International Journal of GEOMATE, Feb., 2020, Vol.18, Issue 66, pp. 56-61
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.66.9366
Geotechnique, Construction Materials and Environment

NUMERICAL SIMULATION FOR SEASONAL AND INTER-ANNUAL CHANGE OF DISSOLVED OXYGEN IN LAKE BIWA, JAPAN

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*Corresponding Author, Received: 15 June 2019, Revised: 29 Nov. 2019, Accepted: 05 Jan 2020

ABSTRACT: The dynamics of dissolved oxygen in lake is a fundamental issue of comprehending the water environmental habitats of aquatic organisms. In recent years, the decrease in dissolved oxygen has been observed at the bottom of the northern part of Lake Biwa, Japan. In recent years, eutrophication and global warming caused the decrease in the dissolved oxygen in the deep layer. Under these circumstances, in order to preserve the ecosystem of Lake Biwa and to provide water resources, the environmental changes in Lake Biwa should be accurately grasped. In our present study, a water quality model considering the flow field from hydrodynamic model was developed in order to grasp the concentration of phytoplankton, zooplankton, nitrogen, phosphorus, dissolved oxygen and chemical oxygen demand in Lake Biwa. Numerical simulation was carried out for 3 years from 2007 to 2009. Comparisons of the simulations with the observations showed that the seasonal and inter-annual change of dissolved oxygen was well reproduced. The dissolved oxygen decreased during decomposing the organic matter by bacteria in the bottom layer with little oxygen supply from the atmosphere and the photosynthesis from the phytoplankton under the thermocline from spring to autumn. The simulation confirmed that in each year, the dissolved oxygen was supplied in all layers by the overturning in winter.

Keywords: Dissolved Oxygen, Water Quality Model, Thermocline, Overturning, Lake Biwa

1. INTRODUCTION

Water quality in lakes and reservoirs are of importance to daily life water but are vulnerable to external load. In various lakes, eutrophication due to increased nutrient loadings from the watershed and global warming caused deterioration of lake water quality [1] [2].

Lake Biwa which is the largest freshwater lake in Japan serves drinking water for approximately 15 million people in Shiga and other surrounding prefectures. Lake Biwa has undergone eutrophication since 1950s. After the improvement of water quality by promoting the use of non-phosphorus synthetic detergent from the late 1970s, the trends in the eutrophication in Lake Biwa had decreased. Until 1980, eutrophication was the main reason why the dissolved oxygen decreased in the deep layer. However, after the 1980s, low levels of dissolved oxygen under 2 mg/L in the bottom layer became evident. At this level, aquatic life cannot breathe naturally. The reason for the decrease in dissolved oxygen has been considered to be the strengthening of stratification due to global warming in recent years [3] [4].

The meteorological elements have direct and indirect impacts on the change of dissolved oxygen in the bottom layer. Direct impacts are due to changes in forcing factors such as air temperature, wind speed and precipitation. In particular, the rise in air temperature and the decrease in wind speed have been thought to weaken the vertical mixing of lake water, which maybe the cause of the hypoxia [5] [6].

Indirect impacts are changes in biogeochemical cycles and related biological activities. The biological metabolism to change in water temperature was observed in the deep layer after 1990, therefore the meteorological elements could cause the significant influences on the ecosystem of Lake Biwa.

In many lakes, eutrophication and climate change impacts causes the deterioration of water quality so that it is difficult to distinguish their effects [7]. It is necessary to figure out the biochemical processes together with considering the hydrological processes.

A box model was used to calculate the division of one box for the south lake and 2 boxes for the north lake in upper and lower part in Lake Biwa [8]. However, box models cannot consider spatial distribution because values in the box are uniform. The ecological simulation for the eutrophication in Lake Biwa were performed [9], [10]. It is better to use a one-dimensional model to predict long term changes in water quality ecosystem. However, three-dimensional physical processes such as the surficial flow, internal waves and turbulence caused by the wind should be included to capture the nutrient circulation.

In the present study, a water quality model considering the flow field from hydrodynamic model was developed in order to grasp the concentration of phytoplankton, zooplankton, nitrogen, phosphorus, dissolved oxygen and chemical oxygen demand in

Lake Biwa. Numerical simulation was carried out for 3 years from 2007 to 2009. The seasonal and inter-annual changes of vertical distribution of dissolved oxygen in Lake Biwa was simulated to compare with the observations from 2007 to 2009.

