Thermal Stratification and Its Influence on Water Quality of Plain Reservoir in Subtropical Region

Xinlin Wang

Shenzhen Middle School-High School Division, Shenzhen 518000, China 518000

Abstract: Thermal stratification is an important factor causing deterioration of water quality in source water reservoirs. To explore the occurrence of thermal stratification and its impact on water quality of plain reservoirs in subtropical region, water temperature and main water quality parameters of Reservoir A, B, and C in City S (South China) were continuously monitored from March to July 2021. The results showed that thermal stratification occurred in all the three reservoirs with different stability. Thermal stratification of Reservoir A and C was relatively weak due to shallow water depth (<10 m) and the influence of water diversion, whereas thermal stratification was more stable in Reservoir B with a water depth of approximate 12 m. Thermal stratification hindered transfer of dissolved oxygen (DO) from surface water to the lower water layer, and oxygen consumption by water and sediment in plain reservoirs in subtropical region was relatively high due to high temperature and microbial activity. Therefore, DO concentration dropped rapidly with water depth, leading to anaerobic layers with heights of 2-4 m at the bottom of the three reservoirs. As a result, release of nitrogen, phosphorus, iron and manganese from the sediments was significant, especially in Reservoir B. In early July, the concentrations of total nitrogen, ammonium, total phosphorus, iron and manganese in the bottom layer have all substantially exceeded the standard limits for drinking water source. In general, water quality deterioration caused by thermal stratification of plain reservoirs in subtropical region cannot be ignored, and measures should be taken to combat the hypoxic environment and pollutants release at the bottom layer.

Keywords: Plain Reservoir; Thermal Stratification; Anaerobic Layer; Nitrogen and Phosphorus; Iron and Manganese

1. Introduction

Reservoirs and lakes, as the main forms of surface water, have become the main sources of drinking water in many cities [1], and "river reservoirization" has shown an increasing trend year by year [2]. The thermodynamic conditions of rivers are changed significantly after damming and reservoir construction, and seasonal thermal stratification is a common phenomenon of reservoirs [3]. At the end of spring and early summer, the temperature of surface water is increased quickly due to the strong solar radiation, and the water density decreases. Meanwhile, the water temperature of the lower layer remains at a low level, and therefore the water density is greater. Because the density of the bottom water body is greater than that of the surface water body, stable thermal stratification will be formed [4]. The schematic diagram of thermal stratification in a reservoir is shown in **Figure 1**. Generally, the surface water body is affected by solar radiation, wind and waves and other factors, and the temperature also changes with the change of temperature, so this layer is called **epilimnion**. The lower water body is relatively static and stable in temperature, which is called **hypolimnion**. Between the upper and lower water bodies is a transition layer with the largest temperature gradient, called the **thermocline**.

