WATER QUALITY MODELING IN MIHARU RESERVOIR

Duong Hai THUAN[1], Makoto UMEDA[2]

ABSTRACT

In this study, we have applied the coupling of a two-dimensional laterally averaged reservoir model and a mechanistic eutrophication model to one year full data set of Mihaure reservoir to simulate the seasonal dynamics of water quality in the reservoir. The hydrodynamics model was validated by temporal and vertical variation of water temperate data. And the water quality model was validated by temporal and vertical variation of dissolved oxygen (DO) and Chlorophyll-a data. With very good agreements in predicted water temperature and acceptable water quality parameters such as DO, Chlorophyll-a, T-N, and T-P, the model have shown its ability in predicting of water quality for eutrophic reservoir. And the model could become a tool for research and management of water quality in dam/reservoir.

Keywords: Miharu reservoir, water quality modeling, eutrophication

1. INTRODUCTION

Miharu reservoir, located in Fukushima prefecture, about 200 km north of Tokyo, on the Ohtakine River, is a multi-purpose reservoir for flood control, water supply for irrigation, domestic, and industry and maintenance of the environmental flow in downstream river. The dam was completed in 1998. Miharu reservoir is the main water resources of nearby cities. With high nutrient level income from one main stream and three large tributary inflows, Miharu reservoir is a eutrophic lake and faces with water bloom problems. Therefore, several facilities and technologies including 5 bubble diffusers, 2 hypolimnion aerations, 4 predams, a selective water intake, and a water bypass have been implemented in the reservoir for water quality conservation. As a result, there has been no occurrence of serious water quality problem up to now.

However, small patches of water bloom, created by *Microcystic* spp., one of major bloom forming cyanobacteria, have been observed in the reservoir in most of the year since the dam was constructed. And the dominant species cyanobacteria in the reservoir have not yet replaced by diatoms species as expected. This phenomenon has been regarded as the efficiency or capable of artificial destratification systems or the effectiveness of predams and bypass facilities in term of sedimentation treatment.

In order to quantify the effectiveness of the water preservation measures technologies implemented in the reservoir and to obtain the ideal operating regulations for water bloom control, many kind of field measurements have been carried out in and around the Miharu reservoir. Besides the application of new monitoring technologies for water quality parameters, a numerical model was built as a tool for research and management of water bloom.

In this study, we have applied the developed model to one year full data set to simulate the seasonal dynamics of water quality in Miharu reservoir. To validate the model for further research, and to quantify the role of Microcystic species, which is the major bloom forming cyanobacteria, in nutrient cycle in the Miharu reservoir.

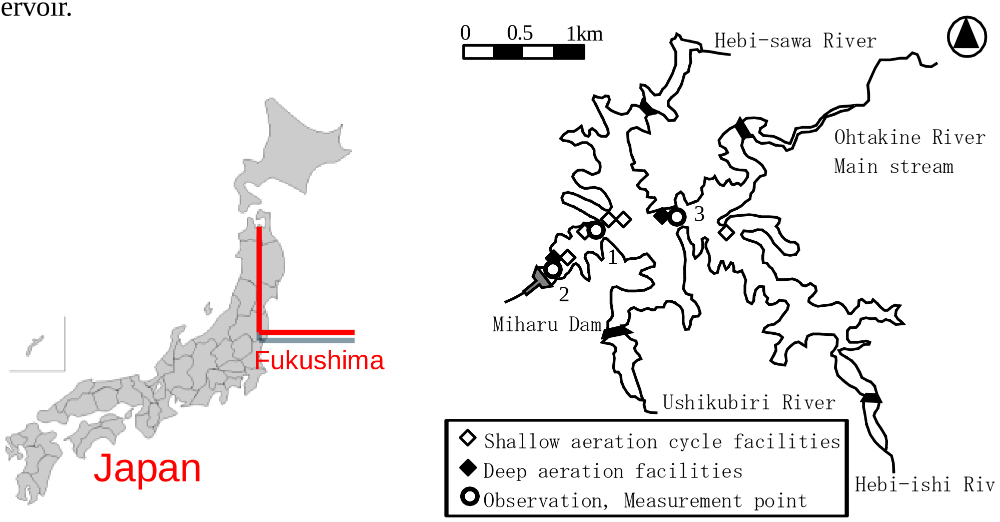

Figure 1- On-site equipments and stations at Miharu

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[1] **Graduate Student, Department of Civil Engineering, Tohoku University, Japan**