2. Water Quality Model in Lake Biwa

2.1 Calculation domain

This study focused on Lake Biwa in Japan. Fig. 1 shows the calculation domain and water depth in the water quality model of Lake Biwa. The horizontal domain is 36 km × 65.5 km with a horizontal resolution of 500 m. The vertical domain consists of 86 layers from the lake surface to the depth of 107.5 m. The vertical grid size is 0.5 m from the surface to the depth of 20 m and gradually increases up to 2.5 m.

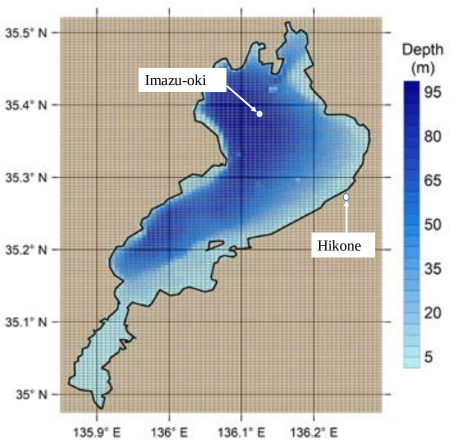

Fig. 1 Calculation domain with the topography of Lake Biwa

2.2 Each component in water quality model

Many factors are involved in water environment with large and complicated ecosystem like Lake Biwa. For simplifying this ecosystem, this model consists of nine state variables such as phytoplankton, zooplankton, particulate and dissolved organic chemical oxygen demand, inorganic and organic phosphorus and nitrogen, and dissolved oxygen. Phytoplankton have chlorophyll a, b and c. Based on the amount of each chlorophyll, the amount of phytoplankton is calculated. Phosphorus and nitrogen are two limiting nutrients that control the photosynthesis. Fig. 2 shows a conceptual diagram of a water quality model considering chemical and biological change terms.

The components are shown in Table 1. A summary of the chemical and biological processes of each component is shown in Table 2.

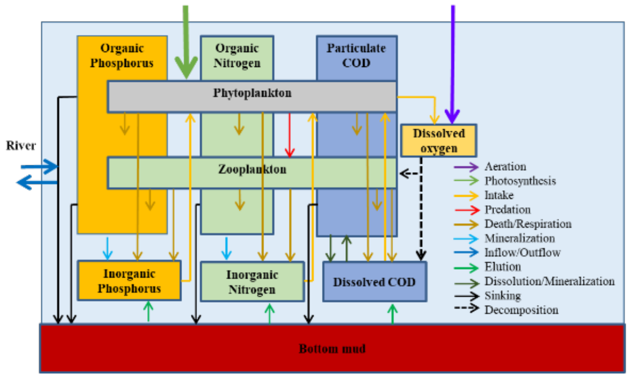

Fig.2 Conceptual diagram of water quality model

Table 1 Each component of water quality model

Component	Symbol	Unit
Phytoplankton	C_{PX}	mgC/l
Zooplankton	C_{Z}	mgC/l
Inorganic nitrogen	C_{IN}	μgN/l
Organic nitrogen	C_{ON}	μgN/l
Inorganic phosphorus	C_{IP}	μgP/l
Organic phosphorus	C_{OP}	μgP/l
Dissolved oxygen	C_{DO}	mgO/l
Particulate COD	C_{PC}	mg/l
Dissolved COD	C_{DC}	mg/l

Table 2 Balance of water quality elements

C_{PX}	Proliferation by photosynthesis − Respiration of phytoplankton − Predation by zooplankton − Sinking of phytoplankton
C_{Z}	Proliferation by predation of phytoplankton − Death of zooplankton
C_{IN}	− Intake by phytoplankton through photosynthesis − Intake by zooplankton + Death of zooplankton + Mineralization of organic nitrogen + Elution from the bottom mud
C_{ON}	Death of phytoplankton − ingestion of zooplankton + Death of zooplankton − Mineralization of organic nitrogen + Sinking of organic nitrogen
C_{IP}	− Intake by phytoplankton through photosynthesis − Intake by zooplankton + Death of zooplankton + Mineralization of organic phosphorous + Elution from the bottom mud
C_{OP}	Death of phytoplankton − Intake of zooplankton + Death of zooplankton − Mineralization of organic phosphorous + Sinking of organic phosphorous
C_{DO}	Supply by photosynthesis − Consumption by Respiration of phytoplankton − Consumption by Respiration of

