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Application of EFDC and WASP7 in Series for Water Quality Modeling of the Yongdam Lake, Korea

Seo, Dongil* / Kim, Minae**

Abstract

This study aims to test the feasibility of combined use of EFDC (Environmental Fluid Dynamics Code) hydrodynamic model and WASP7.3 (Water Quality Analysis Program) model to improve accuracy of water quality predictions of the Yongdam Lake, Korea. The orthogonal curvilinear grid system was used for EFDC model to represent riverine shape of the study area. Relationship between volume, surface and elevation results were checked to verify if the grid system represents morphology of the lake properly. Monthly average boundary water quality conditions were estimated using the monthly monitored water quality data from Korean Ministry of Environment DB system. Monthly tributary flow rates were back-routed using dam discharge data and allocated in proportion to each basin area as direct measurements were not available. The optimum number of grid system was determined to be 372 horizontal cells and 10 vertical layers of the site for 1 year simulation of hydrodynamics and water quality out of iterative trials. Monthly observed BOD, TN, TP and Chl-a concentrations inside the lake were used for calibration of WASP7.3 model. This study shows that EFDC and WASP can be used in series successfully to improve accuracy in water quality modeling. However, it was observed that the amount of data to develop inflow water quality and flow rate boundary conditions and water quality data inside lake for calibration were not enough for accurate modeling. It is suggested that object-oriented data collection systems would be necessary to ensure accuracy of EFDC-WASP model application and thus for efficient lake water quality management strategy development.

Keywords: EFDC, WASP, hydrodynamic model, water quality model, yongdam lake

1. INTRODUCTION

Many major water resources reservoirs in Korea are located in the upper stream areas. Recent rapid increase of organic farming practices in high sloped mountainous areas that requires addition of top soil and climate change toward more frequent intensive rainfall in Korea have lead tremendous increase in soil erosion, especially in the upper stream areas. As a result, many of reservoirs have shown year long turbidity problem. Turbidity in reservoirs caused by clay or colloidal particles of eroded soil may have negative effect on water quality. Adsorbed pollutant in clay particle can be released to water phase and this effect can last extended period of time. While soil erosion protection in the basin is the most important

* *Corresponding Author*, Professor, Dept. of Environmental Eng., Chungnam National University, 220 Gung-dong Yuseong-gu Daejeon 305-764, Korea (e-mail: seodi@cnu.ac.kr)
** Dept. of Environmental Eng., Chungnam National University, 220 Gung-dong Yuseong-gu Daejeon 305-764, Korea (e-mail: kminae2@nate.com)

factor, it is also important to understand behavior of turbidity dynamics inside reservoirs. Movement of sediment particles and variations in turbidity are complex functions of water movement and density changes. Therefore, it is necessary to consider hydrodynamics to predict turbidity and water quality dynamics of a water body properly.

Dependent on the purpose of modeling, steady state model such as QUAL2E (Brown and Barnwell, 1987) or dynamic model such as WASP (Ambrose et al., 1993) can be chosen. Ambrose et al. (2009) reported the history of water quality model development in US from 1960s to the present. It has been common that water quality models do not consider hydrodynamic characteristic of water in a great depth. The presence of effective tool to link water movement and water quality processes was the major cause of this problem, especially for unsteady modeling cases. Buchak (1995) developed CE-QUAL-W2 model that includes 2-D hydrodynamic and water quality kinetics. This can be considered as the first successful case to link water movement and water quality model in the same model. Park et al. (1995) developed HEM3D water quality model to predict 3-D water quality dynamics along with 3-D hydrodynamics model, EFDC (Hamrick, 1992). EFDC can be regarded as an another successful case to consider movement water and kinetics of water quality in the same model. USEPA uses EFDC to provide hydrodynamic information to WASP. In this study, authors aimed to test the feasibility of combined use of hydrodynamic model of EFDC with water quality model, WASP in the prediction of water quality of a reservoir in Korea.

