IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: Xianren Sun *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **643** 012079

Simulation of the anoxic effect of ecological regulation on Guanting Reservoir

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Abstract. Water transfer is an effective approach to improve water quality in reservoir area. However, the research focusing on optimum efficiency of water transfer is limited, especially the dissolved oxygen (DO) in reservoir area. As a case study of Guangting reservoir (GTR) in Beijing City, the three-dimensional DO model was built based on environment fluid dynamic code (EFDC). And the spatial and temporal distributions of DO concentration with and without ecological regulation were analysed. The results show that both water transfer and ecological discharge will disturb the "oxycline" of the water body, while the effect on the surface DO is not obvious, ranging from -4.65% to 7.28%, but it has a significant impact on increasing oxygen in the bottom layer. The DO concentration in the bottom water increased by 1.85-8.52 mg/L when the output ecological discharge was used in the reservoir, and the oxygen enrichment effect of bottom water was more obvious when considering water transfer and ecological discharge simultaneously, with an increase of 2.71-12.83 mg/L. this study has the guiding significance to improve the dissolved oxygen in the bottom water of GTR area, and can also provide a method reference in evaluating the DO variation driven by the upstream water transfer or ecological discharge similar reservoirs.

1. Introduction

Dissolved oxygen (DO) is an important evaluation index of lake and reservoir water quality, and also a key limiting factor affecting species distribution in river ecosystem [1]. In addition, it plays a significant role in the study of lake and reservoir water ecosystem as an important sensitive physical and chemical index [2]. Most of the reservoirs in China has a water supply function, and their water intakes are generally located in the middle and lower layers of the water body in front of the dam, that is, the area where the anoxic phenomenon appears frequently. The anoxic phenomenon can cause seriously influence on the normal performance of the water supply function of the reservoir [3]. Numerous studies have been done to investigate the spatiotemporal evolution process of anoxic zones in lakes and reservoirs, which mainly focus on the formation mechanism of anoxic phenomenon [4], the inter annual variation of anoxia in the reservoir area [5] and the periodic changes of anoxic process

IOP Conf. Series: Earth and Environmental Science **643** (2021) 012079 doi:10.1088/1755-1315/643/1/012079

[6]. While numerous studies have reported the impacts of dams on DO of reservoir area, the understanding of anoxic state of reservoir area based on the numerical modelling under upstream water diversion and ecological discharge is still limited. Water diversion results in the variation of hydrological and hydrodynamic conditions in the reservoir, which drives the anoxic state change in reservoir system.

The GTR serves important strategic role in Beijing, other cities and rural counties s as an important drinking water sources; however, its water quality began to deteriorate in the 1990s and its role is replaced as a function of backup drinking. To improve water quality and restore the ecological function of Yongding River, a scheme of water transfer from upstream basin has been adopted for the GTR. Reservoir water diversion changed the hydrodynamic conditions significantly, however, few studies have considered the variations of anoxic condition in water and DO concentration of the GTR under the influence of water diversion scenario. It is still not clear that how hydrologic and hydrodynamic variations influence DO distribution and evolution in the GTR.

In this work, a three-dimensional numerical model of DO in GTR area is proposed, and the model is used to analyze the change of dissolved oxygen in reservoir area. The objectives of this study were to characterize variations of DO concentration under the water diversion scenario and to explore the effects of upstream reservoir inflows and reservoir operation on anoxic condition in GTR area. the results of this study may provide an improved understanding of dissolved oxygen variation processes in the GTR, other reservoirs with similar spatial region attributes. Furthermore, this study may also provide the basis to improve anoxic condition in reservoir area and to manage water quality in GTR.

2. Material and methods

2.1. Study area

The Guangting reservoir (E115°34′20″~115°49′30″, N40°13′446″~40°25′42″) is located on the south border of the Zhangjiakou, Hebei Province and Yanqing District, Beijing(Fig.1). Its drainage area is approximately 43400 km^2, which include the outflows of the Shanggan and Yang river basins. The study area has a temperate continental monsoon climate with rapid and severe climate transitions. Annual mean temperature is 6.9 ℃. Precipitation is subject to large inter-annual variability, with 360-650 mm/year, of which 75% is concentrated between June and September [7]. The GTR dam was heightened in 1986, from 482.0 to 492.0 m, and its total storage capacity increased from 2.27 billion m^3 to 4.16 billion m^3[8], as a basics to the large water transfer projects that followed. And a series of water diversion projects have been carried out [9-10].

