Calibration of CE-QUAL-W2 for a monomictic reservoir in a monsoon climate area

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Abstract The impact of inflow mixing on reservoir stratification is significant for reservoirs situated in a monsoon climate area. It cause difficulty in the calibration of a two-dimensional hydrodynamic and water quality model, CE-QUAL-W2 that was recently adopted for a real-time turbidity monitoring and modelling system (RTMMS) for a reservoir in Korea. This paper presents a systematic calibration and verification processe of the model for the reservoir. A sensitivity analysis showed that wind sheltering, Chezy, and sediment heat exchange coefficients are most sensitive to stratification structure. Inflow temperature was very sensitive during a year of normal precipitation, but it is not significant during a year of drought. Residual analysis revealed that the model has shortcomings in the simulation of water temperature near the metalimnetic zone without calibration. After calibration, however, the absolute mean errors between observed and simulated values were placed within 0.116–1.190 °C. Its performance was maintained under heavy flood events during the verification stage, which implies that the model is ready to use for the simulation of turbidity plume in the RTMMS under various hydrologic conditions. The suggested model calibration strategy and relevant results may be adopted for other reservoirs located in a monsoon climate area.

Keywords CE-QUAL-W2; monsoon area; reservoir stratification; sensitivity analysis; water temperature modelling

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Introduction

The effects of thermal stratification on the hydrodynamic mixing and water quality of a reservoir are significant (Fischer *et al.*, 1979; Kennedy *et al.*, 1982). In particular, the flow path and travel time of contaminated turbidity flows that are typically induced by heavy rainfall and runoff events during the summer flood season at most of the large artificial reservoirs in the Republic of Korea are directly influenced by thermal structure, and vice verse. Once a turbidity plume enters a reservoir, its fate and transport are complicated if the reservoir is stratified, and density flow, such as plunge flow, underflow, and interflow, forms due to the temperature difference between river and ambient waters (Martin and McCutcheon, 1999).

In general, the thermal structure of a reservoir is influenced by exchange of solar radiation, wind mixing, inflow and outflow hydrodynamics, geometry, and the latitude and elevation of the reservoir (Fischer *et al.*, 1979; Wetzel, 1983; Martin and McCutcheon, 1999). Most reservoirs located in Korea are classified as warm monomictic reservoirs that experience one turnover during late fall as the air temperature drops, show well-mixed conditions until early spring, and begin to reform thermal stratification from late spring (Na *et al.*, 2002; Park and Park, 2002). Typically at most deep reservoirs a strong thermal stratification is developed until the middle of June when the monsoon season starts. However, about 70% of the annual precipitation amount is concentrated during the summer season from June to September, and the impact of inflow mixing on the reservoir thermal structure is significant (Kim *et al.*, 2001; Chung, 2004). This so-called ‘monsoon

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effect' has caused difficulty in the calibration of a two-dimensional reservoir hydrodynamic and water quality model, CE-QUAL-W2 (hereafter W2) that was adopted for a real-time turbidity monitoring and modelling system (RTMMS) in a reservoir. The RTMMS is a decision support system designed to identify the flow regimes of turbidity plume in time using a W2 model and to accommodate adequate controls such as selective withdrawal. To make the system more reliable, it was obviously required to calibrate and validate the model parameters for accurately simulating the thermal structure and flow regime of the turbidity plume in the reservoir. The objectives of this study were (1) to make a sensitivity analysis of W2 model parameters that affect water temperature simulation considering hydro-meteorological conditions of the study reservoir, (2) to calibrate the parameters to minimize the errors between observed and simulated water temperature profiles, and (3) to identify the model weakness using residual analysis.

Description of study site and field monitoring

The Daecheong Reservoir, which is located in the Geum River basin of Korea, is a deep, warm, monomictic reservoir with a maximum depth of 50 m (Figure 1). It is the most important water resource in the basin that supplies 922 000 m^3 of drinking water per day to 2 million people dwelling in the surrounding cities. However, the turbidity inflow degraded the quality of water and increased the cost of water treatment during the summer season.

Weekly field monitoring has been performed using a continuous water quality monitoring system (YSI6000 series) at six sampling stations (Sta.1–6) in the reservoir since 2001 to obtain water temperature, turbidity, conductivity, pH, and dissolved oxygen (DO) profiles in the reservoir. Another continuous water quality monitoring device (YSI6920) has been deployed at Sta. 7 located at 89 km upstream from the dam to acquire inflow data every hour since June 2004.