	zooplankton－Consumption by suspended organic matter－Consumption by dissolved organic matter－Consumption at the bottom mud +Aeration
C_{PC}	Death of phytoplankton－Ingestion by zooplankton＋Death of zooplankton－Dissolution of Suspended COD＋Suspending of dissolved COD－Sinking of COD
C_{SC}	Respiration of phytoplankton－Ingestion by zooplankton＋Respiration of zooplankton－Mineralization of dissolved COD＋Dissolution of dissolved COD＋Elution from the bottom mud

The advection-diffusion equation of constituent elements is shown in Equation (1). The left-hand side represents the time-varying term and the advection term, and the right-hand side represents the diffusion term and the change by the biochemical process.

$$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial x} + v\frac{\partial C_i}{\partial y} + w\frac{\partial C_i}{\partial z} = \kappa_h\frac{\partial^2 C_i}{\partial x^2} + \kappa_h\frac{\partial^2 C_i}{\partial y^2} + \kappa_z\frac{\partial^2 C_i}{\partial z^2} + Q_{C_i} \quad (1)$$

C_i : Concentration of each component
i : Component
Q_{C_i} : Amount of change per unit time due to chemical and biological processes

The formulation of material circulation for each component and the details of each term are also shown in [8].

2.3 Initial conditions

As for the initial condition, the current velocity was set to be 0 m/s. The initial concentration of each component on April 1st, 2006 was derived from linear interpolation of observed data on March 20th and April 10th, 2006. The observations were conducted by the Lake Biwa Environmental Research Institute twice a month at the monitoring point Imazu-oki (35°23’41” N., 136°07’57” E.), the depth of which was 0.5 m, 5 m, 10 m, 15 m, 20 m, 30 m, 40 m, 60 m, 80 m, approximately 90 m.

2.4 Boundary conditions

The boundary conditions for hydrodynamic model were used as the same conditions described in [11]. Air temperature, atmospheric pressure, wind direction and speed, and relative humidity over Lake Biwa were derived from the Grid Point Value produced by the Meso-Scale Model (GPV MSM) of the Japan Meteorological Agency. GPV MSM data has a spatial resolution of 0.0625° longitude by 0.05° latitude (approximately 5 km) and a temporal resolution of one hour. The data was horizontally interpolated into each surface mesh of the hydrodynamic model. Solar radiation was derived from hourly observation data at the Hikone Local Meteorological Observatory (35°16’30” N, 136°14’36” E), (Fig. 1). Solar radiation was assumed to be horizontally uniform over the lake. The water temperature and flow rate simulated by the Yodo river basin model [12] were used as the boundary conditions for 56 rivers flowing into Lake Biwa.

2.5 Simulation conditions

The data of water temperature, flow direction, and flow velocity used in water quality model are input using the calculation results of the flow field model every three hours, and the calculation results of each component from the Yodo river basin model are used for the inflow from the river. The simulation was conducted for a period from 1st April 2007 to 31st March 2010 (Japanese fiscal year (JFY) 2007 to 2009) with a spin-up period from 1st April 2006 to 31st March 2007 using meteorological data derived from GPV MSM. Table 3 shows the simulation conditions for water quality model. The parameters of chemical and biological processes are based on [8].