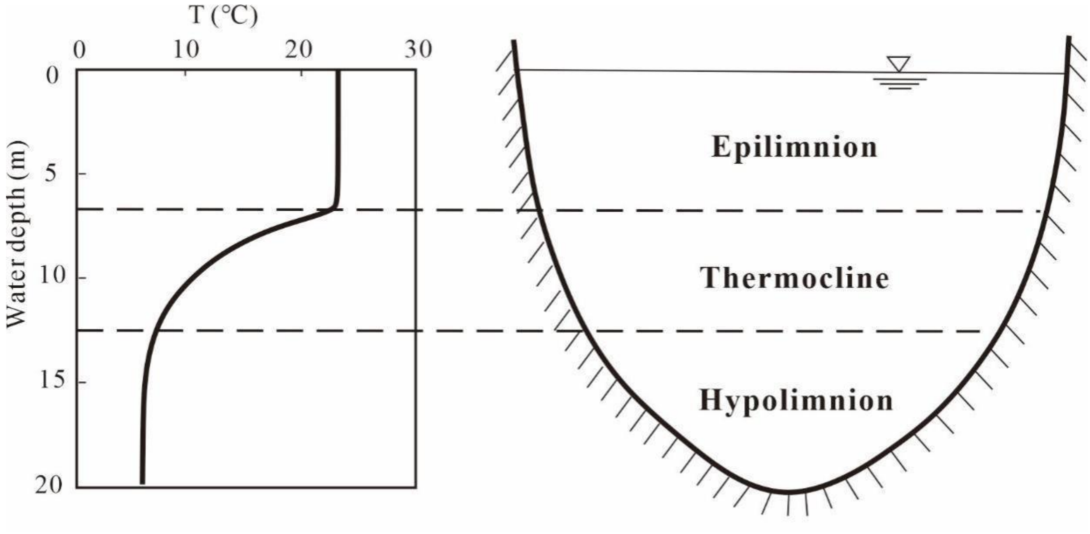

Figure 1 Schematic diagram of thermal stratification in reservoirs

Reservoir stratification will lead to deterioration of water quality, including reduction of bottom dissolved oxygen (DO), deterioration of aquatic ecological environment, release of sediment pollutants [5]. Due to the lack of water exchange between the upper and lower layers and the respiration of microorganisms and aquatic animals, DO in the lower layer gradually decreases and eventually approaches zero [6]. Under anaerobic conditions, nitrogen (N) and phosphorus (P) are released into the water, which can significantly promote the growth of algae [7].

Most of the current studies on water pollution related to thermal stratification focused on deep reservoirs [3-5]. Thermal stratification and the related water quality variation of plain reservoirs has not been paid enough attention. Water depths of plain reservoirs are generally 5-15 m, and therefore stratification stability and related hypoxia in bottom layer is supposed to be less severe [8]. However, in comparison with reservoirs in temperate region, higher water temperature of reservoirs in subtropical region might result in faster consumption of DO by biological and chemical oxidation in sediments and bottom water layer [9]. Therefore, whether hypoxia in bottom water layer and release of pollutants from the sediment can occur in plain reservoirs of subtropical region requires further investigation.

In this work, water temperature, DO and related water quality parameters at different depths of three plain reservoirs in City S (South China), were continuously monitored from March to July 2021. The formation and changes of thermal stratification and its effect on water quality was analyzed. The results were expected to provide some guidance for the management of plain reservoirs in subtropical region.

2. Materials and Methods

2.1. Overview of the research area

The three reservoirs studied are located in City S of South China. The average temperature of the city for many years was 21.4-22.3℃. Reservoir A is mainly supplied by a water diversion project, and the three reservoirs are connected through culverts. During this study, the depths of Reservoir A, B and C were 8.63±1.02 m, 12.22±1.11 m, and 9.90±0.99 m, respectively.

2.2. Sample collection and analysis

The sampling point was located at the deepest point of each reservoir. Water temperature (T) and DO were measured by a HACH Hydrolab DS5 multi-parameter water quality tester in situ. Meanwhile, water samples were taken at different depth of the reservoirs for examination in lab. The surface layer sample was collected 0.5 m below the surface of the reservoir. The water sample in the middle layer was collected in the middle of the thermocline layer, and the water samples in the bottom layer are collected 0.5 m above the surface of the sediment. TN, TP and NH_4^+-N are measured by spectrophotometry, Fe and Mn are measured by flame atomic absorption method. Continuous monitoring was conducted from March 2021 to July 2021, and the frequency of testing was once every two weeks.

3. Results and discussion

3.1. Characteristics and dynamics of reservoir thermal stratification

3.1.1. Water temperature change

Water temperature at different depth of the three reservoirs is shown in **Figure 2**. For all the three reservoirs, water temperature of the whole water body gradually increased from March to July, but water temperature of the bottom layer raised slowly relative to the temperature of the upper water, resulting in water temperature difference between the upper and bottom layer. The water temperature difference between the upper and bottom layer of all the three reservoirs was similar (7-8 ℃) in late March. However, it increased to about 10 ℃ in early July for Reservoir B, but decreased significantly for Reservoir C.

