Desalination and Water Treatment
www.deswater.com

19 (2010) 42–48
July

doi: 10.5004/dwt.2010.1894

3-D hydrodynamic modeling of Yongdam Lake, Korea using EFDC

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Received 7 October 2009; Accepted 11 February 2010

ABSTRACT

The successful water quality prediction requires accurate information of water movement and interaction kinetics of components in water. Recent researches showed significant advancement in the combined use of hydrodynamic model and water quality model for surface water quality predictions. USEPA upgraded this progress to 3-dimensional (3-D) level through modification of Environmental Fluid Dynamics Code (EFDC) hydrodynamic model to provide water movement information to Water Quality Analysis Simulation Program (WASP) water quality model for multiple components. However, a 3-D model requires heavy computation time and extensive data for calibration, therefore, optimum layout of computational grids is a most important factor for application. This study summarizes performance of EFDC in the prediction of water level thus water volume change dynamics and vertical water temperature profile variations. This model was applied to Yongdam Lake, Korea and successfully modeled water level and vertical temperature profile of the study site. The resultant 3-D hydrodynamic information can be transferred to 3-D water quality model, WASP and can be used for water quality management purposes.

Keywords: 3-D hydrodynamic model; EFDC; WASP; Water quality model; Yongdam Lake

1. Introduction

Water quality modeling had been implemented without proper consideration of hydrodynamic characteristics of water body in the past and this had been a major source of error in predictions. The Water Quality Analysis Simulation Program (WASP) is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos [1–4]. It included DYNHYD to consider kinematic hydraulics but it was not widely used. In Ref. [5] developed a 2-D CE-QUAL-W2 model that can consider hydraulic and water quality dynamics in the same model. While this model had been recognized to have wide applicability there also had been another demand to develop 3-dimensional (3-D) models [6]. The Environmental Fluid Dynamics Code (EFDC) is a public domain, open source surface water modeling system incorporating fully integrated hydrodynamics, sediment and contaminant, and surface water quality modeling system [7]. The model was originally developed by Ref. [8] at Virginia Institute of Marine Science. EFDC has the capabilities to analyze 3-D hydrodynamics with coupled salinity, temperature, sediment and contaminant transport modules in surface water systems. It has been has been applied over 100 water bodies including rivers, lakes, estuaries, reservoirs, wetlands, and near-shore to shelf-scale coastal regions. The hydrodynamic module also includes a variety of forcing, including tides, wind, inflow and outflow, high frequency of surface wave radiation stresses and supports much

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type of boundary conditions. EFDC can simulate both cohesive and non-cohesive sediment transport including settling, resuspension, and bed process. The model also includes HEM3D [9] a water quality model based on the CE-QUAL-ICM model developed by the USACE waterways experiment station [10] and a toxicant transport and fate model based on the EPA model TOXI5 [11, 12].

USEPA funded Tetra Tech to revise the original EFDC and issue an EFDC-Hydro version [13] that can be used with USEPA's WASP water quality model. This revised version is called EFDC-Hydro version. In Ref. [14] applied this EFDC-Hydro and WASP combination in the Han River. Our study aims to test the feasibility of EFDC-Hydro module in the calibration of hydrodynamic characteristics of the study area for the purpose of application with WASP model to predict turbidity and water quality of a reservoir in the future. Yongdam Lake located in Jeonrabuk-do province in Korea was chosen as a study site.

2. Methods

2.1. Site description

The Geum River is the third greatest river in South Korea, is approximately 400 km long and has a basin area of 9,959 km^2. This river provides benefits for several million people in the form of water supply, irrigation, hydropower, and recreation. Two major dams are located on this river, the third largest Daechung Dam (1.5 billion m^3 of storage) and the fifth largest Yongdam Dam (0.8 billion m^3 of storage). Yongdam Dam is taken as our study area and its location is as shown in Table 1 and Fig. 1.

2.2. EFDC model

The structure of the original EFDC model includes four major modules: (1) a hydrodynamic model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics model as shown in Fig. 2. The EFDC hydrodynamic model itself, which was used for this study, is composed of six transport modules including dynamics, dye, temperature, salinity, near field plume, and drifter as shown in Fig. 3 [15].

