Water quality improvement strategies for a coastal artificial lake

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Abstract. Coastal artificial lakes were encouraged to construct in China for coastal areas remediation. However, it was difficult to keep good water quality. This study investigated water quality improvement strategies for a new coastal artificial lake, located on the coast of Zhejiang Province, China. The expected objectives of water quality in the lake were identified as controlling of algae outbreak accidents under medium eutrophication state, transparency of 1.2 m and ensuring other water quality indicators to maintain or lower than the source water quality. Water exchange was implemented, and the water retention time was designed to be less than 30 days. The sediment could be mostly removed after precipitation in the preliminary precipitation basin. For phosphorus reduction, phosphorus concentration change was predicted by box model. Suppose the active phosphate concentration of inflow water was 0.02 mg/L, when the supplied water volume increased to 18 million m$^3$/a, the active phosphate concentration of the lake could achieve 0.03 mg/L. As the water quality was poor in summer, the amount of water supplied was suggested increased. This study established feasible water quality guidelines for sustainable operation, and suggested effective water quality improvement strategies for similar coastal artificial lakes.

1. Introduction

Nowadays, construction of coastal artificial lakes was encouraged in China for coastal areas remediation, and meanwhile for landscape/recreation. A few coastal artificial lakes have been built along the east coast of China in the last decade [1-2]. The lakes were isolated from the outer coast by sea walls, and muddy sediment was excavated. Then a closed or semi-closed environment was formed.

However, it has been found difficult to keep good water quality of the new systems [3]. Because most coastal lakes were shallow, lack of tidal flushing and ecological function. The lakes suffered from great contaminants loads from land-based pollution. The sediment in the lakes may re-suspend and heavy metals could release from the sediment. These may induce poor water quality, such as enthusiasm and algae blooming[4].

Many strategies have been implemented for the water quality improvement. Temporarily open/close the gate of the lakes to exchange the water has been found useful [5-7]. But outside the lakes, the coastal water was of poor water quality, containing high nitrogen, phosphorus load and sediment concentration. This greatly weakened the effect of the strategies.

Under these circumstances, it is very necessary to investigate effective water quality improvement strategies. The aim of this study is to establish feasible water quality guidelines for sustainable
operation; and to suggest effective water quality improvement strategies for similar coastal artificial lakes.

2. Study area and methods

2.1 Study area

The artificial coastal lake is located on the coast of Zhejiang Province, China. The lake composes a preliminary precipitation basin and a big lake (Figure 1), with the area of 300,000 m² and 2,000,000 m². The average depth of the lake is 3 m.

The lake is isolated from the outer coast by the dam. It is constructed for sightseeing, tourism, vacation, leisure and entertainment. When the dam was built, the muddy sediment in the lake were excavated. Water circulation inside the lake was mostly controlled by gates of the dam. Water from the outer coast firstly flow into the preliminary precipitation basin through the gate. After preliminary treated, such as precipitation, the water flow into the big lake. The other gate of the big lake will temporarily open to let partial water of the lake flow into the ocean.

The water quality of the adjacent coastal water was analyzed. The main pollutants were inorganic nitrogen and active phosphate. Inorganic nitrogen is 1.317 mg/L, and active phosphate is 0.104 mg/L, which is over 3 times of the second category of Seawater Quality Standard in China. The sediment concentration is 1.26 kg/m³, so transparency is only 0.23 m.

2.2 Methods

Box model was used to predict the water quality. According to the principle of conservation of mass, the pollutants in the lake are supposed to be uniformly mixed, settled and degraded. So box model can be used to investigate the change of pollutants concentration in the lake. The conservation law of substances in the lake is obtained:

$$\overline{V} \frac{dc}{dt} = (Q_w C_w \, dt + Q_i C_i \, dt) - Q_e C_e \, dt + P A C_0 \, dt - \overline{V} C_k \, dt$$

(1)

Where $\overline{V}$ is the volume of the lake under normal water level (m³), $C$ and $dc$ are the concentration and concentration change of a pollutant in the lake, $Q_w$ and $C_w$ are the flow and pollutant concentration of sewage flowing into the lake area, $Q_i$ and $C_i$ are the flow and pollutant concentration of water from the preliminary sedimentation.
basin,

\( Q, A, C_0 \) are the rainfall, area of the lake and pollutant concentrations of the rainfall,

\( k \) and \( dt \) are the sedimentation coefficient and the unit time.