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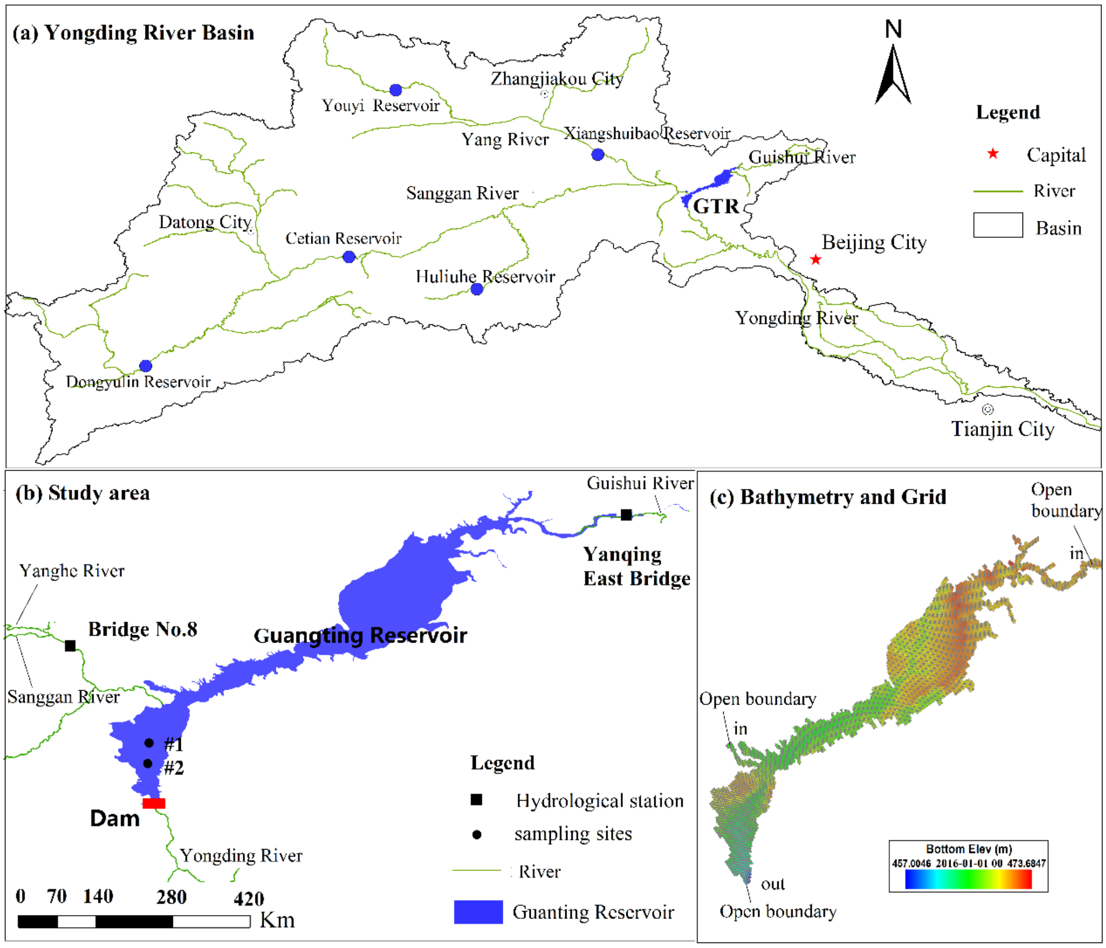

Figure 1. Study area of the Guangting Reservoir.

2.2. Model description and setup

In this study, EFDC was used to simulate the dissolved oxygen in the GTR. EFDC is a 3-D hydro-environment numerical simulation software developed by Virginia Institute of Marine Science, and subsequently developed by the US Army Corps of Engineers sponsored by the US EPA [11]. The study area covers the whole Guanting Reservoir Area with the outline altitude equal to 472.36 m (Fig. 1c). The number of grid cells in the GTR is 477 in the longitudinal direction and 98 in the lateral cell dimension of 90m×100 m (longitudinal × lateral). Lastly, the model was set by 13873 active grids in the horizontal plane with 10 layers along the vertical direction.

Based on this grid, the time step of the calculation is set to 10 s. The model contains three open boundaries (Fig. 1c). The upper boundary is located Bridge no.8, which is the confluence of the two main tributaries of the Yongding river. The other open boundary was defined by the daily average discharge and DO observed at the Yanqing East Bridge (Fig.1b and c). The GTR open lower boundary is located at the head of dam sites which the water level condition is given. The simulation started on January 1, 2016 (Julian data 0), with a cold start (the velocity was set to zero and the DO was set to the arithmetical mean of values of the open boundaries), and the calibration period was from January 1, 2016 to December 31, 2016. The elevation of the initial water surface of the reservoir was 473.26 m based on the hydrological station at the Guangting Dam.