EFDC model can be grouped to full versions and simplified (or Hydro) versions as shown in Fig. 4. The Hydro version was prepared by modifying hydrodynamic module of EFDC model to be used with WASP model. In Ref. [14] reported EFDC and WASP combination can be used in more accurate water quality predictions. In this study EFDC1 was used that is the most updated hydro version of EFDC.

The formulation of the governing equations for ambient environmental flows characterized by horizontal length scales which are orders of magnitude greater than their vertical length scales begins with the vertically hydrostatic, boundary layer form of the turbulent equations of motion for an incompressible, variable density fluid. To accommodate realistic horizontal boundaries, it is convenient to formulate the equations such that the horizontal coordinates, x and y, are curvilinear and orthogonal. To provide uniform resolution in the vertical direction, aligned with the gravitational vector and bounded by bottom topography and a free surface permitting long wave motion, a time variable mapping or stretching transformation is desirable. The mapping or stretching is given by:

Table 1
Physical information of Yongdam Lake.

Watershed area	930 km^2	Storage area	36.2 km^2
Total storage	815×10^6 m^3	Effective storage	673×10^6 m^3
Annual inflow	24.2 m^3/s	Dam length	498 m
Dam volume	$2,206 \times 10^3$ m^3	Dam height	70 m

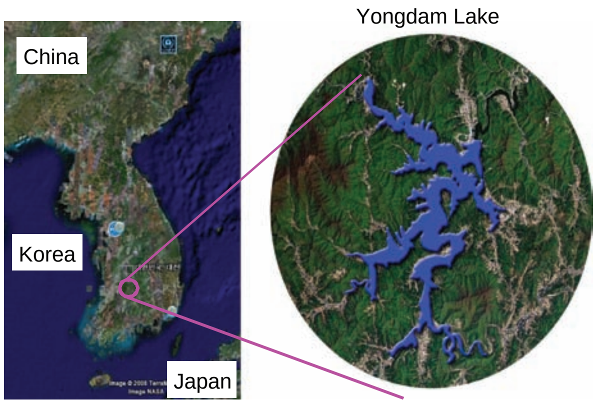

Fig. 1. Location of Yongdam Lake.

$$Z = (Z^* + h)/(\zeta + h) \tag{1}$$

Z^* = original physical vertical coordinates
h = physical vertical coordinates of the bottom topography
ζ = physical vertical coordinates of the free surface.

Transforming the vertically hydrostatic boundary layer form of the turbulent equations of motion and utilizing the Boussinesq approximation for variable density results in the momentum and continuity equations and the transport equations for salinity and temperature. Governing equations are explained in Ref. [8].

2.3. Input development

Table 2 shows required input file to execute EFDC model. All the parameters for water quality used in

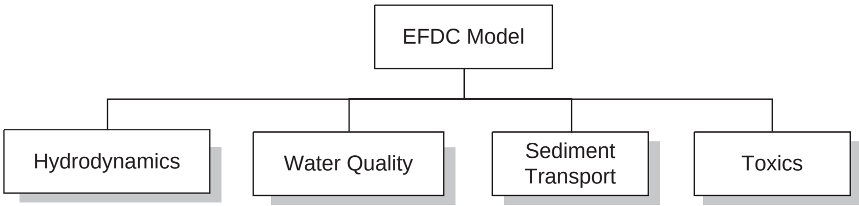

Fig. 2. Major modules of the EFDC model (full version).

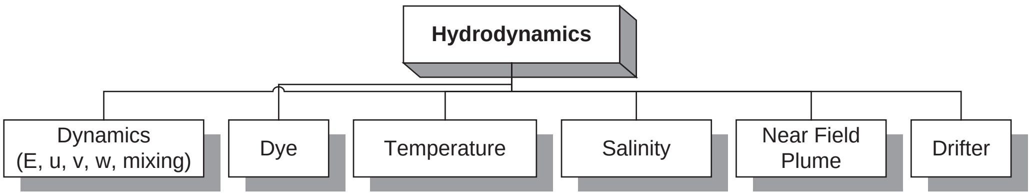

Fig. 3. Structure of the EFDC hydrodynamic module.

