Analysis on Changes of Water Quality in Xuanmen bay due to Construction of Eastern Artificial Lake

Huang Shichang1, Liu xu1,2,*, Chen Lixiao1

1 Zhejiang Institute of Hydraulics & Estuary, Hangzhou, China, 310020
2 Department of Hydraulic Engineering, College of Civil Engineering, Tongji University, Shanghai, China

*Corresponding author, liuxulixiu1022@163.com

Abstract: In this paper, the data of water quality before construction of Xuanmen eastern artificial lake is compared with the data after construction to analyze the change of water quality inside and outside the lake in Xuanmen bay. After the lake was built, the phosphorus remained basically unchanged, and the salinity dropped sharply in the lake, COD increased sharply, and inorganic nitrogen increased more. The lake is close to a freshwater system. According to local requirement for water, inorganic nitrogen has become a pollution factor. the water quality of the seawater outside the lake was stable, and the construction of the lake had no effect basically on the water quality. Basing on regulation of the basin incoming water quality and lake area, a box model is used to predict the water quality change in the future, it will take 5 years to reach 0.5 below of the salinity. To reduce concentration of nitrogen in the lake, the incoming water needs to be treated to reduce the nitrogen, and at the same time, it should be to take biological measures to reduce nitrogen in order to meet local water quality requirements.

1. Preface
In the coast around bays of Zhejiang province, the river runoff changes greatly from dry to flood season during a year, the mountain reservoirs upstream mostly belong to small reservoirs or mountain ponds whose storage capacity is small, and cannot regulate flood. In flood season, the water level of flood rise or fall suddenly and sharply in rivers, and most of the rainfall is discharged into the sea as runoff, and the coast are often confronted with flood risks. In dry seasons, rivers are cut off, and there is a shortage of fresh water. Local government has always attached importance to the construction of artificial lakes. From 1950 to 2000, Government adopted the method of blocking tidal branches and enclosing tidal flat to construct artificial lake, to save freshwater during the flood season. Some artificial lakes have been built in Sanmen Bay and Yuhuan city, such as Datang lake, Checheng lake, Huchen lake, Maoyu lake and Xuanmen western lake, and the total storage capacity is 300 million m³. The water of artificial lake can be used as unconventional water resources in the dry season, and the water of surface layer can be directly used for short-term agricultural water. It can also be used as general industrial water, miscellaneous domestic water, and landscape water to alleviate the plight of water shortage in the dry season. Water resources in Yuhuan city are very scarce, the water resources of per capita are only a quarter of the average level in Zhejiang Province. Yuhuan city belongs to a region with extreme water shortages, being prone to drought during dry season. After the artificial lake on the west side of Xuanmen in Yuhuan city was completed, the artificial lake on the east side was built at the end of 2010. The land around the lake is mainly agricultural land. This
article analyzes changes and trends of water quality inside and outside the artificial lake in Xuanmen bay, which is beneficial to the utilization of water resources and promotes local agricultural development.

2. Overview of the study area
Xuanmen bay in Yuhuan city is located in the southeast of Zhejiang Province which belongs to the subtropical monsoon climate zone, there are 4 small streams entering in the bay. The rainfall in the stream basin not only varies greatly from year to year, but is unevenly distributed throughout the year. The average annual rainy day is 158 days in a year, the average annual rainfall in the basin is 1421mm, the largest is 2004.2mm and the smallest is 889.5mm in a year. The average annual evaporation is 1392.2mm. Multi-year average runoff of stream is 91.12 million m$^3$. The main rainy season of the basin is divided into Meiyu-season from April to July and typhoon-season from June to October. The rainfall is mainly concentrated in May to September, accounting for 80% of the annual rainfall. The eastern artificial lake that is adjacent to the lake on the west side of Xuanmen, was formed by enclosing tidal flat in Xuanmen bay which is divided into two parts of water area inside and outside the lake by seawall. The lake occupies most of Xuanmen bay, and the seawall is 5.38km of length. The project was built in 2010, is equipped with two sluices which are used to drain for the lake. The basin area of eastern artificial lake is 130km$^2$, the enclosed area is 4203.5033 ha, and the normal water level in the enclosed area is 0.0 m to -0.2 meters (predicted elevation, same as below), the water area is 1955.72 ha, the total storage capacity is 44.2 million m$^3$. The area above normal water level is exposed all years, losing properties of intertidal zone, becoming breeding ponds and farmland, the average elevation is 0.9m. The lowest location of the water area (-7.9m) is located on the northwest side of the seawall. The waters outside the lake are shallow in the north and deep in the south. There is a Kanmen tide level station near the project. The tidal property of sea area belongs to type of regular half-day tide. The average time of rise and fall in Kanmen station is about 6h, the average tidal range is 3.96m and the maximum tidal range is 6.85m. After the completion of seawall, there will be no water exchange of lake with sea area outside of lake.