Define \( W(t) \) as the pollutants into the lake, that is.

\[
W(t) = Q_w C_w + Q_i C_i + PAC_0
\]

Then we get

\[
Q_i C dt - W(t) dt + V dc + kV C dt = 0
\]

It can be simplified as:

\[
\frac{V}{dt} \frac{dc}{dt} + C \left( \frac{1}{t_0} + k \right) = W
\]

Where \( t_0 \) is defined as retention time, \( t_0 = \frac{V}{Q_i} \),

When \( \frac{dc}{dt} = 0 \), the average annual or monthly concentration could be obtained as

\[
C_0 = \frac{\sum_{i=1}^{m} W_i}{\sum_{i=1}^{m} Q_i + kV}
\]

When \( W = 0 \),

\[
C(t) = C_0 \exp \left\{ -\left( \frac{Q_i}{V} + k \right) \right\} = C_0 \exp \left\{ -\left( \frac{1}{t_0} + k \right) \right\}
\]

Where, \( C_0 \) is the initial concentration, if consider the change of concentration and flow, then we get

\[
C(t) = \frac{\sum_{i=1}^{m} W_i}{\sum_{i=1}^{m} Q_i + kV} \left[ 1 - \exp\left\{ -\left( \frac{\sum_{i=1}^{m} Q_i}{V} + k \right) t \right\} \right] + C_0 \left\{ \exp\left\{ -\left( \frac{\sum_{i=1}^{m} Q_i}{V} + k \right) t \right\} \right\}
\]

3. Water quality objectives of the coastal artificial lake

Setting the water quality objectives of the coastal artificial lake is very complicated. The following aspects should be concerned: (1) the function of the lake; (2) economy and feasibility of sustainable management.

The function of the lake includes sightseeing, tourism, vacation, leisure and entertainment as a whole, so the water quality standard should meet the requirements of landscape and recreational water. This needs the water to meet the second category of Seawater Quality Standard in China[13].

The comparison of the main indicator of the current water quality with the standard was shown in Figure 2. Inorganic nitrogen and active phosphate were far above the standard. This may induce enthusiasm, thus the Transparency and Chlorophyll \( a \) were also considered as important indicators. The two indicators were not required by the standard, so the Transparency referred to the Water Quality Standard for Scenery and Recreation Area. Chlorophyll \( a \) referred to Standard for Investigation of Lake Eutrophication (Table 1) [14].

As the adjacent coastal water was poor quality, it was very difficult to achieve above objectives. Within these semi-enclosed systems there is now an increasing awareness of the importance in maintaining acceptable water quality standards [15].

The objectives of water quality should consider the source water quality, protection requirements of artificial lake, capacity and cost of the water quality purification system. Therefore, momentarily not
considering the ecological measures, the objectives of water quality in artificial lake were identified as controlling of algae outbreak accidents under medium eutrophication state, transparency of 1.2 m and ensuring other water quality indicators to maintain or lower than the source water quality level.

![Figure 2. Comparison of water quality indicators and standards of source water. IN, Chl a, AP, FC, T in the graph represent Inorganic Nitrogen, Chlorophyll a, Active phosphorus, Fecal Colibacillus and Transparency. The bar represents the value of IN, Chl a, AP, FC, T and the black dot point represents the value of the standard.](image)

**Table 1. Comparisons of water quality indicators of source water with standards.**

| Current status                      | Value of standard | Meet or not | Notes                                                        |
|------------------------------------|-------------------|-------------|--------------------------------------------------------------|
| Inorganic Nitrogen (mg/L)          | 1.317             | Not         | The second Category of Seawater Quality Standard in China    |
| Active Phosphate (mg/L)            | 0.104             | Not         | Category A of Water Quality Standard for Scenery and Recreation Area |
| Fecal Colibacillus (a/L)           | 197               | Meet        | Medium eutrophication of Standard for Investigation of Lake Eutrophication |
| Transparency(m)                    | 0.23              | Not         |                                                              |
| Chlorophyll a                       | 1.79              | meet        |                                                              |

4. Water quality improvement strategies

As the objectives of the water quality improvement were to avoid algae outbreak; to decrease sediment concentration; and to maintain or decrease nitrogen and phosphorus. Water exchange was implemented for water quality improvement. Controlling of water retention time has been proven an effective way to restrain the excessive growth of algae [16]. Most reservoirs should exchange 10% to 15% of the total volume of water daily; and medium-size reservoirs should exchange all the water once every 30 days [17]. Then algae blooms could be effectively controlled [18]. Shallow water lake system design guide [19]believed that the lake had a very low risk of large algal blooms if it had 80% exchange of the water in less than 20 days, and low risk of large-scale algae in the lake if the lake has 80% exchange of the water in less than 30 days. Investigations showed that the domestic famous freshwater lakes, such as West Lake in Hangzhou city, had no algae blooms if all the water of the lake were completely exchanged once a month. Therefore, the water retention time was designed to be less than 30 days.