2.3 Calibration and validation

Herein, the Mean Absolute Error (MAE) were used to determine the accuracy of the simulations

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$$MAE = \frac{\sum_{i=1}^{n} \left| X_{obs,i} - X_{model,i} \right|}{n} \qquad (1)$$

and Root-Mean-Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_{obs,i} - X_{model,i})^2}{n}} \qquad (2)$$

The model was calibrated and validated using the field-measured dissolved oxygen and water level data at the sampling sites locations shown in Fig.1b.

Fig.2 shows the comparisons between predicted and measured water level (the MAE was 0.029m and RMS was 0.043m). Fig.3 shows the comparisons between the model-simulated and field-measured dissolved oxygen distributions. The vertical dissolved oxygen profiles predicted by the model generally conforms the field-measured oxygen with the locations of oxycline agreeing to the field-measurements at most of the observation stations (Fig.3, MAE ranges from 0.22 to 1.58mg/L and RMS ranges from 0.27 to 1.92 mg/L). The calibration and validation indicated that the model can represent the hydrodynamic and oxygen features in the GTR and the statistics parameters indicated that the accuracy of the model is acceptable.

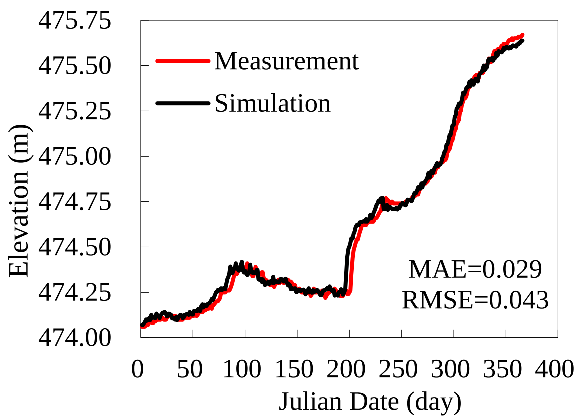
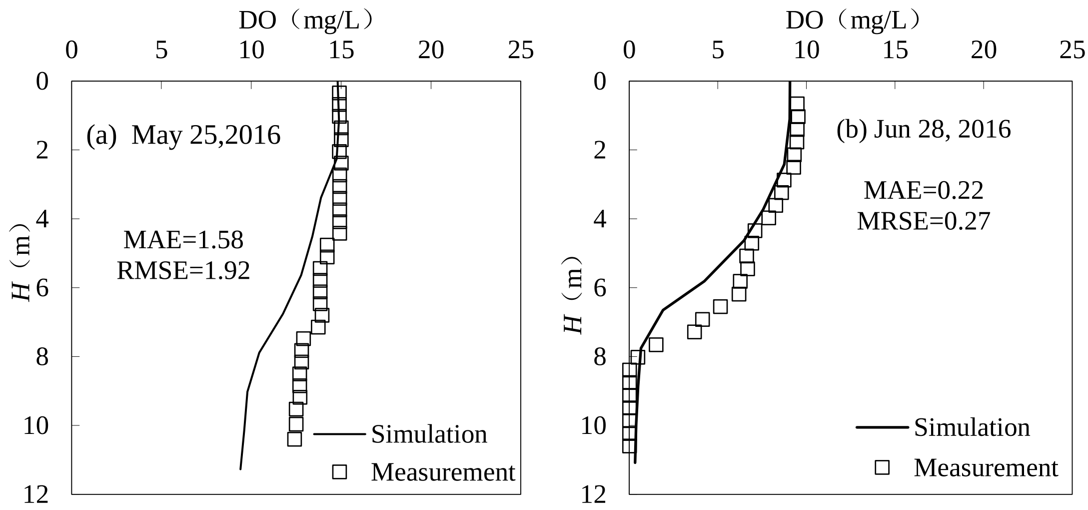