2. MATERIALS AND METHODS

2.1 Environmental Fluid Dynamics Code (EFDC)

The EFDC is a public domain surface water modeling system incorporating fully integrated hydrodynamics, water quality, sediment transport and toxic chemical transport and fate submodels in a single source code frame work as shown in Fig. 1. EFDC has the capabilities to analyze three-dimensional hydrodynamics coupled with salinity, temperature, sediment and contaminant transport modules in surface water systems including: rivers, lakes, estuaries, reservoirs, wetlands, and near-shore to shelf-scale coastal regions. The physics of the EFDC model and many parts of the computational scheme are similar to the Blumberg-Mellor model (Blumberg & Mellor, 1987) and the U.S. Army Corps of Engineers' Chesapeake Bay model (Johnson et al., 1993). The EFDC model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable density fluid. The model uses a stretched or sigma vertical coordinate and Cartesian or curvilinear, orthogonal horizontal coordinates. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The model was originally developed by Hamrick (1992) at Virginia Institute of Marine Science (VIMS). The EFDC model has been listed and supported as a tool for the development of Total Maximum Daily Load (TMDL) by US Environmental Protection Agency. USEPA has supported to link EFDC 3-D hydrodynamic module with WASP, one of the USEPA's most representative water quality simulation.

2.2 Water Quality Analysis Simulation Program (WASP)

The WASP is a USEPA's generalized modeling framework that simulates contaminant fate and transport in surface waters (Ambrose et al., 1993; Ambrose et al., 2009). Based on the flexible compartment modeling approach, WASP can be applied in one to three dimen-