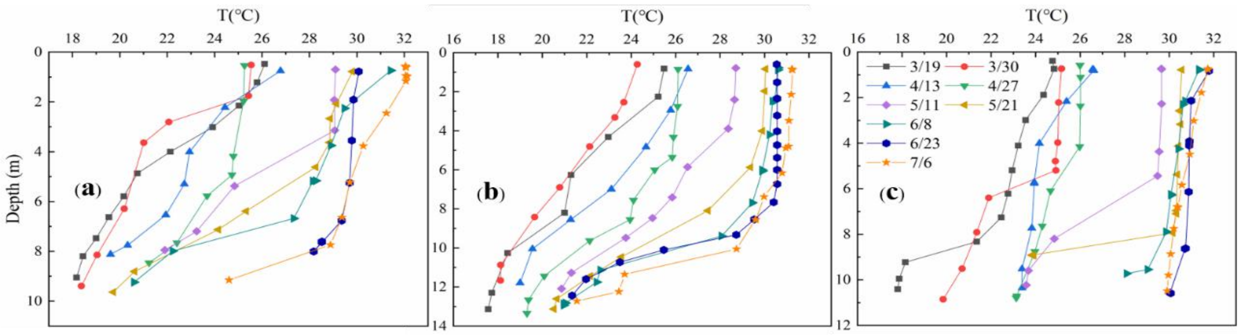

Figure 2 Temperature changes of Reservoir A (a), B (b) and C (c)

The average water depth of Reservoir B (Figure 2b) was 12.22±1.11 m during the study. The average surface layer temperature was 26.67 ℃ before May 11, and the average bottom layer temperature was 18.97 ℃. After May 11, the average surface layer temperature reached 30.61 ℃, and the average bottom layer temperature reached 21.10 ℃, resulting in a water temperature difference of 9.67℃. For reservoir B, as the temperature raised, the thickness of the thermocline layer was reduced, but the thermal stratification structure was stable.

The temperature difference between the upper and lower layers of Reservoir A and C decreased to 1.55℃ and 1.72℃ at June 23, respectively. The thermal stratification of Reservoir A and C was weaker than that of Reservoir B, probably due to shallower water depth and disturbance of water body due to water conveyance. The average water depth of Reservoir A and C was 8.63±1.02 m and 9.90±0.99 m, respectively. When the water depth is less than 10m, it is difficult to form long-term stable stratification; even if it is formed, it is very fragile and easily affected by wind, temperature and other factors [10]. Meanwhile, Reservoir A and Reservoir C were affected by water conveyance, and the water body was disturbed during the water delivery process.

3.1.2. Dissolved oxygen changes

Affected by the stratification of water temperature, DO in the three reservoirs also presented a stratification phenomenon (**Figure 3**). The surface layer of the reservoir exchanges with the atmosphere, and the DO in the surface layer was relatively high, generally 7-10 mg/L. Sometimes, DO in the surface layer was as high as 10-14 mg/L, probably due to generation of oxygen by algal photosynthesis [4]. But DO decreased significantly with the increase of water depth, especially when stable thermal stratification existed. The thermocline had a barrier effect on mass transfer between the upper and lower layers, and therefore DO in the upper layer cannot be transferred to the bottom layer. DO of the bottom layer water was consumed by biological and chemical oxidation in sediment and water, but cannot be compensated by reoxygenation from upper layer [11].

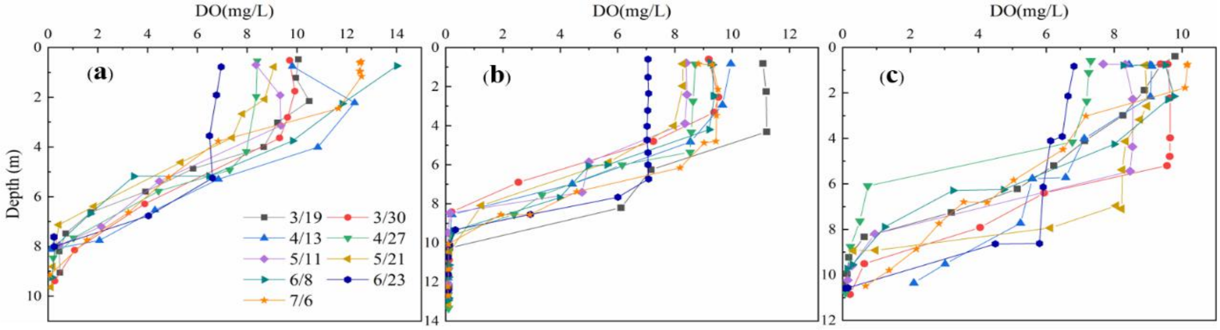

Figure 3 Changes in dissolved oxygen (DO) in Reservoir A (a), B (b) and C (c)

Due to the continuous and stable thermal stratification structure of Reservoir B (**Figure 2a**), there was a stable hypoxic zone in the bottom layer, with an average hypoxic thickness of 4.19m. Thermal stratification of Reservoir A and C was weaker, but hypoxic zones also existed in the bottom layer, with an average hypoxic zone thickness of 2.39 m and 1.99 m for Reservoir A and C, respectively. Generally, anaerobic zone occurred in all the three plain reservoirs, and more stable thermal stratification in Reservoir B resulted in the thickest anaerobic zone.