Figure 2 presents the isothermal contours of the reservoir for two years. Typically, the reservoir experienced turnover mixing from October, and well-mixed conditions remained until early spring. It began to form thermal stratification from May, and by June a stable thermocline was established at 10 to15 m below the water surface. However, the structure of thermal stratification was considerably disrupted by several rainfall events during the monsoon season that usually occurs from late June to July, and typhoon inundations during late summer. During this period, turbidity inflow tends to carry a huge amount of non-point source pollutants such as organic chemicals, nutrients, suspended solids, and

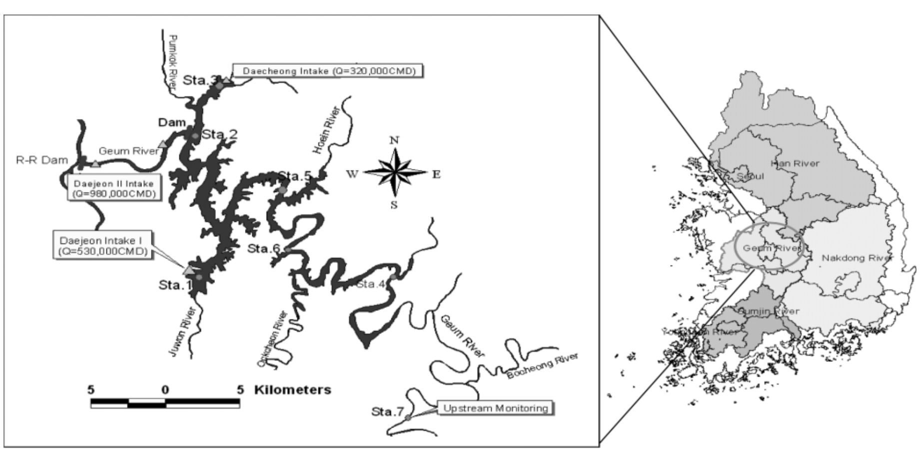

Figure 1 Location of the study reservoir and field monitoring stations

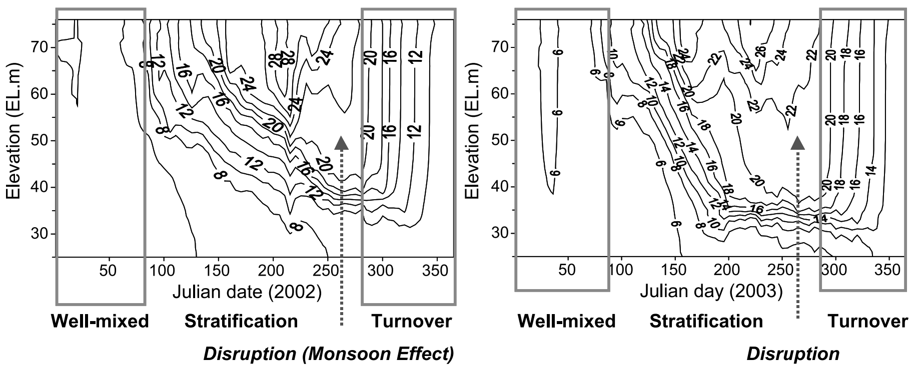

Figure 2 Thermal structures of the Daecheong Reservoir and the monsoon effect

debris to the reservoirs, which sometimes ignite a significant bloom of algae in the reservoir.

CE-QUAL-W2 model

The W2 model solves six governing equations including horizontal momentum, water surface elevation, hydrostatic pressure, continuity, water density, and constituent transport to obtain laterally averaged fluid motion and mass transport using finite difference methods (Cole and Buchak, 1995; Cole and Wells, 2003). The model is appropriate for water bodies where lateral variations in flow velocity, temperature, and water quality are insignificant. The model has been tested extensively and successfully applied to many reservoirs in simulating thermal stratification and water quality problems such as dissolved oxygen, nutrients, eutrophication, and toxicant spill (Martin, 1988; Bath and Timm, 1994; Chung and Gu, 1998; Bartholow *et al.*, 2001; Na *et al.*, 2002; Park and Park, 2002).