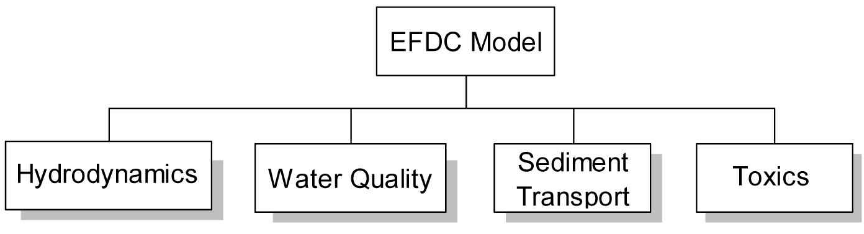

Fig. 1. Primary Modules of the EFDC Model

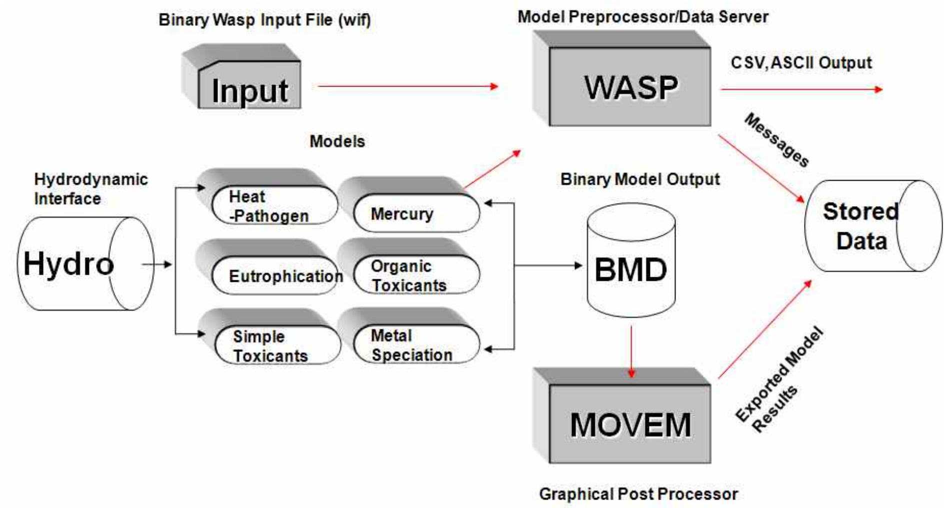

Fig. 2. Structure of WASP7 Model

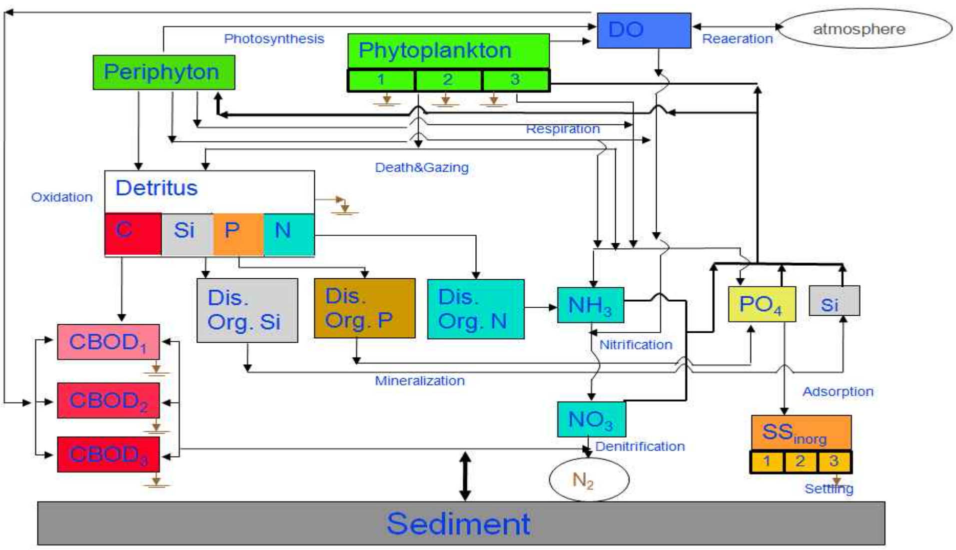

Fig. 3. Interactions of Water Quality Variables in WASP7 Model

sions. WASP water quality model has 6 modules including "Eutrophication" as shown in Fig. 2. In this study, Eutrophication was selected and tested for water quality simulation using EFDC hydrodynamic information. Interactions among major constituents in Eutrophication module are shown in Fig. 3. Phytoplankton plays a central role in Eutrophication module, affecting all other components. Phytoplankton uses NH_3, NO_3 and PO_4 for their growth and decreased due to death, settling and endogenous respiration. Detritus represents pool of organic particulate matter including dead phytoplankton. Detritus will be decomposed to dissolved particulate matter and inorganic nutrients. Some portion of carbon settles to the bottom and the other remaining portion becomes $CBOD_1$, $CBOD_2$ and $CBOD_3$. Dissolved organic phosphorus becomes PO_4 by mineralization and similarly dissolved organic nitrogen changes to NH_3, which is further changed to NO_3 by nitrification. When there is no enough oxygen in the water NO_3 becomes N_2 by denitrification. DO reacts with atmosphere, CBOD, NBOD, Phytoplankton and Periphyton. Inorganic materials settle as solids. The WASP program includes six mechanisms for describing transport including advection, dispersion settling and resuspension. To describe advection within WASP, each inflow or circulation pattern requires specification of the fraction routed through relevant water column segments and the time history of the corresponding flow. Dispersion requires specification of cross-sectional areas between model segments, characteristic mixing lengths, and the time history of the corresponding dispersion coefficient. This can be very complicated and difficult process if number of water segments is large. EFDC can dramatically eliminate the effort to describe advection and dispersion among grid networks.

2.3 The Yongdam Lake, Korea

The Geum River is the third greatest river in South Korea. This river provides water for over five million people in the vicinity areas. Two major dams are located on this river, Daechung Dam and Yongdam Dam, the 3rd and 5th largest reservoir in South Korea, respectively. The location of Yongdam Lake, the study site is as shown in Fig. 4. This lake supplies water to people in areas around lower western central part of South Korean peninsula through withdrawal facilities while natural flow is discharged through spillways and hydropower generation discharges to the Geum River as shown in the figure.