Table 3 Simulation conditions for biological model

Parameter		Condition
Time step		45 s
Output interval		Every 3 hour
Horizontal grid size		500 m
Vertical grid size		0.5-2 m
Meteorological Data		GPV MSM data
Flow field data		Hydrodynamic Model
Inflow from river	Dissolved oxygen	Observed data from Ado river
	Inorganic nitrogen, Organic nitrogen, Inorganic phosphorus, Organic phosphorus, COD	Yodo river basin Model
Initial value	Phytoplankton (chl a,b,c)	Observed data from Imazu-oki
	Inorganic nitrogen	
	Organic nitrogen	
	Inorganic phosphorus	
	Organic phosphorus	
	Dissolved oxygen	
	Particulate COD	
	Dissolved COD	
	Zooplankton	Vertical uniform

3. RESULTS AND DISCUSSIONS

3.1. Seasonal change of nutrients and dissolved oxygen at Imazu-oki

Fig. 3, 4 and 5 show the seasonal changes in vertical distribution of observed and simulated total nitrogen (TN), phosphorous (TP), and dissolved oxygen (DO) at the monitoring point in Imazu-oki in 2007. The vertical distributions of TN, TP, and DO each year are not very different from each other, therefore we picked the values in 2007 as a representative year. The concentration of TN in the simulation didn't change seasonally above the thermocline. This may be because the amount of intake of inorganic nitrogen by phytoplankton was not enough in summer and autumn in this model. The concentration of TP in the simulation at the bottom layer was underestimated. The possible reason for it is that the amount of elusion in the bottom layer was not sufficient in this model. On the other hand, the trend of vertical distribution of DO in the simulation was well reproduced. In a stratified season, DO decreased under the thermocline while the organic matter was decomposed. In winter, DO increased because of the supply of the oxygen from the upper layer during overturning.

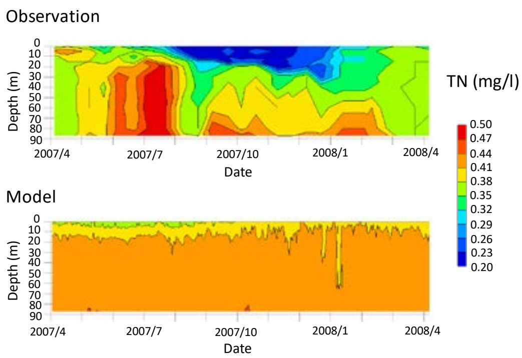

Fig. 3 Seasonal change of vertical distribution of observed and simulated total nitrogen at Imazu-oki in 2007.

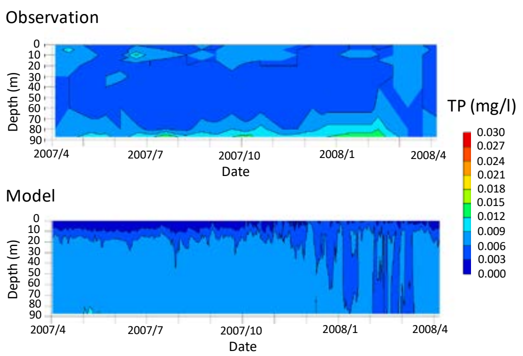

Fig. 4 Seasonal change of vertical distribution of observed and simulated total phosphorous at Imazu-oki in 2007.

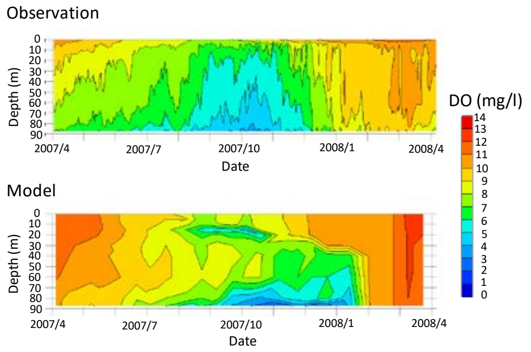

Fig. 5 Seasonal change of vertical distribution of observed and simulated dissolved oxygen at Imazu-oki in 2007.

3.2. West-east vertical cross sections through Imazu-oki for DO in the simulation

The distributions of simulated DO along the line passing from west to east through the monitoring point in Imazu-oki are shown in Fig. 6. The snapshots were taken at 12:00 p.m. from April 2007 to February 2008 every two months. DO in the eastern coast tended to decrease from spring to autumn compared with the one in western side. One reason for it was the water temperature increased more in the eastern coast and less oxygen could be dissolved in water. The other reason for it was that since the slope in the eastern coast was more moderate than that in the western side, the organic carbon in the bottom layer was accumulated more in the eastern coast than in the western coast.