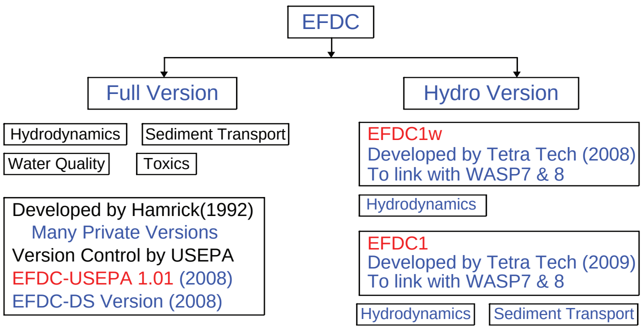

Fig. 4. Full version and hydro version of EFDC model.

this study were obtained from websites of governmental agencies in Korea including Korea Water Resources Corporation (www.kwater.or.kr), Water Resources Management Information System of Korean Government (www.wamis.go.kr), and the National Institute of Environmental Research (www.nier.go.kr).

2.4. Grid development

One must choose the proper resolution of modeling grid in order to account for spatial variation of the parameters to be considered. One of the greatest challenges of the littoral region is the wide range of spatial and temporal scales that must be represented. In this study, the orthogonal curvilinear grid technique was used to generate grid of the study area. One of the distinctive advantages of the use of an orthogonal curvilinear grid systems is the economy of computational and storage resources that can be attained. The grid optimization is the most important factor in the grid generation. Such kind of factor combines refinement, smoothing and reconnection tools which modify the grid to provide more spatial resolution where needed by the problem being solved, which is can be done by an orthogonal curvilinear coordinate. Figure 5 shows developed grid of the study site using two different grid generation techniques, Cartesian and Curvilinear Orthogonal, respectively.

Various attempts have been made for grid networks of Yongdam Lake by using EFDC tools. Volume-elevation curve of the dam and annual surface elevation data

Table 2
List of required input files for EFDC model.

File name	Types of input data
cell.inp	Horizontal cell type identifier file
cellLT.inp	Horizontal cell type identifier file for saving mean mass transport
dxdy.inp	File specifying horizontal grid spacing or metrics, depth, bottom elevation, bottom roughness and vegetation classes for either Cartesian or curvilinear- orthogonal horizontal grids
lxly.inp	File specifying horizontal cell centre coordinates and cell orientations for either Cartesian or curvilinear- orthogonal horizontal grids
show.inp	File controlling screen print of conditions in a specified cell during simulation runs
qser.inp	Volumetric source- sink time series file
aser.inp	Atmospheric forcing time series file
pser.inp	Open boundary water surface elevation time series file
wser.inp	Wind forcing time series file
EFDC.wsp	Controlling the linkage of EFDC and WASP
EFDC.inp	Master input file

were used to compare prediction accuracies. Since this study considers 3-D cases, number of horizontal cells should be multiplied by the number of vertical layers and this attempt results in greater number of cells and calculation time. Therefore, it was necessary to select optimum grid size of the site. Grid sizes from 10 to 40,000 for Yongdam Lake were tested and attempts had also made to limit grid size to its minimum. Average Mean Error (AME) and Residual Mean Square Error (RMSE) were used to estimate accuracy of predictions as shown in Eqs. (2) and (3), respectively.