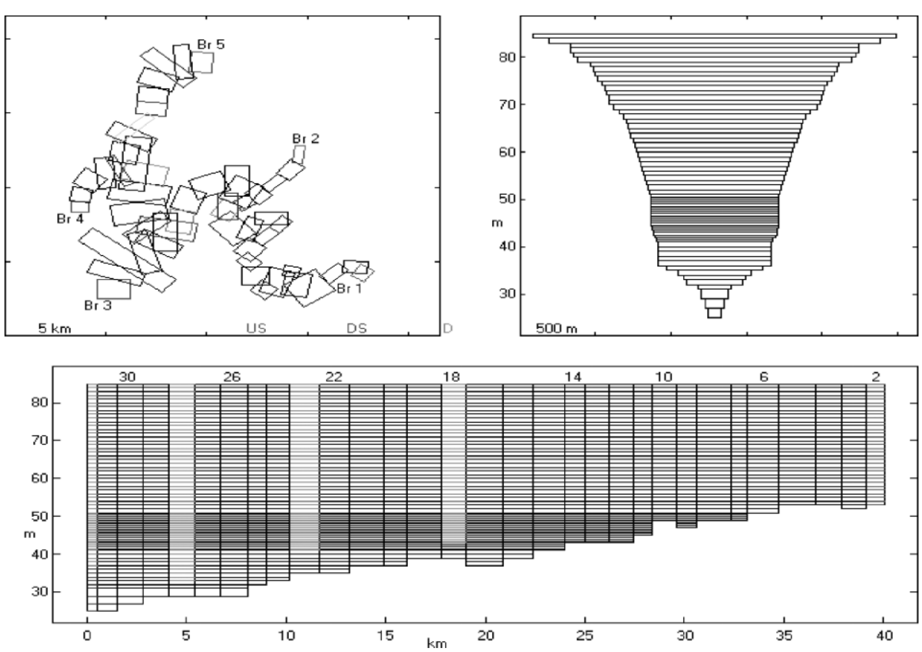

Figure 3 Finite difference grids representing the bathymetry of the Daecheong Reservoir

Results and discussion

Sensitivity analysis

The finite difference grid, which consists of 5 branches with 64 segments and 69 layers, was created based on the surveyed reservoir bathymetry (Figure 3). The accuracy of bathymetry data was examined by comparing the observed and simulated storage-water elevation curves, and reservoir water surface elevations. Table 1 shows the model parameters selected for sensitivity analysis and their perturbation ranges from each default value. The sensitivity of inflow water temperature, which is not a parameter but an important input data specifying boundary conditions, on reservoir thermal structure was also evaluated to identify the influence of inflow energy. The time frame for sensitivity analysis and model calibration was selected considering hydro-meteorological conditions of the study reservoir. As shown in Figure 4, 2001 was the year selected for the sensitivity analysis and model calibration because there were no significant runoff events during the flood season, which is assumed to be good to avoid the monsoon effect and isolate the effect of each model parameter from the massive impact of inflow mixing energy.

Meteorological data including air temperature, dew point temperature, cloudiness, and wind direction and velocity were obtained from an automated weather station situated near the dam site. For generating daily inflow water temperature (T_w), a multiple regression model (Neumann *et al.*, 2003) was developed. The regression parameters in Equation (1) were derived as a function of average daily air temperature (T_a), dew point temperature (T_d), and river flow rate (Q) using hourly field data obtained from June to

Table 1 Model parameters selected for sensitivity analysis and ranges of their values

Description	Variable	Unit	−50%	−20%	Default	20%	50%
Longitudinal eddy viscosity	AX	m^2/s	0.5	0.8	1	1.2	1.5
Longitudinal eddy diffusivity	DX	m^2/s	0.5	0.8	1	1.2	1.5
Chezy coefficient	FRICC	m^2/s	35	56	70	84	105
Wind sheltering coefficient	WSC	–	0.5	0.85	1.0		
Solar radiation absorbed in surface layer	BETA	–	0.25	0.36	0.45	0.54	0.68
Extinction coefficient for pure water	EXH20	m^{-1}	0.25	0.36	0.45	0.54	0.68
Sediment heat exchange coefficient	CBHE	$W/m^2/s$	0.15	0.24	0.3	0.36	0.45
Inflow water temperature		°C	$0.75T_w$	T_w*	$1.25T_w$		

*T_w is the estimated daily inflow water temperature using a multiple regression model

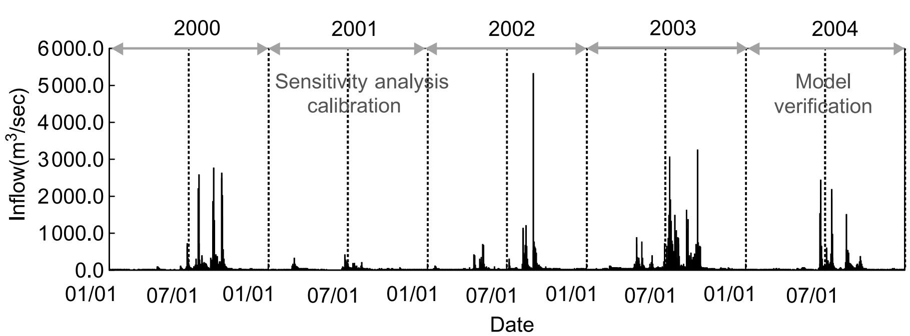

Figure 4 Daily inflow data of the reservoir during the past five years and selection of time period for sensitivity analysis and model calibration