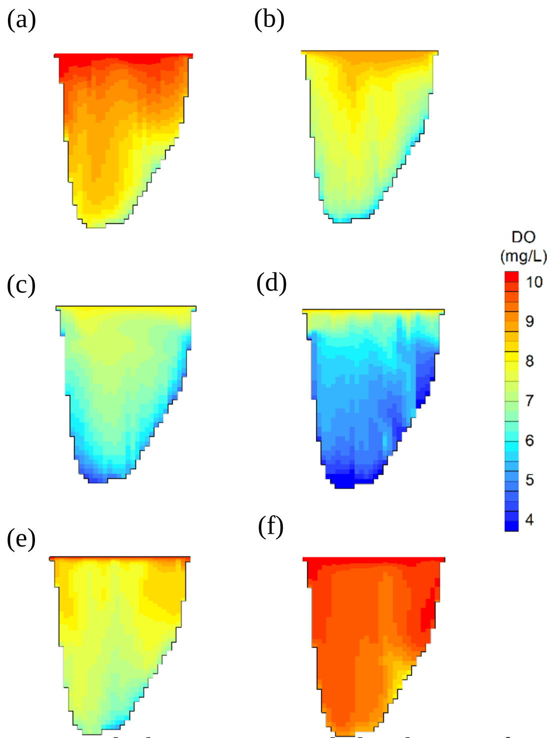

Fig. 6 Seasonal change in vertical distribution of simulated dissolved oxygen (Color contour:

dissolved oxygen (mg/l)) (a) 3rd April; (b) 4th June; (c) 6th August; (d) 1st October; (e) 3rd December; and (f) 4th February.

3.3. Inter-annual change of DO at Imazu-oki

Fig. 7, 8 and 9 show the inter-annual changes in vertical distribution of observed and simulated TN, TP, and DO at depths of 0.5 m, 20 m, and 90 m at the monitoring point in Imazu-oki. The inter-annual change of TN was not well reproduced because the parameter of intake of inorganic nitrogen could be a small value during photosynthesis every year. The inter-annual change of TP in the simulation didn't agree well with the one in the observation in the bottom layer, because the amount of elution from the bottom of the lake could be insufficient.

The inter-annual change of DO in the simulation approximately agreed with the one in the observation above the thermocline. In the surface layer, the seasonal change of DO was influenced by the dissolution rate.The saturated concentration of DO is 11.8 mg/l in 8°C water in winter and 7.8 mg/l in 28°C water in summer every year. DO in the bottom layer decreased during decomposing the organic matter by bacteria with little oxygen supply from the atmosphere and the photosynthesis from the phytoplankton from spring to autumn every year. DO was supplied in all layers by the overturning in winter and the timing of recovery of DO depended on the start of overturning. The difference of DO between simulation and observation in the bottom layer possibly derived from not giving enough parameter values of consumption of DO during decomposing organic matters.

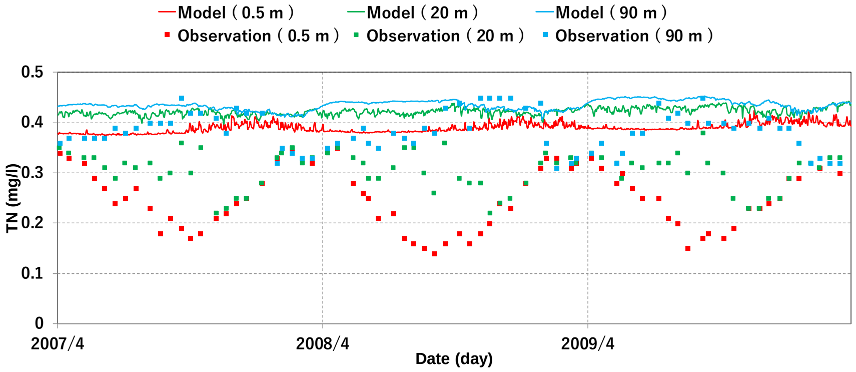

Fig. 7 Inter-annual change of vertical distribution of observed and simulated total nitrogen at Imazu-oki.