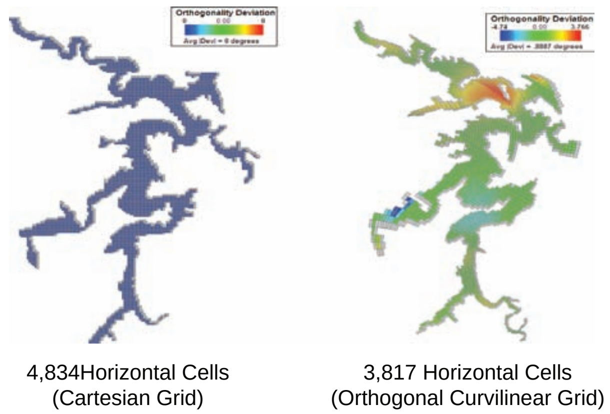

Fig. 5. Developed grid of Yongdam Lake using two different grid system.

$$\text{AME} = \frac{1}{N}\sum_{i=1}^{N}|Q_f - Q_o| \tag{2}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[Q_f - Q_o]^2} \tag{3}$$

Q_f = calculated data
Q_o = observed data
N = number of data.

3. Results and discussions

Figure 6 shows that greater number of girds can provide less error in terms of AME and RMSE. However, number of grids increases length of calculation time also

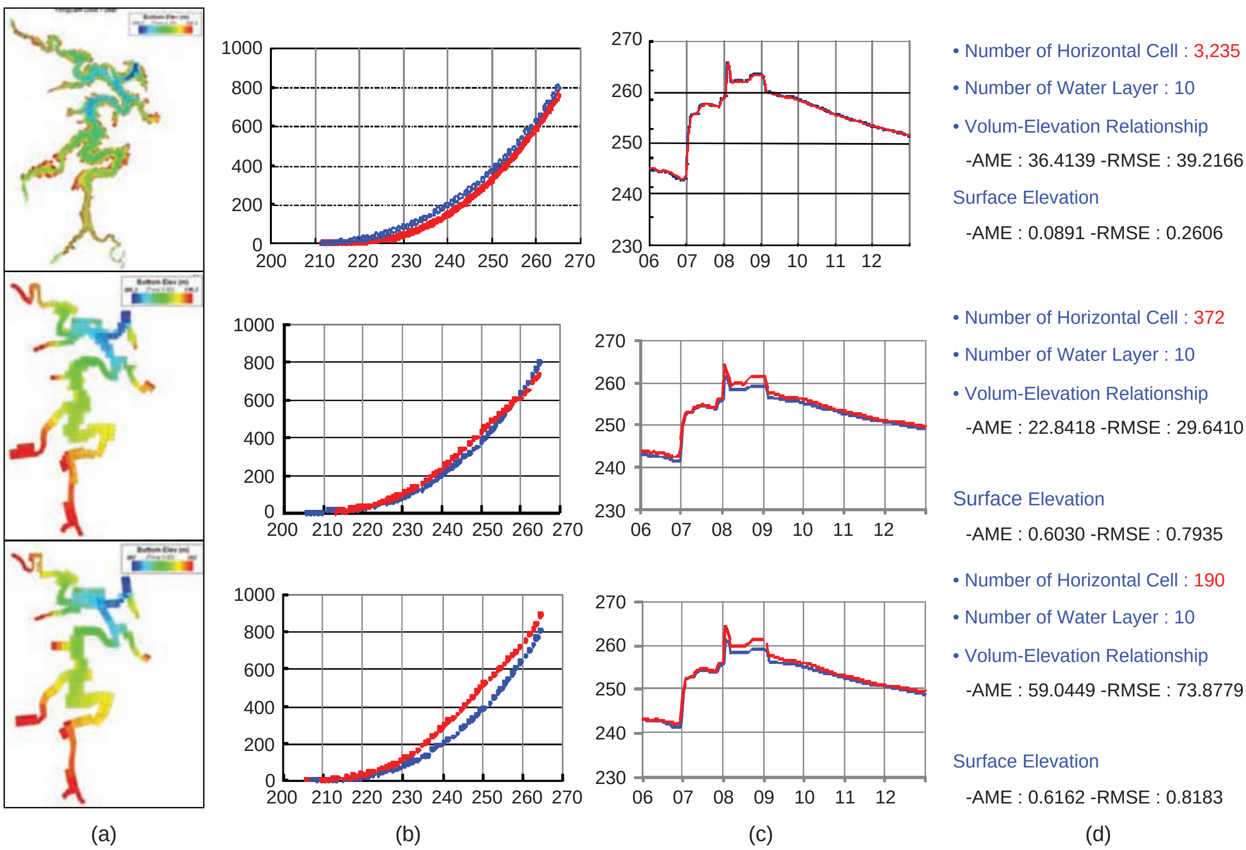

Fig. 6. Three grid systems and error analysis: (a) grids, (b) volume (Y axis-million m^3)-Elevation (X axis-m) curve, (c) surface water level (Y axis, m) – time (X axis-month) curve, (d) error analysis.