[2] **Associate Professor, Department of Civil Engineering, Tohoku University, Japan**

2. METHODS

Hydrodynamics model

In this study, a vertical two-dimensional reservoir hydraulic simulation model is employed that includes the effect of buoyancy caused by water temperature and suspended sediment. In addition, in order to represents the mixing phenomenon in more detail in the reservoir a k-ε turbulence model was used. The basic equations are as follows

Continuity equation reads

$$\frac{\partial}{\partial x}(uB)+\frac{\partial}{\partial z}(wB)=0 \tag{1}$$

horizontal momentum equation is

$$\frac{D(Bu)}{Dt}-\frac{\partial}{\partial x}\left(v_L B\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial z}\left(v_{eff} B\frac{\partial u}{\partial z}\right)=-\frac{B}{\rho}\frac{\partial p}{\partial x}+\frac{\tau_x}{\mathbf{n}_s\cdot\mathbf{n}_y} \tag{2}$$

and vertical momentum equation

$$\frac{D(Bw)}{Dt}-\frac{\partial}{\partial x}\left(v_L B\frac{\partial w}{\partial x}\right)-\frac{\partial}{\partial z}\left(v_{eff} B\frac{\partial w}{\partial z}\right)=-\frac{B}{\rho}\frac{\partial p}{\partial z}+Bg\delta+\frac{\tau_z}{\mathbf{n}_s\cdot\mathbf{n}_y} \tag{3}$$

Transport equation of turbulence energy (k)

$$\frac{D(Bk)}{Dt}-\frac{\partial}{\partial x}\left(\frac{v_L}{\sigma_k}B\frac{\partial k}{\partial x}\right)-\frac{\partial}{\partial z}\left(\frac{v_{eff}}{\sigma_k}B\frac{\partial k}{\partial z}\right)=BP_r-Bg\frac{v_{eff}}{\sigma_t}\frac{\partial\delta}{\partial z}-B\varepsilon+\frac{F_k}{\mathbf{n}_s\cdot\mathbf{n}_y} \tag{4}$$

Transport equation of energy dissipation rate (ε)

$$\frac{D\varepsilon}{Dt}-\frac{\partial}{\partial x}\left(\frac{v_L}{\sigma_\varepsilon}B\frac{\partial \varepsilon}{\partial x}\right)-\frac{\partial}{\partial z}\left(\frac{v_{eff}}{\sigma_\varepsilon}B\frac{\partial \varepsilon}{\partial z}\right)=C_1 B\frac{\varepsilon}{k}P_r-C_2 B\frac{\varepsilon^2}{k}+\frac{F_\varepsilon}{\mathbf{n}_s\cdot\mathbf{n}_y} \tag{5}$$

Transport equation of temperature (T)

$$\frac{D\left(BT\right)}{Dt}-\frac{\partial}{\partial x}\left(\frac{v_L}{\sigma_T}B\frac{\partial T}{\partial x}\right)-\frac{\partial}{\partial z}\left(\frac{v_{eff}}{\sigma_T}B\frac{\partial T}{\partial z}\right)=\frac{F_T}{\mathbf{n}_s\cdot\mathbf{n}_y} \tag{6}$$

Transport equation of concentration of suspended solids (C)

$$\frac{D\left(BC\right)}{Dt}+\frac{\partial\left(BuC\right)}{\partial x}+\frac{\partial\left(B(w-w_s)C\right)}{\partial z}-\frac{\partial}{\partial x}\left(\frac{v_L}{\sigma_C}B\frac{\partial C}{\partial x}\right)-\frac{\partial}{\partial z}\left(\frac{v_{eff}}{\sigma_C}B\frac{\partial C}{\partial z}\right)=\frac{F_C}{\mathbf{n}_s\cdot\mathbf{n}_y} \tag{7}$$

And,

$$P_r=v_t\left[2\left\{\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right\}+\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)^2\right] \tag{8}$$

$$v_{eff}=v+v_t=v+C_\mu\frac{k^2}{\varepsilon} \tag{9}$$

$$v_L=0.01(\Delta x)^{4/3} \tag{10}$$

where x =horizontal direction; z =vertical direction; B = river width; (u,w) = horizontal and vertical velocity; (v_L,v_{eff}) = horizontal and vertical eddy viscosity; p = pressure; ρ = water density; τ_x = bed shear stress acting on the direction x; τ_z = bed shear stress acting on the direction z; ($\mathbf{n}_s\cdot\mathbf{n}_y$)= the dot product of unit vector perpendicular to the shore line $\mathbf{n}_s$ and transverse unit vector $\mathbf{n}_y$.