Figure 2. Comparison between simulated and measured water level of GTR



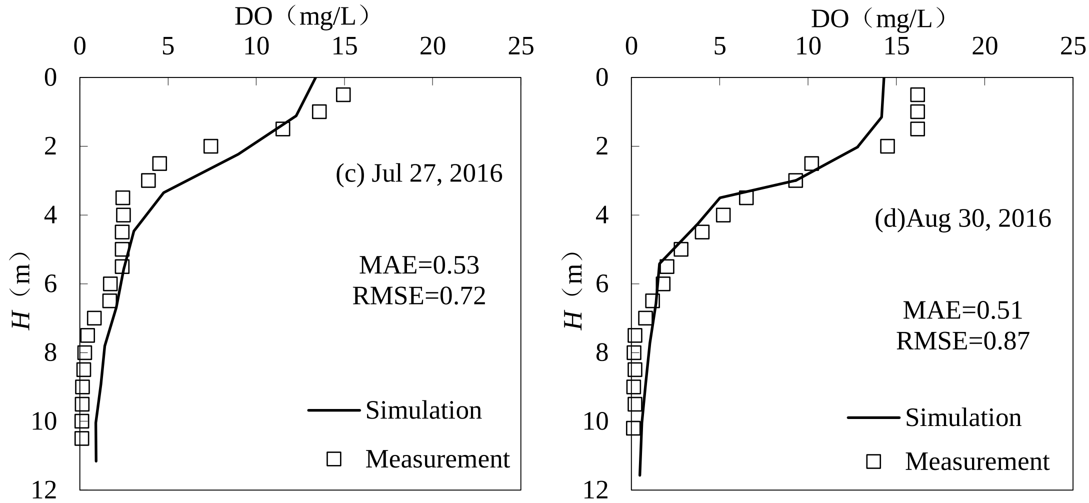


Figure 3. Comparison of simulated and measured values of DO in section #1 of GTR

3. Model applications

For the impact of water diversion on the spatial and temporal distribution of dissolved oxygen, four scenarios were planned in this study. Scenario 1 is refered the predicted DO process without the water diversion in 2016, Scenario 2 is the predicted DO process after the implementation of water diversion from Wanjiazhai to the Yellow River, which is from March to May every year.The annual water diversion volume was 1×10^8 m^3, and the GTR was 0.5×10^8m^3, and the discharge flow is discharged according to the original discharge mode. Scenario 3 is the predicted results driven by the original reservoir operation and considering the flow process limit under the minimum ecological water demand of downstream. Scenario 4 is a comprehensive scenario, which simulates the change of dissolved oxygen considering both water diversion (same as scenario 2) and the minimum ecological water demand limit.

4. Results and Discussion

4.1. Simulation results

The monthly distribution of DO in section 2 of the reservoir area is shown in Fig.4. The concentration of DO in surface water (0~4 m) ranged from 6 to 15 mg/L every month, which indicating that the surface water was rich in oxygen, and its concentration fluctuated with seasons, with higher in winter and spring, and lower in summer and autumn. The maximum and minimum value appeared in January and September respectively. The vertical distribution shows that the dissolved oxygen concentration in the surface layer is higher, while the bottom layer is in anoxic state with a DO concentration less 2 mg/L or even anaerobic state with a DO concentrantion close to 0 mg/L [12].