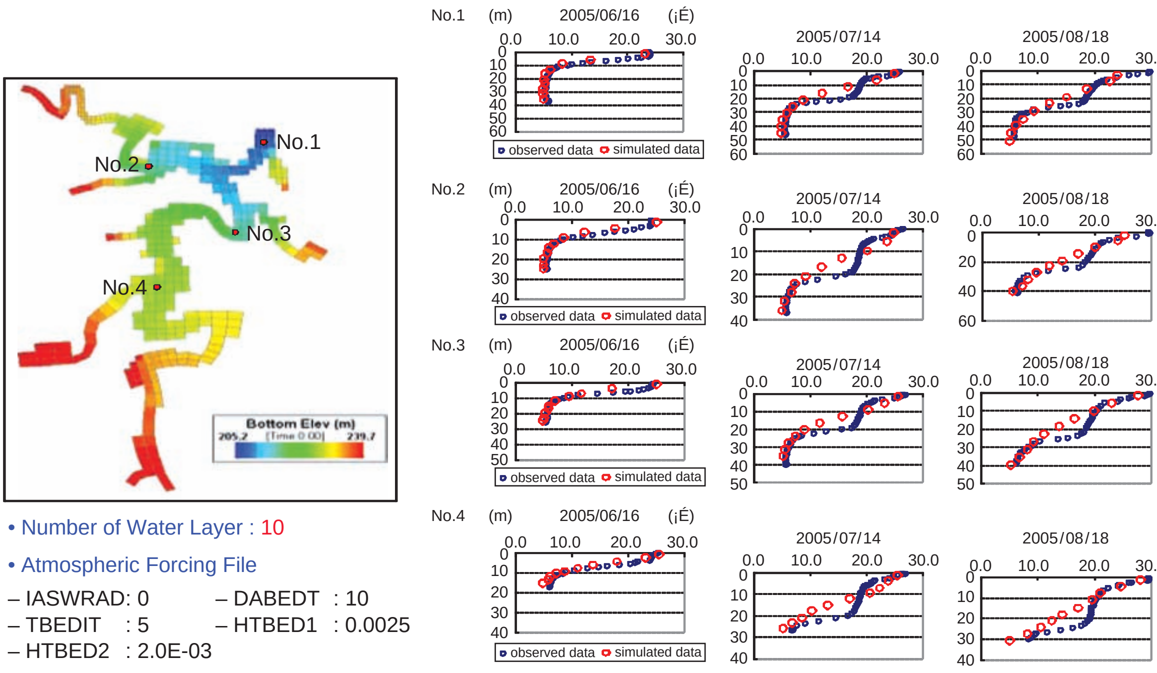

Fig. 7. Vertical temperature calibration of Yongdam Lake (372 horizontal grid with 10 vertical layers).

increases. For example, to execute hydrodynamic module for 4,000 cell horizontal cell and 10 vertical cells case on an annual basis for the study site, it took more than a week. Although, increasing the number of cells improve the resolution of the grid, it is time consuming and is complicated to link with WASP. This seems not feasible for the application of water quality management strategy of the study site at lease now. Since this application is considered to be linked with WASP model, the maximum numbers of cells for WASP also have to be considered. Authors of WASP (Tim Wool in USEPA, personal communication) suggested to limit the number of grids less than 4,000. Therefore, a case that consider 372 horizontal cells with 10 vertical layers was regarded to be maximum number of grid for the study site.

Figure 7 shows vertical temperature calibration results of 372 horizontal cells with 10 vertical layers for the study site. Simulated vertical temperature profiles show differences compared to observed values.