3. Changes in water quality in artificial lake
The report collected the data about marine water quality in the project area in 2002 (before the construction) [1], 2008 and 2009 (during period of construction) [2], 2013 and 2014 (after the project was
fulfilled) [2], and 2019 [2]. The locations of water quality measurement stations before and during the construction are shown in Fig.2, and the locations of stations after construction are shown in Figure 3. The salinity measurement was conducted by salinity meters, DO was measured by an electrochemical probe method, COD in seawater was measured by an alkaline potassium permanganate method, and COD in fresh water by a potassium dichromate method. DIN (inorganic nitrogen) measurement and DIP (active phosphate) by flow-injection colorimetry.

![Figure 2. Stations location before construction](image1)
![Figure 3. Stations location before construction](image2)

Notes: In Fig.2, S1–S10 are location of stations for water quality measured in 2002, Z1-Z20 are location of stations in 2008 and 2009. In Fig.3, S10~S17 are locations of station in 2013 and 2014, S1~S17 are location of stations in 2019, among them, the location of S10~S17 is the same with the location in 2013.

3.1. Changes of water quality after the completion of Xuanmen eastern artificial lake

The water quality data of each period are averaged according to location of stations inside or outside the artificial lake, the changes of water from 2002 to 2019 are shown in Fig.4 and Fig.5.

In the artificial lake waters, the dissolved oxygen (DO) and active phosphate (DIP) were basically unchanged after the construction of the artificial lake. Concentration of active phosphate was 0.024–0.041 mg/L before the construction, and was 0.032 mg/L after the construction. Concentration of dissolved oxygen was 6.0–9.8 mg/L before the construction, and was 9.79 mg/L after the construction. There are significant changes in salinity and COD in eastern artificial lake. From the year of completion (2010) to 2019, the water in lake has changed from seawater to fresh water, and the salinity has been reduced from 27.5 to 1.68. Concentration of COD<sub>mn</sub> is 0.59 – 0.95 mg/L before the construction, increased up to 7.9 mg/L, which is transformed by 19.8 mg/L of COD<sub>er</sub>. Inorganic nitrogen (DIN) increased from 0.43 to 1.05 mg/L before the lake was built, and increased to 1.71 mg/L after construction. It can be seen that inorganic nitrogen became the main pollution factor after the construction of the lake, COD increased significantly, and the water in the lake is mainly eutrophic.

In the seawater area outside the artificial lake, there was no significant change since the construction of the lake. Before the construction, the concentration of COD was 0.544–0.95 mg/L, and after the construction, it was 0.53 ~ 0.71 mg/L. DO was 6.0–9.8 mg/L before construction, 6.16–10.5 mg/L after construction. active phosphate was 0.025 ~ 0.041 mg/L before construction, 0.03–0.036 mg/L after construction. inorganic nitrogen was 0.4–1.05 mg/L before, was 0.5 ~ 0.75 mg/L after construction. According to monitoring data in 2002, 2013, 2014, and 2019 data, inorganic nitrogen and active phosphate were the main pollution factors for the water environment outside the artificial lakes. The wastewater was not discharged into the sea during the period of construction and after the completion of the project. The main reason is the discharge of land-based pollutants into the sea in recent years, which has led to eutrophication in coastal waters. The engineering construction has little impact on seawater quality.
3.2. Comparison of the water quality of Eastern and Western artificial lakes

Before the eastern artificial lake was completed in 2010, the western artificial lake was completed in July 2001. The basin area of western artificial lake in Xuanmen is 166.2km², the water surface area of the western lake is 16 million m², the total storage capacity of the freshwater is 83.12 million m³ (normal water level 1.0m), and the average annual water supply is 55.46 million m³. The area of the western artificial lake and the total storage capacity of the lake are slightly larger than those of the eastern artificial lake. The active phosphate and inorganic nitrogen in the eastern artificial lake are lower than those in the western artificial lake, which indicates that the western artificial lake is more polluted than the eastern artificial lake.

The fresh water from lake basins merges into the lakes to desalinate the water of lake, and to maintain the normal water level, the sluices is opened during flood season to let water of lake into the sea. The eastern artificial lake has run for 8 years(2010.10~2019.01), and the salinity of the lake is 1.2 ~ 1.8, and the western artificial lake has run for 18 years, and the salinity is 0.8 ~ 0.9. It can be seen that the water in the eastern artificial lake need be further desalinated for a long time. The traditional method of desalination is adopted since construction, that is to mix incoming water from lake basin with water of lake and then discharge water during flood season, the seawater desalination in artificial lakes takes a long time, which significantly effects the utilization of water resources.