Constants for k-ε turbulence model are

$$C_\mu=0.09,\ C_1=1.440,\ C_2=1.92,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.3$$

In order to improve the stability for the model, three kind of schemes were used in solving governing equations. In discretization of the equations of motion, SIMPLE scheme [3] was applied. For scalar transport equation (e.g., temperature, concentration of suspended solids or eutropic state variables), temporal term was discretized by using SIMPLE scheme, while, discretization of horizontal advection-diffusion term was conducted by using a HYBRID scheme [1] (a combination of central difference and upwind difference method). The discretization of vertical advection-diffusion term was conducted by using a second order scheme- QUICK scheme [6].

To take in to account the disturbance of destratification system on ecosystem in reservoir, the aeration cycle model proposed by Asaeda and Imberger [2], implemented and developed on Umeda [5] was used to simulate effect of bubble diffusers.

For the model in this study, if the reservoir's geometry is complex, it will be divided into branches each of which would be analyzed in parallel to the mesh downstream of the confluence. Thus, the model is available for reservoirs with geometrical complexity.

Water quality and ecosystem model

The fresh water ecosystem model was modified from the concepts represented in [3]. In this model, to allow more detailed analysis of the phenomenon represented in the reservoir water, even for ecosystem model, a complex ecosystem more general sophistication than traditional models was used. In particular, for phytoplankton the amount of nutrients retained in the cell was considered. The organic matter is divided into suspended and dissolved organic matter. Inorganic nitrogen represented by three state variables such as amoni, nitrite, and nitrate . The transportation and transformation of water quality state variables is as follows

$$\frac{\partial(Bf)}{\partial t}+\frac{\partial}{\partial x}(Buf)+\frac{\partial}{\partial y}(Bvf)=\frac{\partial}{\partial x}\left(\frac{\nu_L}{\sigma_f}B\frac{\partial f}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_f}B\frac{\partial f}{\partial y}\right)+\left(\frac{d(Bf)}{dt}\right)^* \tag{11}$$

The governing equation for each water quality item ecosystem model (phytoplankton, carbon, phosphorus, and nitrogen) is solved in the following scheme. Rewrite (11) as

$$\frac{\partial(Bf)}{\partial t}=G+\left(\frac{d(Bf)}{dt}\right)^* \tag{12}$$

where,

$$G=-\frac{\partial}{\partial x}(Buf)-\frac{\partial}{\partial y}(Bvf)+\frac{\partial}{\partial x}\left(\frac{\nu_L}{\sigma_f}B\frac{\partial f}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_f}B\frac{\partial f}{\partial y}\right)+\left(\frac{d(Bf)}{dt}\right)^* \tag{13}$$

After predictor step

$$\tilde{f}=f^n+\frac{\Delta t}{B}G^n+\Delta t\left(\frac{df^n}{dt}\right)^* \tag{14}$$

and calculate modifier step

$$f^{n+1}=f^n+\frac{\Delta t}{2B}\left(\tilde{G}+G^n\right)+\frac{\Delta t}{2}\left[\left(\frac{d\tilde{f}}{dt}\right)^*+\left(\frac{df^n}{dt}\right)^*\right]=\frac{1}{2}\left[f^n+\tilde{f}+\frac{\Delta t}{B}\tilde{G}+\Delta t\left(\frac{d\tilde{f}}{dt}\right)^*\right] \tag{15}$$

Then let’s introduce kinetic equation

$$s^n=\left(\frac{df^n}{dt}\right)^* \tag{16}$$

Followed by second predictor step

$$\tilde{f}=f^n+\frac{\Delta t}{B}G^n+\Delta t s^n \tag{17}$$

Recalculate kinetic equation

$$\tilde{s}=\left(\frac{df}{dt}\right)^* \tag{18}$$

And second modifier step to obtain next step values

$$f^{n+1}=\frac{1}{2}\left[f^n+\tilde{f}+\frac{\Delta t}{B}\tilde{G}+\Delta t\tilde{s}\right] \tag{19}$$

Therefore, as a predictor calculation procedure is required, it will go through two steps in order to obtain next time step values (values in time step n+1).