The sediment could be mostly removed after precipitation in the preliminary precipitation basin. The inflow of the artificial lake followed the mode of “half a day (seawater from sea into the basin) +1 day (precipitation) + half a day (water from the basin into artificial lake)”. Drainage is not the main control factor in the water exchange process of artificial lake. The initial water level of artificial lake is 1.5m. It can be reduced to about 1.2m within 12 hours before inflow.
Two types of measures could be used for nitrogen and phosphorus reduction. The first is only to reduce sediment concentration of source water quality in the preliminary precipitation basin. Then the processed coastal water goes into the artificial lake from the basin for water exchange and increasing of fluidity. Ecological measures will be adopted in the lake to make the water quality be close to or reach the standard. The second measure is to reduce the nitrogen and phosphorus simultaneously in the preliminary precipitation basin. Then the processed coastal water goes into the artificial lake. The water of the lake will be exchanged when water quality deteriorates because of infiltration, evaporation, atmospheric dust, rainfall and sediment release.

The first measure is more commonly used. Ecological measure may effectively improve the water quality. But whether the concentration of nitrogen and phosphorus can reach the standard needs to be further investigated. The second measure needs to establish a water purification system similar to waste water treatment plant. The phosphorus reduction technology is relatively easy and the cost is acceptable. Nitrogen reduction can adopt biochemical measures by building a water treatment plant. This nitrogen reduction measure was seldom taken by domestic coastal and freshwater lakes. The second measure is quite expensive. According to the cost of West Lake and similar lakes, this project invests will increase about 100 ~ 150 million RMB, which is too much for such an artificial lake.

5. Water quality prediction of the coastal artificial lake - Aiming at phosphorus reduction

For the nitrogen and phosphorus reduction, not considering the ecological measures, it is much economical to reduce phosphorus only. In the early stage of eutrophication, phosphorus is the limiting factor for algae growth, and its increased concentration can lead to the massive growth of algae [20]. Suppose the phosphorus is treated in preliminary precipitation basin to achieve the objective concentration, the phosphorus concentration of the lake was predicted by box model. When the concentration of active phosphate flown into the lake from the preliminary precipitation basin was 0.02mg/L (higher than the second category of seawater quality standard) and 0.03mg/L (it happens to be second category of seawater quality standard), the phosphorus concentration from the precipitation basin was lower than that of the lake. The average water quality change of different annual water supplement was shown in Figure 3.

1)The larger amount of water supply was, the better water quality in the lake would be. And initial phosphorus concentration of 0.02mg/L could achieve better improvement effect than 0.03mg/L.

2) When the concentration of supplied water was 0.02 mg/L, the water quality in the lake improved with the continuous replenishment of the source water. When the supplied water volume increased to 18 million m³/a, the water quality of the lake could achieve 0.03mg/L. When the concentration of supplied water was 0.03 mg/L, the water quality could be improved, but it was very difficult to achieve the standard.

3)The water quality in the lake was worse than the source water, because of the atmospheric settlement and sediment release. The supplied water could only dilute the pollution of the lake. Thus, the water quality of the lake would never be better than the supplied water.

Suppose the supplied water was 18 million m³/a, the change of water quality monthly with supply of 1.5 million m³ each month was shown in Figure 4. According to the atmospheric settlement and sediment release, the phosphorus load ratio of the four seasons was 2:10:2:1. So the water quality was predicted considering the pollution load change.
The active phosphate concentration in the lake was higher from June to October than other months. The water quality faced challenges in summer, especially in August. When the concentration of water source was 0.03 mg/L, the activity phosphate concentration in the lake could reach 0.050 mg/L. When the concentration of water source was 0.02 mg/L, the concentration of activated phosphate could reach 0.046 mg/L, which still exceeded the second category of seawater quality standard. With the annual replenishing of 18 million m³, the average annual active phosphate concentration in the lake area could achieve the second category of water quality standard. When the water quality was poor in summer, and the amount of water supplied was suggested increased.

6. Conclusions
The expected objectives of water quality in artificial lake were identified as controlling of algae outbreak accidents under medium eutrophication state, transparency of 1.2 m and ensuring other water quality indicators to maintain or lower than the source water quality level by ecological measures to improve the artificial lake water quality. Water exchange in coastal artificial lake was implemented for the water quality improvement. When the concentration of supplied water is 0.02 mg/L, the water quality in the lake improves with the continuous replenishment of the source water. When the supplied water volume increased to 18 million m³/a, the water quality of the lake could achieve 0.03 mg/L. As the water quality was poor in summer, the amount of water supplied was suggested increased.

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