3.2. Effect of thermal stratification on water quality

Pollutants in reservoirs are generally classified by their sources as external input and endogenous release. The pollutants those enter reservoirs with inflow rivers are defined as external input [12]. Meanwhile, under anaerobic environment and reducing conditions, the sediments in lakes and reservoirs can release pollutants into the overlying water, which is defined as endogenous release [13]. The effect of thermal stratification on reservoir water quality is mainly reflected in the increase of endogenous pollution.

3.2.1. Total nitrogen (TN)

Changes of TN concentration in the three reservoirs are shown in **Figure 4**. Reservoir A (Figure 4a) showed an overall upward trend in TN concentration, with an average concentration ranging from 0.85 to 1.95 mg/L. Water of Reservoir B was mainly transported from Reservoir A, and therefore the TN concentration showed the same upward trend as Reservoir A, with the average concentration varying from 0.65 to 1.78 mg/L. Reservoir C was also supplied by another water diversion system, and the TN concentration exhibited different trend with Reservoirs A and B.

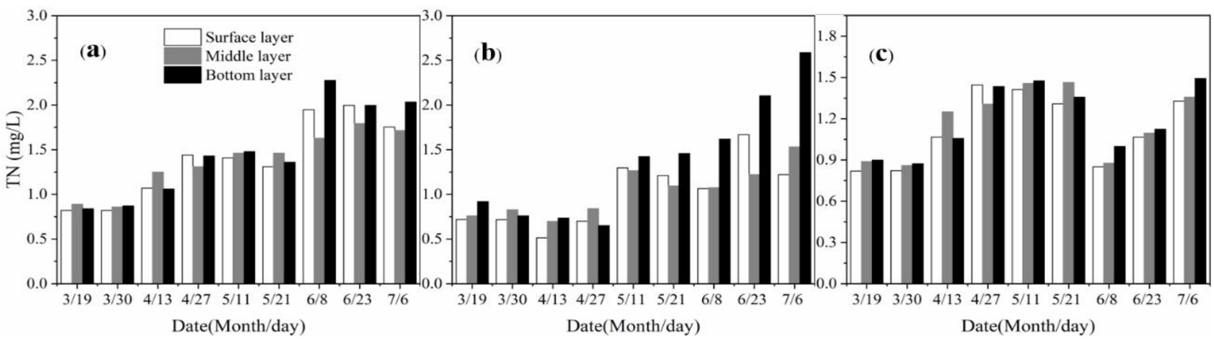

Figure 4 Changes in total nitrogen (TN) in Reservoir A (a), B (b) and C (c)

With respect to vertical distribution, under the condition of continuous hypoxia in the bottom layer, the sediment released nitrogenous substances, which led to an increase in TN in the bottom layer. The maximum concentration occurs in the stable thermal stratification period of Reservoir B. On July 6, the TN in the bottom layer of Reservoir B was 2.58 mg/L, which was 2.12 times of that of the surface layer. In contrast, because of the less stable thermal stratification and smaller anaerobic area of Reservoir A and C, the release of TN was not significant.

3.2.2. Ammonium nitrogen (NH_4^+-N)

Figure 5 shows the change of NH_4^+-N concentration in different water depths of the three reservoirs. Under aerobic conditions in the upper water layer, the NH_4^+-N concentration was at a relatively low level. However, when the bottom water was in anaerobic state, the organic nitrogen in the sediment underwent ammoniating reaction under the action of microorganisms to generate NH_4^+-N, which was released to the overlying water body through the processes of diffusion, convection and resuspension [14].

Reservoir A and C were affected by water diversion, and the thermal stratification structure was not stable. Therefore, NH_4^+-N concentration in the bottom water fluctuated, and the release concentration was 0.031~0.144 mg/L and 0.057~0.518 mg/L, respectively. In contrast, due to the continuous and stable thermal stratification in Reservoir B, NH_4^+-N in the bottom layer continued to accumulate, and the concentration raised from 0.024 mg/L to 1.714 mg/L, far exceeding NH_4^+-N concentration of the surface layer.