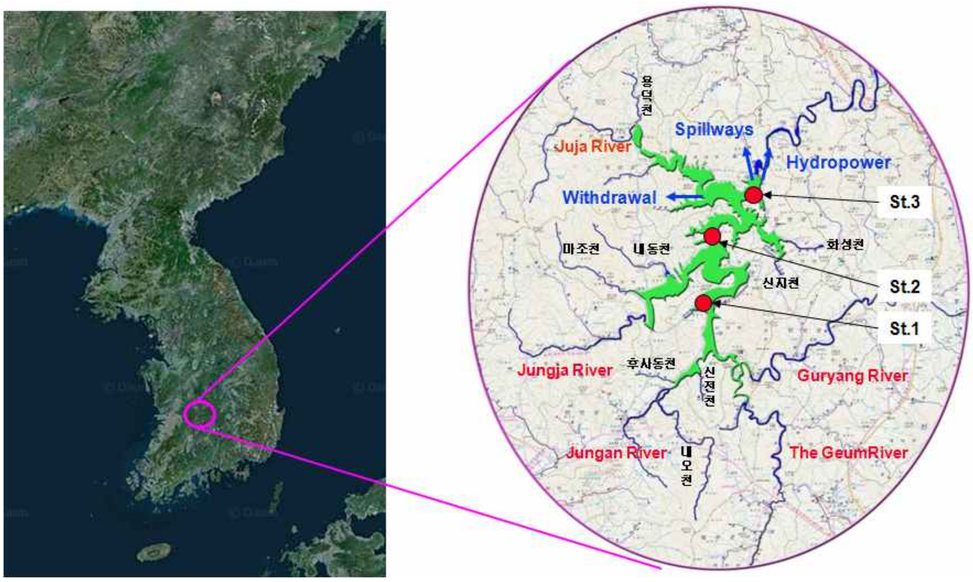

Fig. 4. The Study Site, The Yongdam Lake, Korea

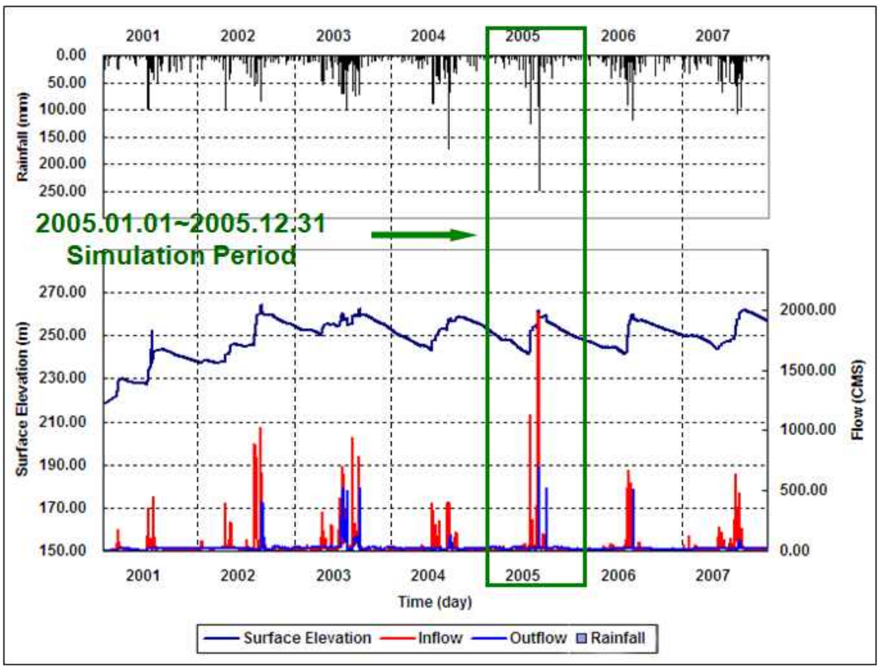

Fig. 5. Rainfall, Flow Rate and Water Levels of Yongdam Lake (2001～2007)

Flow rate and water quality concentrations of five major tributaries are considered as boundary conditions. The year of 2005 was selected as an annual testing period and hydrologic and hydraulic information of the dam between 2001 and 2007 are as shown in Fig. 5. All the input data and forcing function data for water quality used in this study were obtained from Korean public governmental sites including www. wamis.co.kr (Ministry of Land and Ocean), and www.nier. go.kr (National Institute of Environmental Research).

3. Results and Discussion

3.1 Design of Grid Network and EFDC Hydrodynamic Modeling Results

The design of a grid network is an essential part of hydrodynamic and water quality modeling. The proper resolution of modeling grid must be selected in order to account for spatial variation of the parameters to be considered. On the other hand, a 3-D model requires heavy computation time and extensive data for calibration, therefore, selection of the optimum layout of computational grid is the most important factor for application. In this study, the orthogonal curvilinear grid technique was used to generate grid of the study area. The use of an orthogonal curvilinear grid systems provides great advantages in computational and storage resources. Considered number of horizontal grids ranged from 10 to 40,000 horizontal cells and 5 to 10 vertical layers. Volume-elevation curve of the dam and annual surface elevation data were used to compare prediction accuracies.