Similarly with concentration of suspended solid, the horizontal advection-diffusion terms were discretized by HYBRID scheme and applied QUICK scheme for vertical advection-diffusion terms.

Model inputs

The bathymetry of the reservoir was represented by blocks, segments, and width of reservoir at every segment at every certain depth. The meteorological data obtained from station at the dam includes hourly data of solar radiation, wind speed, wind direction, air temperature, humidity, and cloudiest. Outflow data obtained from hourly operation of all facilities at the dam site. Total inflow was calculated from water balance and discharge of each tributary inflow was calculated from total inflow and catchment areas. Water quality of inflows calculated from the relationship between discharge rates and the loads. In order to simulate the artificial destratification system in the reservoir we need the facilities operation information. And the monthly water quality at the dam site was used for model validation.

Model calibration and model validation

All parameters in hydrodynamics model and kinetic parameters in eutrophication model were determined in calibration step based on published literature values, sensitive analysis and expert decision. After parameter identification, the parameter sets were not changed during model validation for case study year. The hydrodynamics model was validated by comparison of predicted and measured water temperate data. And the water quality model was validated by comparison of predicted and measured dissolved oxygen (DO) and Chlorophyll-a data.

3. RESULTS AND DISCUSSIONS

Figure 2 shows the comparison between predicted and measured of water temperature. There are a very good agreements in the temporal variation and the vertical variation of water temperature that demonstrated for the quality of hydrodynamics model. The model could be able to represent the temporal variation of water temperate not only the trend but also the magnitudes.

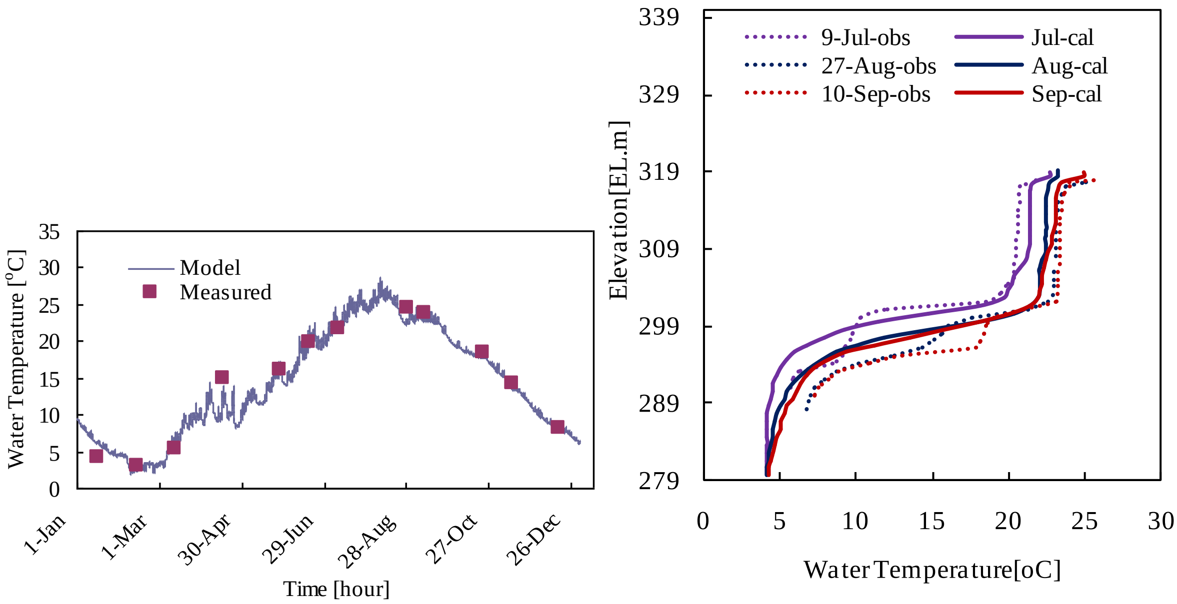

Figure 2- Comparison of water temperature at dam site for hydrodynamic model validation

Figures 3 and 4 show the comparison between predicted and measured of DO and Chlorophyll-a, respectively. The predicted DO and Chlorophyll-a values quite agree with measured data that will stand for acceptable of water quality model. The model shown underestimate result during the winter and pre-summer season in Chlorophyll-a values. However, the peaks of predicted values coincide with the measured one demonstrated for the ability of the model in term of water bloom event prediction. The strong fluctuation of DO at the surface in the calculated data may caused by water bloom. Since, the used model is phytoplankton based concept model, and oxygen created from photosynthesis process of abundant blue-green species during water bloom period will affect on DO values. It explains why the fluctuation of

Chlorophyll-a at the surface coincided with random variation of DO in the surface.channel (Fig. 4).