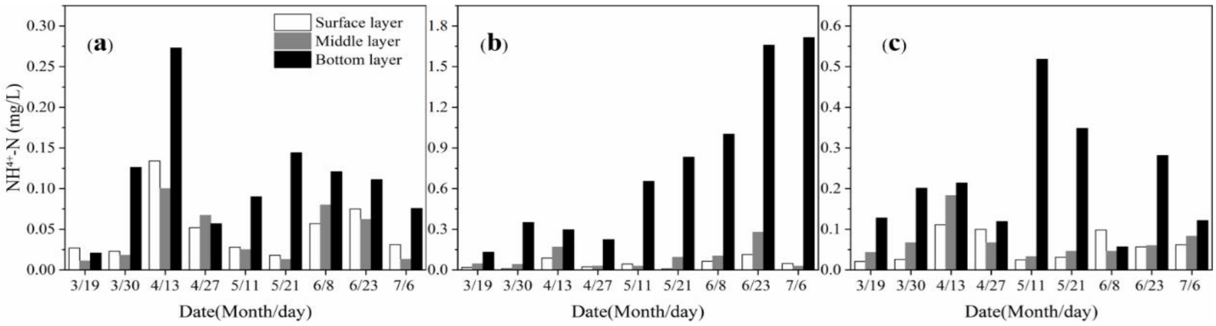

Figure 5 Ammonia nitrogen (NH_4^+-N) changes in Reservoir A (a), B (b) and C (c)

3.2.3. Total phosphorus (TP)

It is generally believed that when the TP concentration exceeds 0.02 mg/L, the water body is in a eutrophication state [15]. **Figure 6** shows the variation of TP in the three reservoirs, and it can be seen that phosphorus release from the sediment occurred in all the three reservoirs.

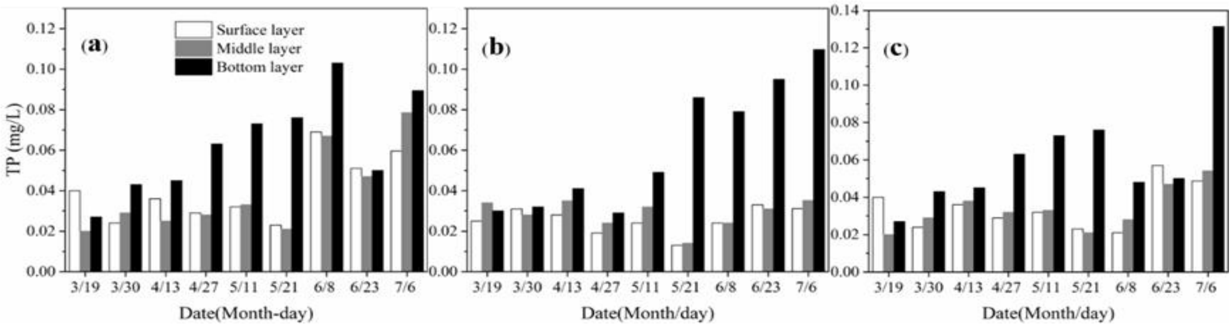

Figure 6 Changes in total phosphorus in Reservoir A (a), B (b) and C (c)

Reservoir B underwent stable thermal stratification conditions during the study, and therefore release of phosphorus pollutants from sediment occurred under anaerobic conditions. TP accumulated in the bottom water due to stratification, and therefore its concentration in the bottom layer was much high than those in the surface and middle layer. The concentration of TP gradually increased during the study, and the maximum concentration reached 0.110 mg/L on July 6.

In Reservoir A and C, release of phosphorus also occurred at the bottom layer due to the anaerobic zone. In Reservoir A, the maximum TP concentration reached 0.103 mg/L on June 8. For Reservoir C, the maximum TP concentration reached 0.131 mg/L on July 6.

3.2.4. Iron (Fe) and manganese (Mn)

When the water is rich in oxygen and alkaline, Fe and Mn are in the form of metal oxides. But under reducing conditions, they are in dissolved state and can diffuse into the overlying water [16]. As shown in **Figure 7**, the Fe and Mn concentrations in the surface and middle layers of the three reservoirs were all at very low level, which did not exceed the standards for drinking water source (Fe<0.3 mg/L, Mn<0.1 mg/L). However, for the bottom layer, Fe and Mn were released to various degrees under anaerobic state.