Fig. 6 shows accuracies in the prediction of volume and water level relationships and annual water level simulation for few selected grid systems.

Table 1 shows calibration results of water level and accuracies of the final grid system selected for this study. A case of 372 horizontal cells and 10 vertical cells seems to show good calibration results for annual water level fluctuations and vertical temperature profile changes. Details of grid size selection processes and hydrody-

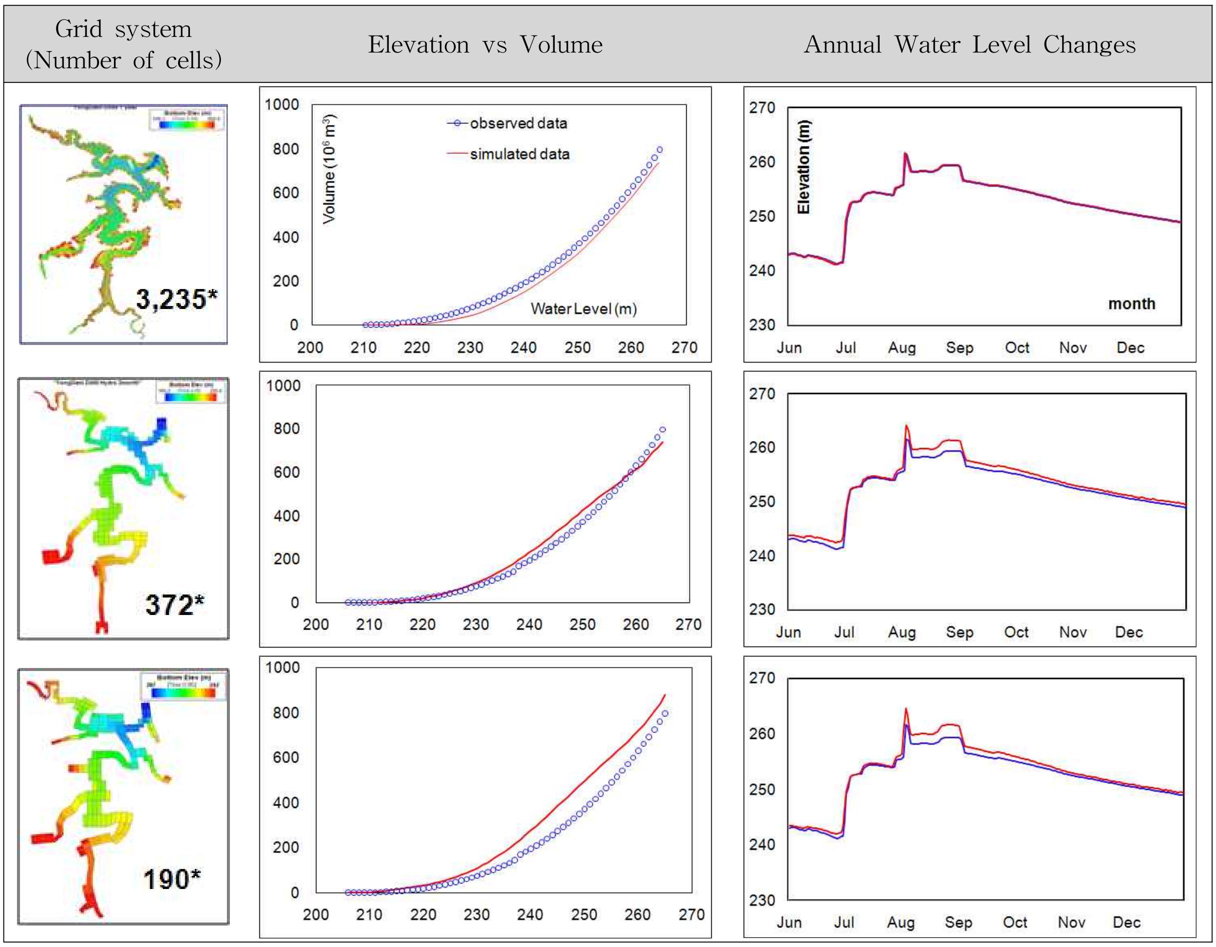

Fig. 6. Physical Modeling Accuracies of Selected Grid Systems for Yongdam Lake

namic calibrations are shown in Seo et al. (2010).