Figure 8 shows volume and surface water level relationship of the study site for few additional grid development cases. Three additional horizontal cells cases were 125, 190 and 370 with vertical layers 10 and compared the volume elevation relationship. Error analysis of these grids is as shown in Table 3. Surface calibration for 190 and 370 grids cases were similar to cases shown in Fig. 5. However, 125 horizontal cells case showed increased error compared to the other cases. Table 4 shows the statistical comparisons of temperature calibration of three different grids. It also seems 190 × 10 cell case would be optimum for temperature calibration among tested cases. Considering error level and computation time requirements, 190 horizontal cells with 10 vertical layers case is preferred among tested in this study. Annual vertical temperature profiles were simulated using the above calibration results of those three different no of grids. The temperature calibration results were quite similar in all three cases by visual observation. The result of 190 horizontal grid cases is as shown in Fig. 9.

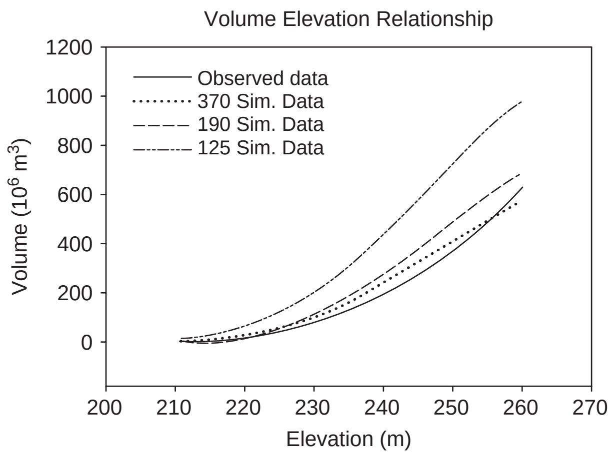

Fig. 8. Volume elevation relationship of additional grid systems.

Table 3
Result for volume-elevation and surface elevation for different grids.

Number of horizontal grids	Volume-elevation curve error		Surface elevation error	
	AME	RMSE	AME	RMSE
370	21.80	28.40	0.60	0.70
190	56.43	69.89	0.60	0.81
125	199.0	237.0	1.19	1.49

4. Conclusions

Through multiple trial and errors, it was possible to find optimum grid network to successfully calibrate water level and vertical profile dynamics on an annual basis. When 370 horizontal and 10 vertical cells were used, satisfactory temperature and surface calibration results were obtained while the originally developed grid size was 10 times greater. It was also found that 190 cells also can be used to generate similar hydrodynamic calibration results with slight loss of accuracy.

Table 4
Statistical comparisons of temperature calibration of three different grid systems.

Error	Grid	June 10	July 14	August 18	September 15	October 6	October 25	November 25	December 15	Total
AME	125	1.41	2.59	3.20	4.46	4.21	3.99	2.53	1.40	23.79
	190	**0.98**	**1.76**	**1.89**	**2.89**	**3.19**	**3.25**	**2.33**	**1.34**	**17.63**
	370	0.95	1.85	2.21	2.66	3.20	3.26	2.60	1.37	18.1
RMSE	125	4.46	8.21	10.12	14.13	13.31	12.64	8.01	4.44	75.32
	190	**3.11**	**5.60**	**5.97**	**9.45**	**10.10**	**10.36**	**7.39**	**4.23**	**56.21**
	370	2.60	5.85	6.99	8.42	10.13	10.33	8.24	4.36	56.92