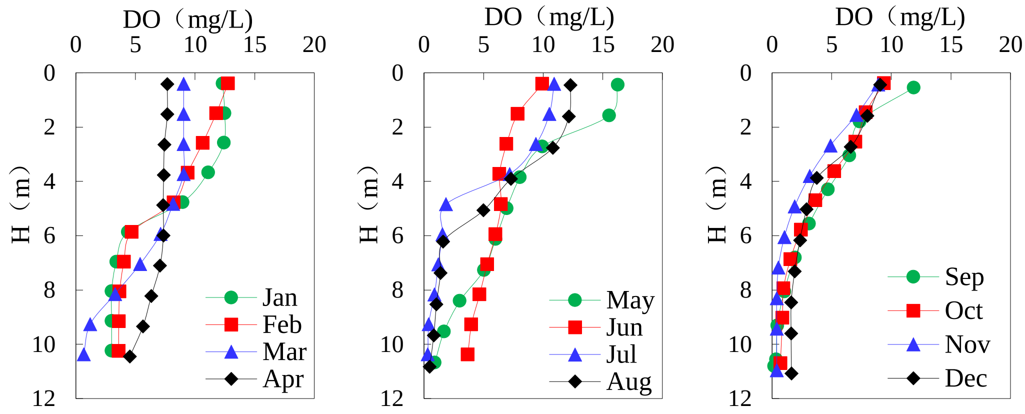


Figure 4. Monthly variation of DO in monitoring site #2 in reservoir area

4.2. Effects of water diversion on the DO in the GTR

The DO concentrations in the surface and bottom layer of different scenarios are selected for comparative analysis (Fig.5). Under the original reservoir scheduling operation (Scenario 1), the anaerobic condition state of bottom water will continue until the end of the year, and the thickness of the low oxygen layer is gradually increasing, and the phenomenon of oxygen stratification is obvious. Compared with scenario 1, the DO process including the water transfer diversion and ecological discharge will destroy the "oxycline", however, the water transfer diversion has little effect on the dissolved oxygen stratification structure. In scenario 2, the concentration of DO in the surface layer increases slightly, with an average increase of 7.28%. The concentration of DO in the bottom water increases slightly in the early stage, but gradually decreases in the later stage, and the anoxic period is prolonged, which leads to the gradual expansion of oxygen stratification.

Under scenario 3, the surface DO concentration decreased about 4.65%, while it increased 1.41% in scenario 4. Different from the surface water, the variation of dissolved oxygen concentration in the bottom layer between scenario 3 and scenario 4 is further decreased, stratification disappeared, and the dissolved oxygen concentration increased significantly. Under scenario 3, DO concentration in the bottom layer increased by 1.85 ~ 8.52 mg/L; similarly, under the scenario 4, the DO in bottom water also had an obvious increasing, with a level ranged from 2.71 to 12.83 mg/L. The duration of hypoxia or anoxic state was significantly reduced, and the bottom water remained an oxygen-enriched state in both scenario 3 and scenario 4.

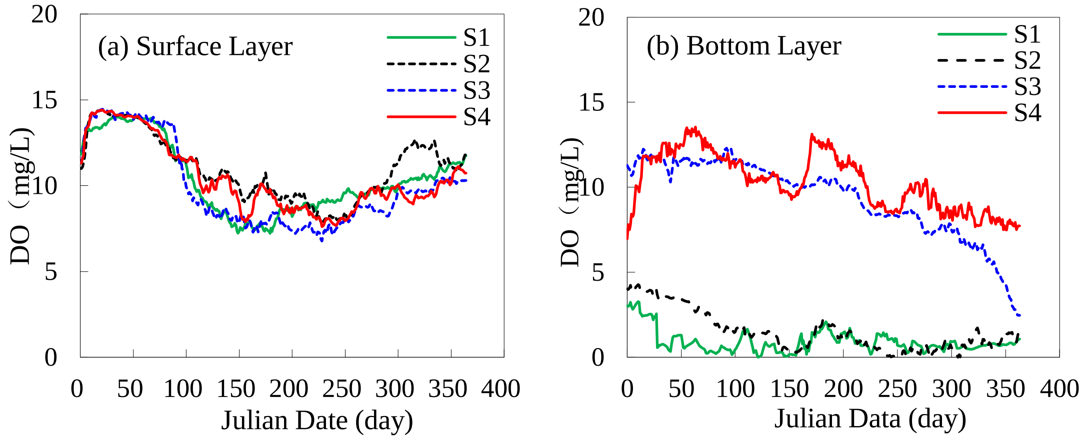


Figure 5. Variation of surface and bottom DO in GTR under different scenarios

5. Conclusion

In the current study, a three-dimensional DO model of GTR was established, which was calibrated and verified using the measured data of water level and dissolved oxygen. The result shows that the model and related parameters have good reliability, and can be used to reveal the change process of hydrodynamic and dissolved oxygen in GTR. According to the current calculation results, the upstream water diversion and reservoir ecological discharge significantly affect the water level process and the three-dimensional distribution of dissolved oxygen in GTR. For example, in scenario 3 and scenario 4, there is almost no oxygen-free zone in the bottom water of GTR, which indicates that water diversion and discharge can effectively improve the dissolved oxygen environment of water body.

Generally speaking, for the reservoirs without enough inflows in the North China, the upstream water diversion can relieve the anoxic state in reservoir area. However, water diversion will increase the water depth and raise the water level of the reservoir. Moreover, it may increase the temperature difference during the formation and development of thermocline, resulting in the decrease of dissolved oxygen in the deep water zone. However, ecological discharge regulation of outlet flow will reduce the reservoir water level, which will weaken the thermocline and narrow the anoxic zone. The quantitative relationship between the amplitude change and the driving factors mentioned above required to be further studied in the next step.

Acknowledgments
This work was partly supported by Major Science and Technology Program for Water Pollution Control and Treatment (2018ZX07111-002) and General Program of the National Nature Science Foundation of China (No.52079130).

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