3.2 Resxults of WASP Water Quality Modeling

Only monthly observed water quality data available for tributaries and inside lake. Also, inflow rate of the lake can only be estimated using discharge and water level information of the lake. Therefore, boundary flow and water quality conditions were estimated using weighted averages to consider nonpoint sources effect (Seo and Lee, 2003). Calibrated constants for WASP water quality modeling in this study are as listed in Table 2.

Table 1. Error Analysis of Water Level Modeling of the Selected Grid System (372x10)

Item	Value	Unit
Correlation Coefficient	0.98	-
Maximum Error	1.76	%
Average Error	0.24	%
Number of Horizontal Cells	372	
Number of Vertical Cells	10	
Time Step	10	sec

Table 2. Calibrated Constants for WASP Modeling

	Description	Value
NH_3^-N	Nitrification Rate Constant at 20℃ (per day)	0.1
	Nitrification Temperature Coefficient	1.04
	Half Saturation Constant for Nitrification Oxygen Limit (mg O/L)	0.5
NO_3^-N	Denitrification Rate Constant at 20℃ (per day)	0.2
	Denitrification Temperature Coefficient	1.04
	Half Saturation Constant for Denitrification Oxygen Limit (mg O/L)	0.5
Phyto-plank-ton	Phytoplankton Maximum Growth Rate Constant at 20℃ (per day)	2.5
	Phytoplankton Growth Temperature Coefficient	1.04
	Phytoplankton Carbon to Chlorophyll Ratio	50
	Phytoplankton Half-Saturation Constant for Nitrogen Uptake (mg N/L)	0.05
	Phytoplankton Half-Saturation Constant for Phosphorus Uptake (mg P/L)	0.005
	Phytoplankton Death Rate Const. (Non-Zooplankton Predation) (per day)	0.1
	Phytoplankton Phosphorus to Carbon Ratio	0.025
	Phytoplankton Nitrogen to Carbon Ratio	0.18
CBOD	BOD (1) Decay Rate Constant at20℃ (per day)	0.01
	BOD (1) Decay Rate Temperature Correction Coefficient	1.04
O_2	Oxygen to Carbon Stoichiometric Ratio	2.67
	Global Reaeration Rate Constant at 20℃ (per day)	2.0
	Theta-Reaeration Temperature Correction	1.04
Org-N	Dissolved Organic Nitrogen Mineralization Rate Const. at 20℃ (per day)	0.4
	Dissolved Organic Nitrogen Mineralization Temperature Coefficient	1.04
	Organic Nitrogen Decay Rate Constant in Sediments at 20℃ (per day)	0.0004
	Organic Nitrogen Decay in Sediment Temperature Coefficient	1.08
Org-P	Mineralization Rate Constant for Dissolved Organic P at 20℃ (per day)	0.2
	Dissolved Organic Phosphorus Mineralization Temperature Coefficient	1.04

Fig. 7 through Fig. 9 show calibrated results of BOD5, TN, TP and Chl-a in the top layers of site1, site2 and site3 of the Yongdam lake, respectively as shown in Fig. 4. Water quality modeling results of all variables seem to follow general trends of observed data though there are some deviations. This is partly due to limited amount of boundary conditions and in-lake data available. This results suggest that water quality monitoring system of boundary conditions and inside lake should be improved for more accurate modeling and thus for effective management.