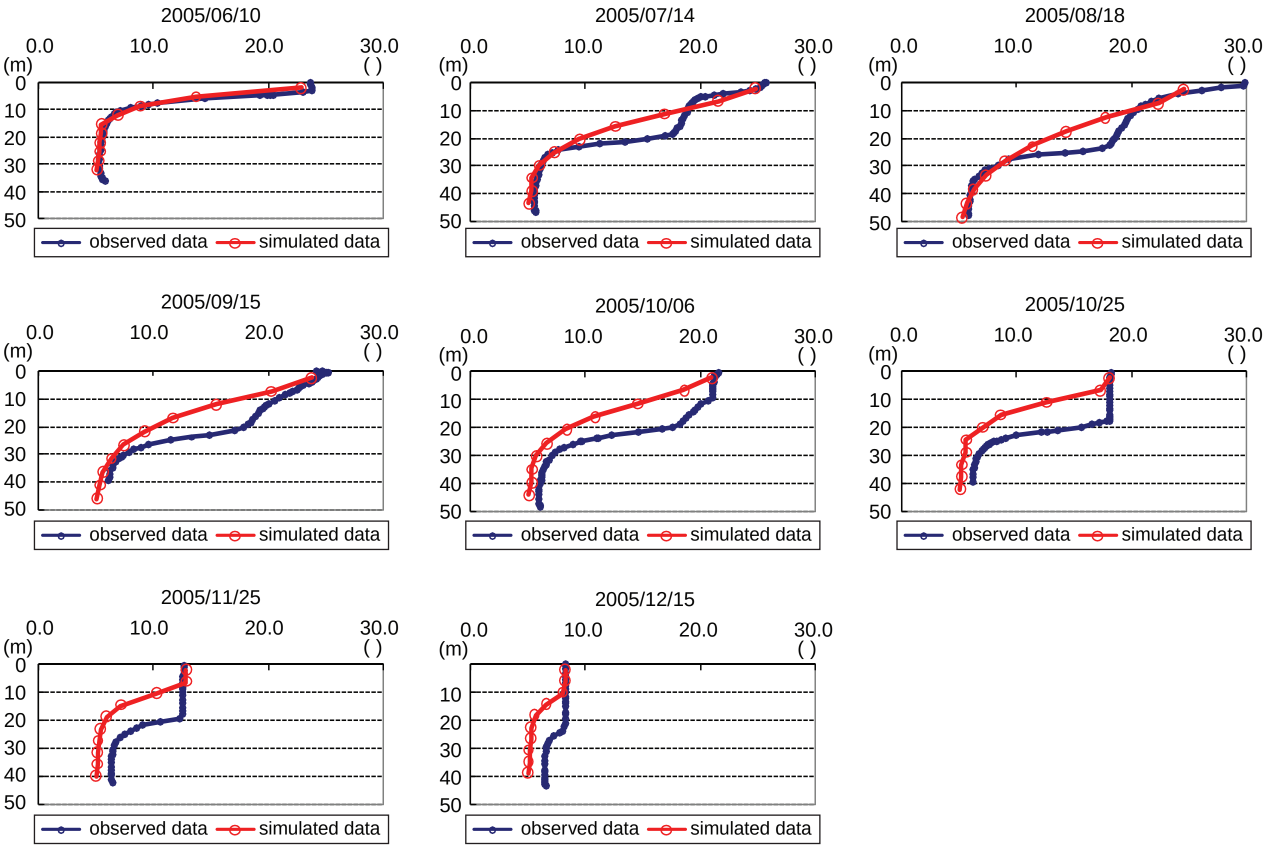

Fig. 9. Temperature calibration of 190 horizontal cell cases (10 vertical layers).

Annual temperature profiles of the study site were simulated using 125, 190 and 370 horizontal cell cases with 10 vertical layers. It was also found that 190 cells case were found to be optimum. Despite of number of attempts errors between simulated and observed data were unavoidable. Possible source of errors in this study would be (1) insufficient daily inflow data due to lack of daily inflows measurements to the lake (2) insufficient information of solar energy related data including heat transfer coefficients between air/water and water/sediment and (3) limited number of vertical layers due to sigma stretch assumption of EFDC model. It is also believed that sigma stretch vertical layer assumption may have limitation in the simulation of vertical temperature profile. Further study is suggested using different vertical grid system such as generalized vertical coordinate system [7].

Through the study, it was possible to reduce number of cells and thus required calculation times for application of EFDC-WASP. Considering the fact that calculation requirement of the most 3-D hydrodynamic water models, this study illustrates that optimal grid cell size selection process in essential.

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