The release of Fe and Mn in Reservoir B was significant because of the continuous thermal stratification and anaerobic state of the bottom layer. The highest concentration of Fe and Mn in the bottom layer reached 1.67 mg/L and 1.04 mg/L, respectively. Release of Mn occurred significantly in Reservoir A, and the maximum Mn concentration in the bottom layer reached 1.32 mg/L on July 6, probably due to more abundance of Mn in the sediment of Reservoir A. The release of Fe and Mn in Reservoir C was not as severe as that in Reservoir A and B, and the maximum Fe and Mn concentration reached 0.35 mg/L and 0.28 mg/L, respectively.

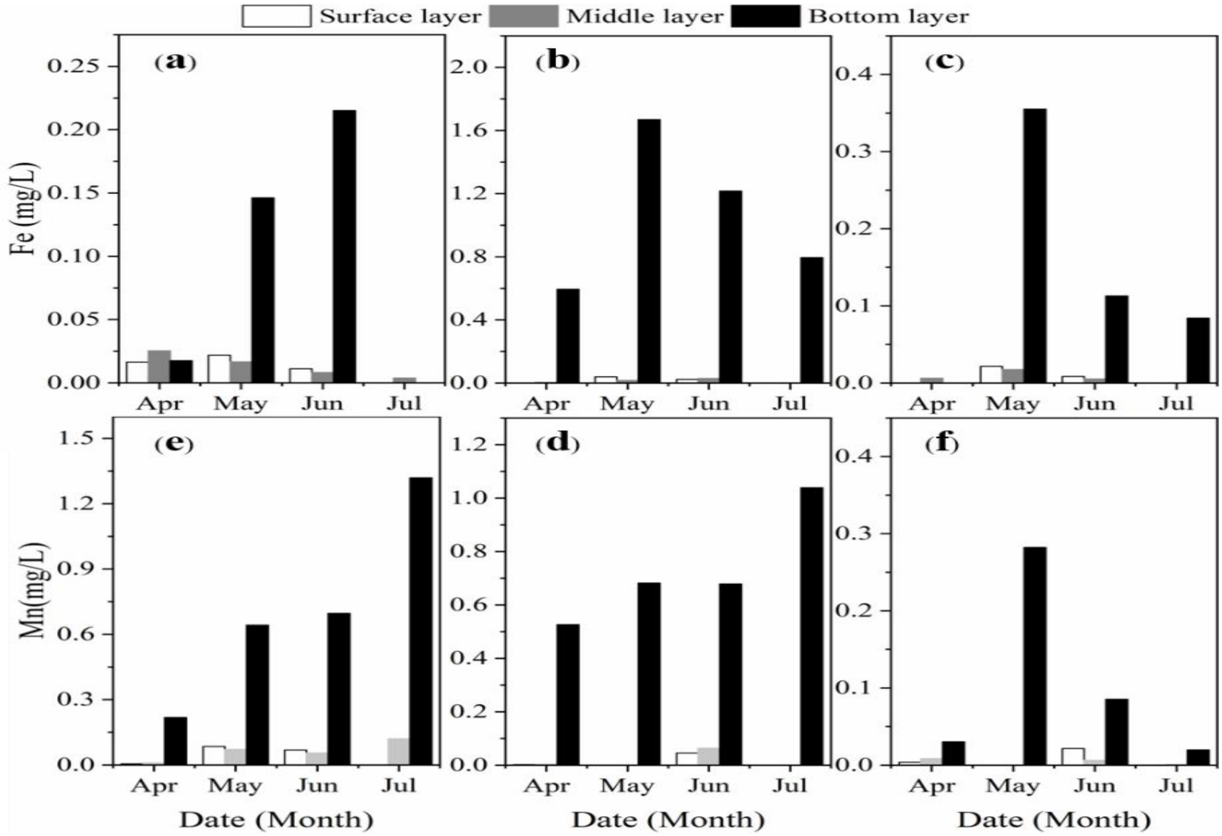

Figure 7 Concentration of iron and manganese in Reservoir A (a), B (b) and C (c)

4. Conclusion

The three plain reservoirs exhibited different degrees of thermal stratification. Reservoir A and C were shallower than Reservoir B, and it was affected by water diversion project. Therefore, the thermal stratification structure was weak, and there was no obvious hypolimnion layer. The thermal stratification structure of reservoir B was relatively stable because of its greater water depth. DO also exhibited stratification along with water temperature stratification. DO concentration dropped rapidly near the thermocline, causing anaerobic zone at the bottom layer of the three reservoirs. Anaerobic condition at the bottom layer led to release of nitrogen, phosphorus, iron and manganese from the sediments, especially for the more stable stratified Reservoir B.