Figure 4. Changes of water quality in lake
(Note:COD is CODMn from 2002 to 2009, CODcr in 2019)

Figure 5. Changes outside of lake
Table 1: Comparison of the water quality of eastern and western artificial lakes in Xuanmen

| Location | Salinity | DO (mg/l) | COD (mg/l) | DIN (mg/l) | DIP (mg/l) | Capacity (*10^4 m^3) | Basin Area (km^2) |
|----------|----------|-----------|------------|------------|------------|----------------------|------------------|
| Eastern  |          |           |            |            |            |                      |                  |
| S01      | 1.8      | 9.85      | 31         | 1.136      | 0.011      | 6375                | 130              |
| S02      | 1.8      | 9.78      | 18         | 2.212      | 0.022      |                      |                  |
| S03      | 1.7      | 9.9       | 20         | 1.696      | 0.022      |                      |                  |
| S04      | 1.8      | 9.97      | 17         | 1.028      | 0.007      |                      |                  |
| S05      | 1.8      | 9.56      | 18         | 1.726      | 0.03       |                      |                  |
| S06      | 1.2      | 9.7       | 15         | 2.468      | 0.097      |                      |                  |
| Western  |          |           |            |            |            |                      |                  |
| S07      | 0.9      | 9.9       | 16         | 4.331      | 0.169      | 8312                | 166.2            |
| S08      | 0.8      | 9.98      | 15         | 7.633      | 0.35       |                      |                  |
| S09      | 0.9      | 9.94      | 8          | 6.164      | 0.322      |                      |                  |

4. Prediction and analysis of artificial lake water quality

The water quality of the eastern artificial lake basically depends on the water coming from the rivers in the basin. The pollution factor is mainly inorganic nitrogen. With the improvement of pollution control in the basin, the water quality of the artificial lake will be improved, and the freshwater inflow of the basin will also promote desalination of lake. Basing on water quality of stream and the amount of fresh water entering the lake, the change of pollution (Inorganic nitrogen) and desalination process of artificial lake will be predicted. According to the principle of conservation of mass, it is believed that the pollutants entering the lake are uniformly mixed in the lake, and the sedimentation and degradation of the pollutants in the lake are also uniform. Therefore, the box model can be used to study the concentration of pollutants in the lake. It can be obtained by the law of conservation of matter after the lake is fully mixed:

$$ V_d c = (Q_w C_w dt + Q_i C_i dt) - Q_e C_e dt + P A C_o dt + S A dt - V C k dt \quad (4-1) $$

Where: $V$ is the water body (m³) under the normal water level of the lake, $C, dC$ are the concentration and change of a substance in the lake, $Q_w, C_w$ are the discharge and concentration of sewage flowing into the lake, $Q_i, C_i$ are the discharge and concentration of replenished water into the lake, $Q_e, C_e$ are the discharge and lake water concentration out of the lake; $P, A, C_o$ are rainfall, area of lake, and concentration of pollutants carried by rainfall; $S$ is the flux of a substance released by the bed mud, and here the area of the lake bottom is approximately equal to the area of the lake surface, $k, dt$ are the settlement coefficient, and the unit time; Multiplying of $V, C, k$, and $dt$ represents the total amount of pollutants sinking into the bottom of the lake.

The load by rainfall on the lake, the amount released by bed mud, and the load carried by the source water can be included in the item of pollutants flowing into the lake, the total is $W(t)$. Let $Q_w C_w + Q_i C_i + PA C_o + SA = W(t)$, so that the formula of (4-1) is transformed to be:

$$ Q_e C_e dt - W(t) dt + V d c + k V C k dt = 0 \quad (4-2) $$

Considering that the load and concentration varies monthly or daily, the non-constant solution is the sum of the solutions of the homogeneous equation and the non-secondary equation, that is:

$$ C(t) = \frac{\sum_{i=1}^{m} W_i}{\sum_{i=1}^{m} (Q_i + k t)} \left[1 - e^{\left(-\frac{\sum_{i=1}^{m} Q_i}{V} + k t\right)}\right] + C_0 \left[1 - e^{\left(-\frac{\sum_{i=1}^{m} Q_i}{V} + k t\right)}\right] \quad (4-3) $$

The unit of $t$ is predicted by month, the first term in formula (4-3) is the increment value of concentration caused by the load of this month, the second term is the attenuation value of concentration from the end of the previous month to this month, $C_0$ is the value of the previous month, and $C(t)$ is concentration value of any time. $\sum_{i=1}^{m} W_i$ is the monthly load for various element of water quality in lakes, $\sum_{i=1}^{m} Q_i$ is the monthly water volume entering or flowing out of the lake, the water level of lake should be kept to be unchanged.