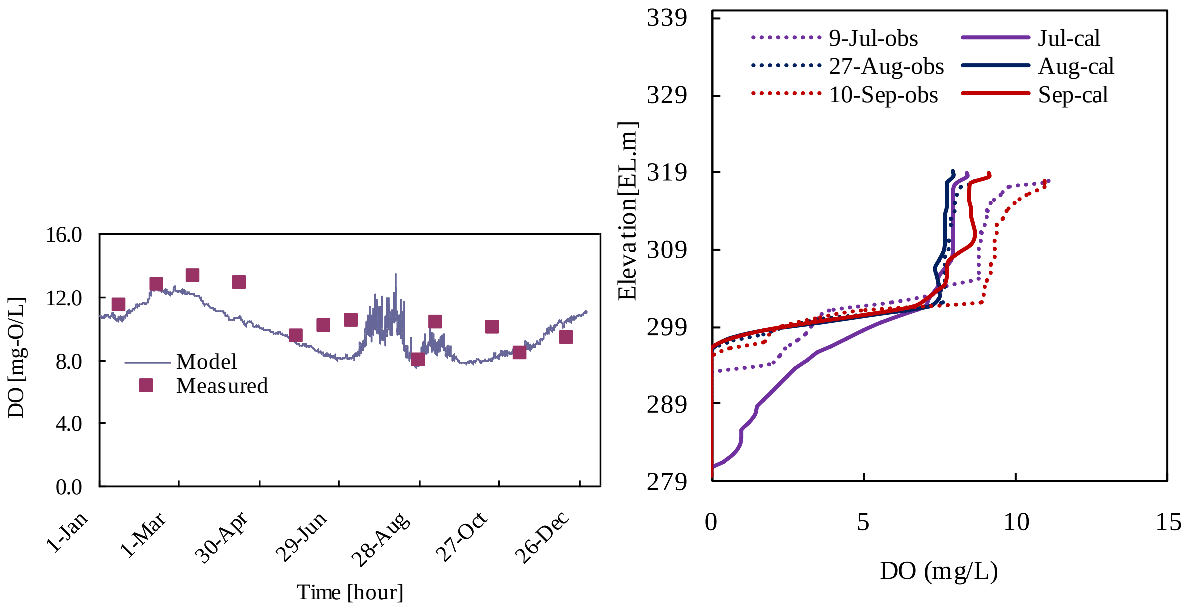

Figure 3- Comparison of dissolved oxygen (DO) at dam site for ecological model validation