The results of this study suggested that thermal stratification also occurred in plain reservoirs in subtropical region. The stability of stratification increased with water depth, and anaerobic zone at the bottom layer would result in pollutants release from sediment. Therefore, to ensure safety of water quality, strategies should be taken to prevent the formation of anaerobic environment and release of pollutants.

References

[1] Han B P. Reservoir ecology and limnology in China: a retrospective comment[J]. Journal of Lake Sciences, 2010, 22(2):151-160.

[2] Lehner B, Liermann C R, Revenga C, et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management[J]. Frontiers in Ecology & the Environment, 2011, 9(9): 494-502.

[3] Zhang Yunlin, Wu Zhixu, Liu Mingliang, et al. Dissolved oxygen stratification and response to thermal structure and long-term climate change in a large and deep subtropical reservoir (Lake Qiandaohu, China) [J]. Water Research, 2015, 75: 249-258.

[4] Huang Tinglin. Water pollution and water quality control of selected Chinese reservoir basins [M]. Springer, 2015.

[5] Liu Miao, Zhang Yunlin, Shi Kun, et al. Thermal stratification dynamics in a large and deep subtropical reservoir revealed by high-frequency buoy data[J]. Science of the Total Environment, 2019, 651: 614-624.

[6] Conley Daniel J., Paerl Hans W., Howarth Robert W., et al. Controlling Eutrophication: Nitrogen and Phosphorus[J]. Science, 2009, 323(5917): 1014-1015.

[7] Rigosi Anna, Rueda Francisco J. Hydraulic control of short-term successional changes in the phytoplankton assemblage in stratified reservoirs[J]. Ecological Engineering, 2012, 44: 216-226.

[8] Cheng Yifan, Voisin Nathalie, Yearsley John R., et al. Reservoirs Modify River Thermal Regime Sensitivity to Climate Change: A Case Study in the Southeastern United States [J]. Water Resources Research, 2020, 56(6): e2019WR025784.

[9] Zhou Z., Huang T., Li Y., Ma W., Zhou S., Long S. Sediment pollution characteristics and in situ control in a deep drinking water reservoir [J]. J Environ Sci (China), 2017, 52: 223-231.

[10] Lulëzim Shuka, Alqi Çullaj, Spase Shumka, et al. The Spatial and Temporal Variability of Limnological Properties of Bovilla Reservoir (Albania) [J]. Water Resources Management, 2011, 25(12): 3027-3039.

[11] Li Nan, Huang Tinglin, Mao Xuejing, et al. Controlling reduced iron and manganese in a drinking water reservoir by hypolimnetic aeration and artificial destratification[J]. Science of the Total Environment, 2019, 685: 497-507.

[12] Zheng Li-wen, Zhai Wei-dong. Excess nitrogen in the Bohai and Yellow seas, China: Distribution, trends, and source apportionment[J]. Science of the Total Environment, 2021, 794: 148702.

[13] Hu K, Pang Y, Wang H, et al. Simulation study on water quality based on sediment release flume experiment in Lake Taihu, China[J]. Ecological Engineering, 2011, 37(4): 607-615.

[14] Mäkelä K, Tuominen L. Pore water nutrient profiles and dynamics in soft bottoms of the northern Baltic Sea[J]. Hydrobiologia, 2003, 492(1): 43-53.

[15] Perrone U, Facchinelli A, Sacchi E. Phosphorus dynamics in a small eutrophic Italian lake[J]. Water, air, and soil pollution, 2008, 189(1): 335-351.

[16] Schwefel R, Steinsberger T, Bouffard D, et al. Using small‐scale measurements to estimate hypolimnetic oxygen depletion in a deep lake[J]. Limnology and Oceanography, 2018, 63(S1): S54-S67.