The change of salinity changes are predicted by the box model. Eastern artificial lake was seawater at initial period after the seawall is built, the water salinity of the lake will gradually decrease, as the
lake fills, water mixes and discharge, and the overall replacement is gradually realized. The salinity of the water body in the lake contains the initial salinity of the seawater and the salinity released by the bed mud, and the salinity of the soil in enclosing area. According to the dispatching principle of the lake, after the lake attains 44.2 million m³ of storage capacity, the water from the basin enters the lake, it is discharged through the sluice to keep the water storage volume unchanged.

Water from basin area of eastern artificial lake enters the lake area through the stream channel, and the water level of the stream channel is adjusted by the sluice. Rainwater is usually stored in the stream channel during the normal period, and only water enters the lake during the flood period. The amount of water entering the lake and the net rainfall in the lake is about 17 million m³. The area of enclosing area is 4200 ha, water area of the lake is 1955 ha, and the salinity of water body in lake. The higher the frequency of water discharge in the lake, the faster the salinity decreases. The release of salinity from the bed mud is closely related to the salinity of the bed mud, the salinity of the overlying water, the water pressure, and the properties of bed mud. The salinity release flux is: 

\[ F = a \times \exp(-bt) \]

where \(a\) is the initial flux, and \(b\) is the attenuation coefficient. \(a\) and \(b\) are taken as 1.601 (g / m².hr) and 0.002 (1 / hr), respectively. There are salinity into the lake from desalination process of exposed tidal flat in the enclosing zone, which is used for agriculture land. The salinity of mud after drying can be taken as 7.07 g / kg, and salinity of gap water taken as 8 800 mg / L, the task of desalination is predicted to be finished in 4 years. According to the model, the curve of salinity is shown in Figure 6, the salinity in the lake is calculated from the construction of the lake to 2019.01, salinity decrease from 27.5 to 1.7 which is near to measured value. It can be concluded that the salinity of the lake will be below 0.5 after about 5 years since 2019.

The concentration of inorganic nitrogen flowing into the lake area according to the regulation of water quality for stream basin is required to be less than 1.0 mg / L. The concentration of the stream into the lake is 1.0 mg / L. The current concentration in the lake is 1.7 mg / L. The amount of atmospheric and sediment release is 5.0 t/a, the change of inorganic nitrogen is shown in Figure 7. The concentration of inorganic nitrogen flowing into the lake area should be below 0.5 mg / L, and the inorganic nitrogen can reach the requirement of 1 mg / L after about 4 years.

5. Conclusion and suggestion

This paper analyzes the changes of water quality in Xuanmen bay inside and outside east artificial lake in Yuhuan city, basing on measured water quality data for many years. After the construction of the lake, the phosphorus has remained basically unchanged, salinity has decreased significantly, COD has increased significantly, and inorganic nitrogen has increased. According to local requirements for water, inorganic nitrogen has become a pollution factor. Basing on utilization of the enclosing area and the regulation of water quality from the basin, a box model is used to predict the change of water quality in the future. It will take 5 years to reduce the salinity below 0.5. For the nitrogen reduction in
the reservoir area, the incoming water needs to be treated to reduce the nitrogen content, and at the same time, it should be to take biological measures to reduce nitrogen content in order to meet local water quality requirements.

 References

[1] Yuan Wenxi 2003 Preliminary Design Report of Xuanmen Phase III Project Zhejiang Institute of Water Resources and Hydropower Design

[2] Huang Shichang Chen Lixiao Liu Xu etc. 2019 Ecological Evaluation of Xuanmen Phase III Project Technical Report of Zhejiang Institute of Hydraulics & Estuary

[3] YE Qinghua 2015 Numerical simulation of water salinity change process in coastal reservoir influenced by salt release of sediment Journal of Hohai University Vol. 43(6) pp 518-523

[4] Chen Dabiao 2011 Study on the salinity change characteristics and salt removal plan of Zhengxu Reservoir Project in Cixi City Zhejiang Water Conservancy Science and Technology Vol.(1) pp 1-6

[5] MAO Xianzhong ZHU Xiaoao CHEN Fuyuan et al. 2005 Study on accelerating water desalination in polder reservoir for storage of fresh water along the coast. Advances in Water Science Vol.16(6) pp 773-776

[6] GAO Zengwen ZHENG Xilai WU Junwen 2006 Experimental studies on salt exchange between freshwater and sediments in a polder reservoir Advances in Water Science Vol.17(2) pp 170-175

[7] ROBINSON C GIBBES B LI L 2006 Driving mechanisms for groundwater flow and salt transport in a subterranean estuary Geophysical Research Letter Vol.33 pp 1-4

[8] ZHANG Peng JIANG Cuiling ZHU Liqin et al. 2014 Study on the salt release law from the bottom sediment of a proposed reservoir in the coastal area Yellow River Vol.35(9) pp 74-7

[9] FORESTERCK 1979 Higher order monotonic convective difference schemes Journal of Computational Physics Vol.23 pp 1-22