. The maximum concentration of NH$_3$-N, Org-N, and Org-P is 0.84, 0.77, and 0.20 mg/L respectively when water inflowing to the lake is 3.5 m$^3$/s, which meets the water quality standards of III class.
So for meeting all the four water quality criteria, the maximum value of the four corresponding inflowing was recommended as the suitable environmental flow in the scenario of 30% pollutant loading reduction.

3.3. Scenario 2: with 50% pollutant loading reduction

In the scenario of 50% pollutant load reduction, we have simulated lake water quality when the inflowing was 1.50, 2.00, 2.50, 3.00, 3.50, and 4.00 m³/s, respectively. The simulated endpoints of the water quality in the different inflowing have been shown in Figure 6, in which all the correlation coefficients are over 0.9000, and the significance levels are lower than 0.05.

Fig. 5. The corresponding optimum inflowing to water quality protection in the scenario of 30% pollutant load reduction

Fig. 6. Relationships between concentrations of DO (a), ammonia (b), organic nitrate (c), and organic phosphorus (d) and inflowing.
Table 5 The fitting curve of between concentrations of DO, ammonia, organic nitrate, and organic phosphorus and inflowing.

| Relationship       | Fitting equations           | $R^2$ |
|--------------------|-----------------------------|-------|
| DO ($y$) ~ Inflowing ($x$) | $y = -0.806x^2 + 4.766x - 0.753$ | 0.906 |
| NH$_3$-N ($y$) ~ Inflowing ($x$) | $y = 0.368x^2 - 2.670x + 5.585$ | 0.970 |
| Org-N ($y$) ~ Inflowing ($x$) | $y = -0.158x^2 + 0.621x + 0.469$ | 0.980 |
| Org-P ($y$) ~ Inflowing ($x$) | $y = 0.019x^2 - 0.199x + 0.633$ | 0.990 |

When the inflowing is over 1.69 m$^3$/s, the spatial-minimum concentration of DO is superior to the water quality standard of III class (5 mg/L). The maximum concentration of NH$_3$-N, Org-N, and Org-P is 0.73, 0.84, and 0.27 mg/L, respectively, when water inflowing to the lake is 3.00 m$^3$/s, in which NH$_3$-N and Org-N could meet the water quality standards of III class, but Org-P.

Based on the fitting curve between concentrations of DO, ammonia, organic nitrate, and organic phosphorus and inflowing, we have obtained the optimum environmental flows to meet the various water quality indexes (as shown in Figure 7). The maximum value of 3.13 m$^3$/s has been selected as the sustainable environmental flows in the scenario of 50% pollutant load reduction.

Fig. 7 The corresponding optimum inflowing to water quality protection in the scenario of 50% pollutant load reduction
3.4. Scenario 3: with 90% pollutant loading reduction

In the scenario of 90% pollutant load reduction, we have simulated lake water quality when the inflowing was 0, 1.50, 2.00, 2.50, 3.00, 3.50, and 4.00 m³/s, respectively. The simulated endpoints of the water quality in the different inflowing have been shown in Figure 8.

When the inflowing is over 1.50 m³/s, the spatial-minimum concentration of DO is superior to the water quality standard of class III (5 mg/L). The maximum concentration of NH₃-N, Org-N, and Org-P is 1.09, 0.21, and 0.62 mg/L, respectively when water inflowing to the lake is 1.50 m³/s, in which Org-N could meet the water quality standards of III class, but not NH₃-N and Org-P.

![Graphs showing DO, NH₃-N, Org-N, and Org-P concentrations vs. inflowing](image)

Fig. 8. Relationships between concentrations of DO (a), ammonia (b), organic nitrate (c), and organic phosphorus (d) and inflowing.

Table 6 the fitting curve of between concentrations of DO, ammonia, organic nitrate, and organic phosphorus and inflowing.

| Relationship          | Fitting equations         | $R^2$ |
|-----------------------|---------------------------|-------|
| DO ($y$) ~ Inflowing($x$) | $y = -0.417x^2 + 1.284x + 5.392$ | 0.912 |
| NH₃-N ($y$) ~ Inflowing($x$) | $y = 0.062x^2 - 0.573x + 1.782$ | 0.997 |
| Org-N ($y$) ~ Inflowing($x$) | $y = -0.08x + 0.330$        | 0.973 |
| Org-P ($y$) ~ Inflowing($x$)  | $y = -0.001x^2 - 0.006x + 0.070$ | 0.931 |
Based on the fitting curve between concentrations of DO, ammonia, organic nitrate, and organic phosphorus and inflowing, we have obtained the optimum environmental flows to meet the various water quality indexes (as shown in Figure 9). The maximum value of 2.12 m$^3$/s has been selected as the sustainable environmental flows in the scenario of 90% pollutant load reduction.

Fig. 9. The corresponding optimum inflowing to water quality protection in the scenario of 90% pollutant load reduction

Fig. 10. Spatial distribution of DO, NH$_3$-N, Org-N, and Org-P with 90% reduction in pollutant load and water releases of 2.12 m$^3$/s.
3.5. Sustainable environmental flows assessment

Table 7 has shown the sustainable environmental flows in Baiyangdian Lake. In the three scenarios, annual inflowing volume to the lake is 1.11, 0.99, and $0.67 \times 10^8$ m$^3$, respectively, and all the corresponding lake levels are above 7.00 m.

Table 7 Sustainable environmental flows for lake quality protection

| Environmental flows | Pollutant load reduction |
|---------------------|--------------------------|
|                     | 30%  | 50%  | 90%  |
| Inflowing rate (m$^3$/s) | 3.52 | 3.13 | 2.12 |
| Inflowing volume ($\times 10^8$ m$^3$) | 1.11 | 0.99 | 0.67 |
| Lake volume ($\times 10^8$ m$^3$) | 1.56 | 1.44 | 1.12 |
| Sustainable environmental level (m) | 7.45 | 7.35 | 7.05 |

Some environmental researchers have done a large amount of work on Baiyangdian Lake protection. Liu and Yang [12] have obtained the environmental water demand ($2.0 \times 10^8$ m$^3$) of the Baiyangdian Lake based on the ruler of water amount balance between the water body and water cycles. Zhong et al. [13] have assessed the ecological water level of the Baiyangdian Lake, which indicates that the amount of the minimal and optimal eco-environmental water requirements are $0.87 \times 10^8$ and $2.78 \times 10^8$ m$^3$ in average monthly, respectively. The method of ecological water level emphasizes that wetland ecosystem adapts to the hydrological conditions, but overlooks the surrounding pollutant load. In our research results, water release has been obtained to simultaneously improve the lake volume and quality. The different results have been used in the different surrounding pollutant load reduction.

4. Conclusions

In this paper, using Baiyangdian Lake as the case study and WASP model as the simulation tool, we have analyzed water quality variations in scenarios with different pollution loads reduction and different environmental flow releases into the lake, and founded out the sustainable schemes for environmental flows management. In the scenarios of 30%, 50%, and 90% pollutant loads reduction, the sustainable environmental flows are 3.52, 3.13, and 2.12 m$^3$/s, and the corresponding lake levels could attain to 7.45 m, 7.35 m, and 7.05 m from the initial 6.0 m.

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