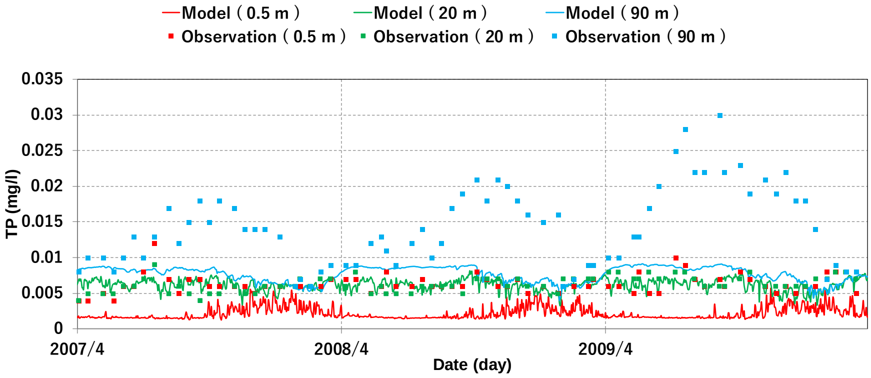

Fig. 8 Inter-annual change of vertical distribution of observed and simulated total phosphorous at Imazu-oki

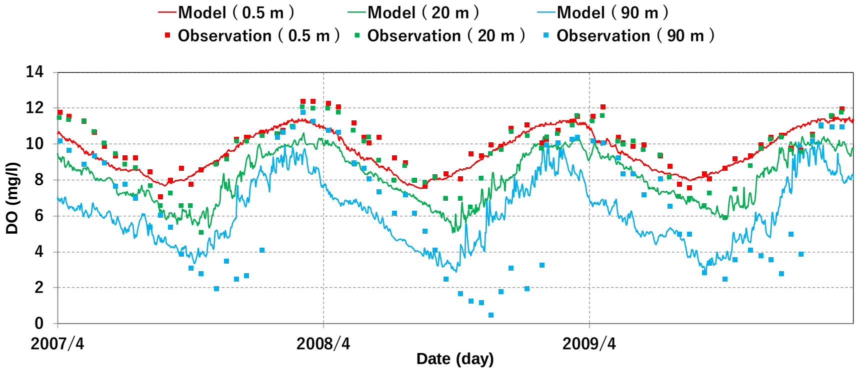

Fig. 9 Inter-annual change of vertical distribution of observed and simulated dissolved oxygen at Imazu-oki.

4. CONCLUSION

A three-dimensional water quality model considering the hydrodynamic processes is necessary for understanding the dynamic analysis of DO in Lake Biwa. Numerical simulations were carried out for 3 years from 2007 to 2009. This model was based on a low trophic level ecosystem. It consisted of phytoplankton, zooplankton, nitrogen, phosphorus, dissolved oxygen and chemical oxygen demand as state variables. In this model, the inflow load from the river was considered and the vertical mesh was in detail for reproducing the thermocline which suppressed the transportation of the substances.

The trend of the seasonal changes in the vertical distributions of DO were approximately reproduced by the water quality model considering the flow field. The simulated DO concentration above the thermocline approximately agreed with the observed one. DO solubility in water is influenced by the water temperature. In the surface water, DO was always saturated. As water depth increased, DO decreased due to the thermocline suppressing the transport from DO in the upper layer. The dynamics of DO above the bottom of the lake was controlled by consumption by bacteria and the supply from DO in the upper layer during overturning.

In order to better reproduce observed DO, minimal and maximal growth temperatures of phytoplankton and bacteria should be considered more in detail. Water temperature affects the biological processes such as algal growth, photosynthesis and decomposition of organic matters which cause the change in oxygen at the bottom of the lake.

As for TN and TP, there was a difference between simulation and observation, because the amount of intake by phytoplankton and mineralization of organic matter could be different from the observed ones. In order to reproduce the change in nutrients concentrations more precisely, the water quality model should consider the biochemical processes in detail to give the exact parameter and include the model of transportations of nutrients at the boundary conditions between bottom water and sediments. The decrease in DO at the bottom of the lake triggers the elution of nitrogen and phosphorus from the bottom sediment.

The model which can reproduce the seasonal and inter-annual change in concentrations of nutrients accurately leads to clarifying the reason why DO in the bottom of the lake decreased in a certain year. It is important to elucidate the effects of global warming and eutrophication. That leads to preserving the water quality and ecosystems of Lake Biwa.

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