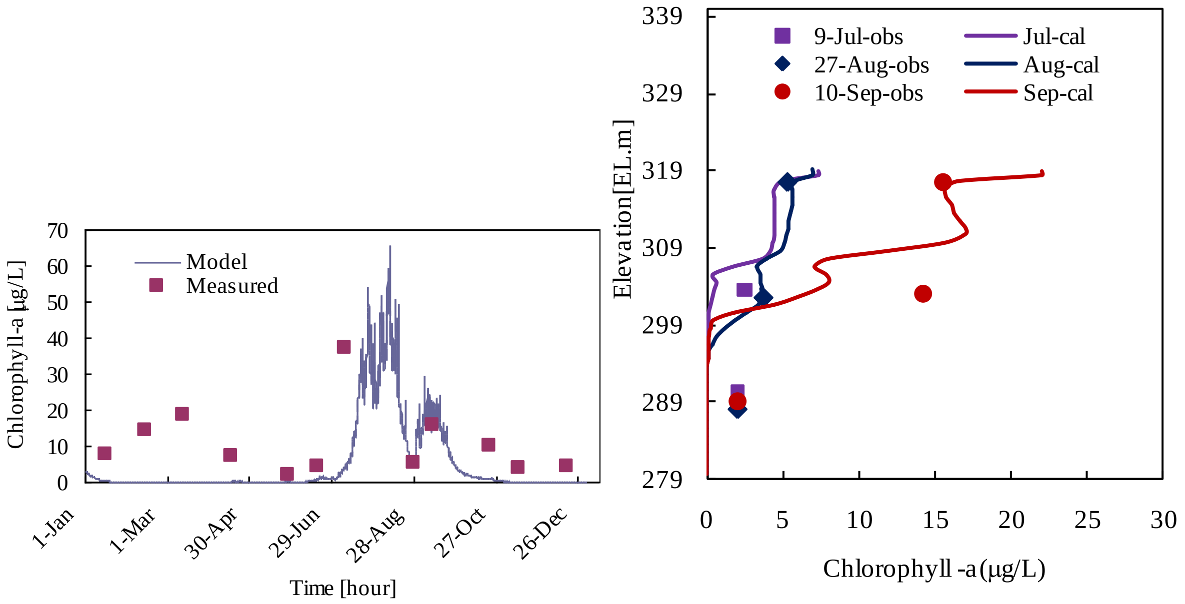

Figure 4- Comparison of Chlorophyll-a (Chl-a) at dam site for ecological model validation

Figure 5 shows the temporal variation at the surface of T-N and T-P. The model give good agreement with observed T-N data at surface, and a little over estimate for T-P. The strong fluctuation of T-P values at surface with quite stable T-N values indicated that phosphorus limited in fresh water lakes. That is, when we can predict the algae we can get better results in T-P, for example, during period form 29-Jun to 28-Aug we obtain better results in T-P since we had good predicted chlorophyll-a values.

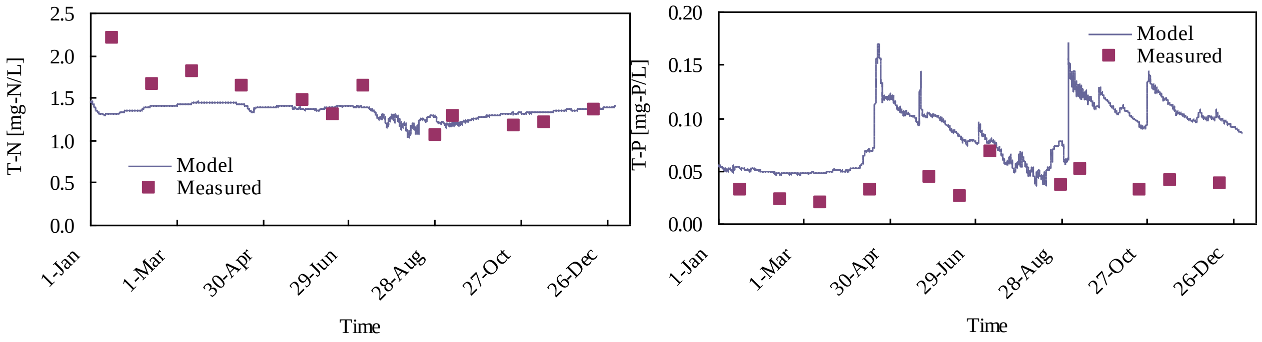

Figure 5- Temporal variation of T-N and T-P at the surface.

4. CONCLUSIONS

A mechanistic eutrophication model incorporated with a two-dimensional laterally averaged reservoir model was applied to a full year data set to simulate the seasonal dynamics of water quality in Miharu reservoir. The good agreements in predicted water temperature and acceptable water quality parameters such as DO, Chlorophyll-a, T-N, and T-P have shown great potential in water quality predictive tool of the model. The ability of the model in giving not only the good predicted water quality parameters of eutrophic reservoir in real time but also comprehensively understanding in mechanisms in the ecosystem indicated that model could become a tool for research and management of water quality in dam/reservoir.

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6. REFERENCES

[1] Arakawa, T.: Numerical Fluid Mechanics, University of Tokyo Press, 1994.

[2] Asaeda, T. and Imberger, J.: Structure of bubble plumes in linearly stratified environments, *Journal of Fluid Mechanics.*, Vol. 249, pp.35-57, 2006.

[3] Nakata K., 1993: Ecosystem model: its formulation and estimation method for unknown rate parameters. *Journal of Advanced Marine Technology Conference 8*, pp.99-138.

[4] Patankar, S. V.: Numerical heat transfer and fluid flow, McGraw-Hill, New York, pp.113-135, 1980.

[5] Umeda M.: Numerical modeling of destratification by bubble diffuser in a dam reservoir and its validation, *Ann. Journal of Hydraulic Engineering*, JSCE, Vol. 49, pp.1-6, 2005.

[6] Yoshimura, H.: Numerical simulation of fluid flow and heat with Java, Publications Morikita, 2001.