4. CONCLUSION

EFDC model and WASP model were successfully applied in series for hydrodynamic modeling and water

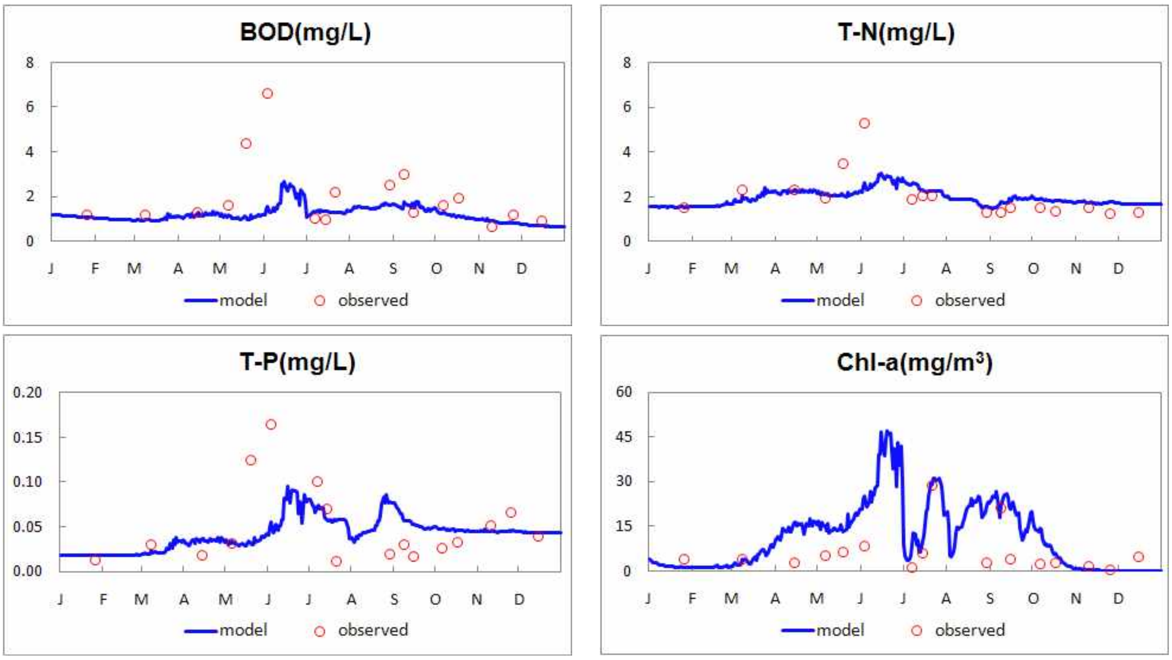

Fig. 7. Water Quality Calibration Results of Site1

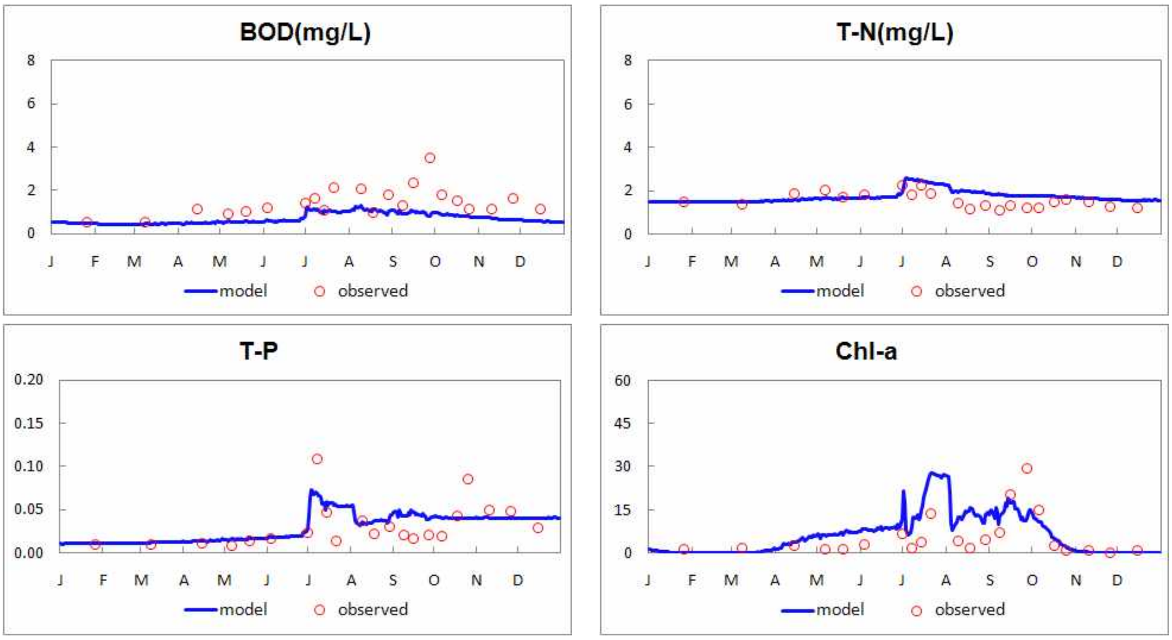

Fig. 8. Water Quality Calibration Results of Site2

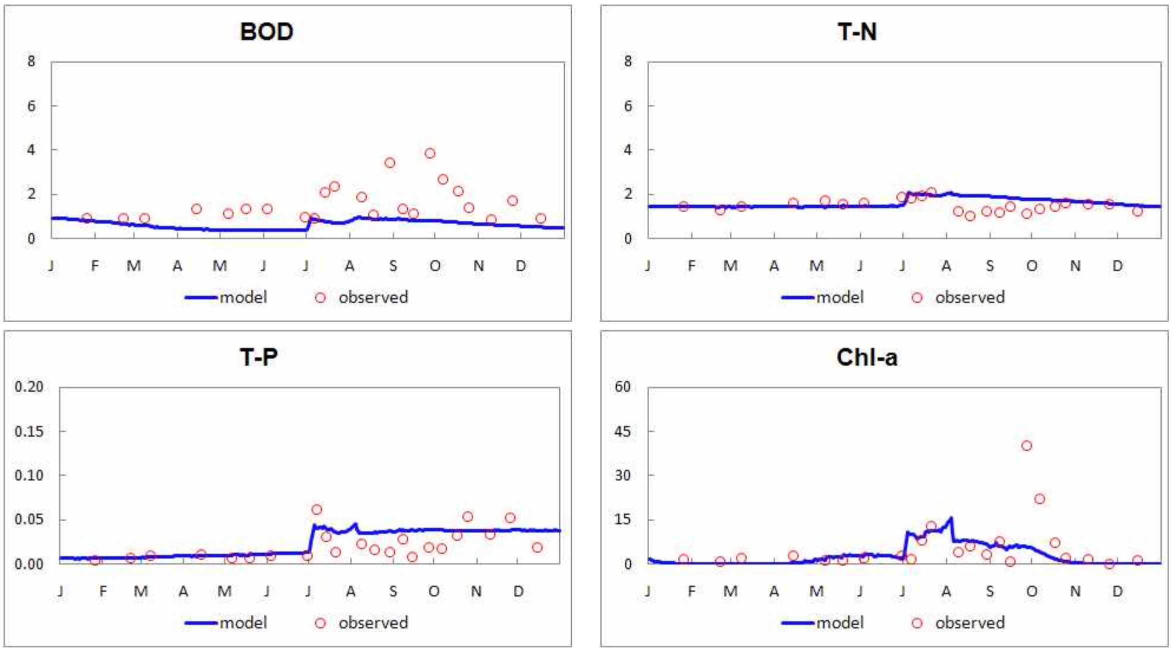

Fig. 9. Water Quality Calibration Results of Site3

quality modeling of the Yongdam Lake, Korea. Through multiple trial and errors, the optimum grid network of 370 horizontal and 10 vertical cells was chosen for 1 year hydrodynamic and water quality modeling of the Yongdam Lake, Korea. Temporal and spatial changes in vertical temperature profiles were checked while relationships among volume, surface area and surface level were maintained accurate hydrodynamic modeling. The observed BOD5, TN, TP and Chl-a concentration inside lake were used for calibration of WASP water quality model. Monthly weighted average water quality concentrations, considering raining event mean concentration, for main flow and tributary flows were developed using Korea Ministry of Environment DB system. Monthly average flow rate of each tributary flow was back calculated by allocating lake discharge data in proportion to each respective watershed area.

This study shows that combined use of EFDC-hydro for 3-D hydrodynamics and WASP for water quality kinetics can be applied to improve accuracy of hydrodynamics and water quality predictions. However, this study also suggests that the current data collection system is not enough to support accurate calibration of hydrodynamic and water quality characteristics. It is strongly recommended to implement object-oriented intensive data collection for the study site to improve accuracy of modeling and thus improve efficiency of water quality management plan development.

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