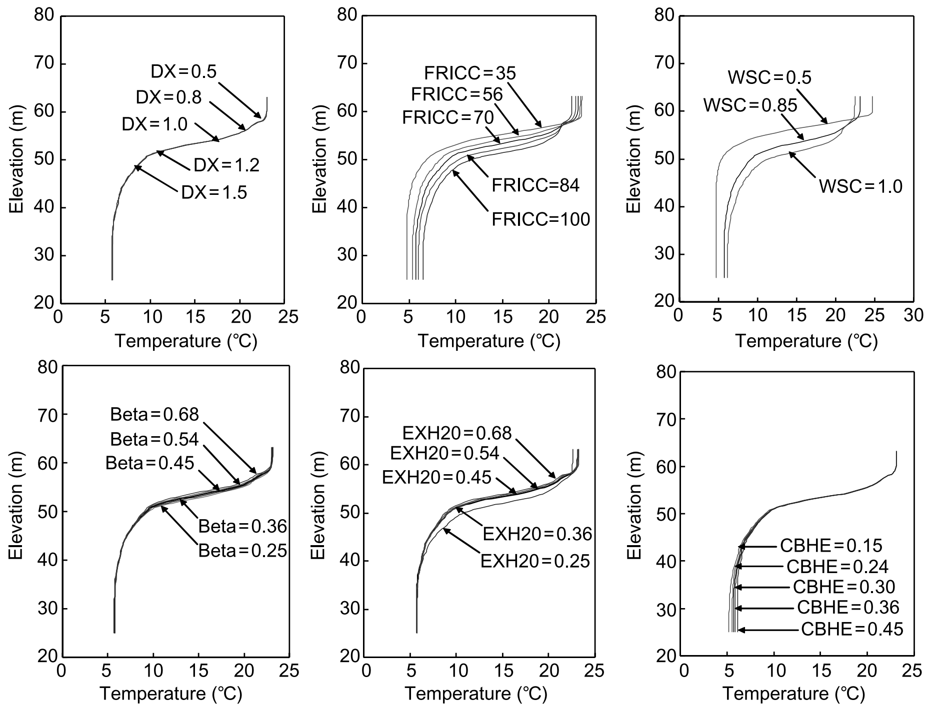

Figure 5 Sensitivity of model parameters on water temperature profiles (JDAY 165, 2001)

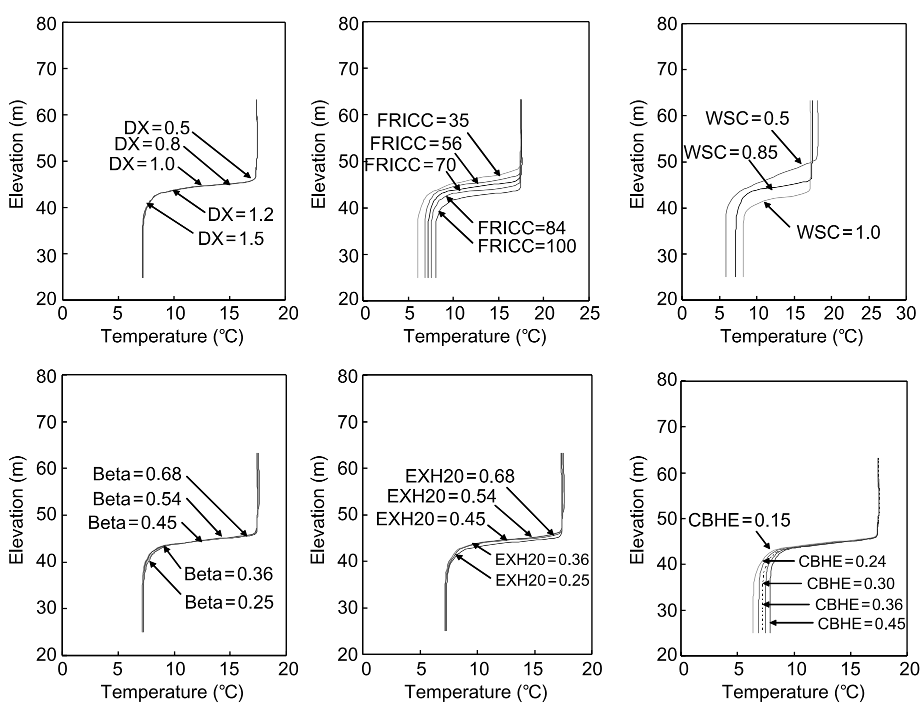

Figure 6 Sensitivity of model parameters on water temperature profiles (JDAY 300, 2001)

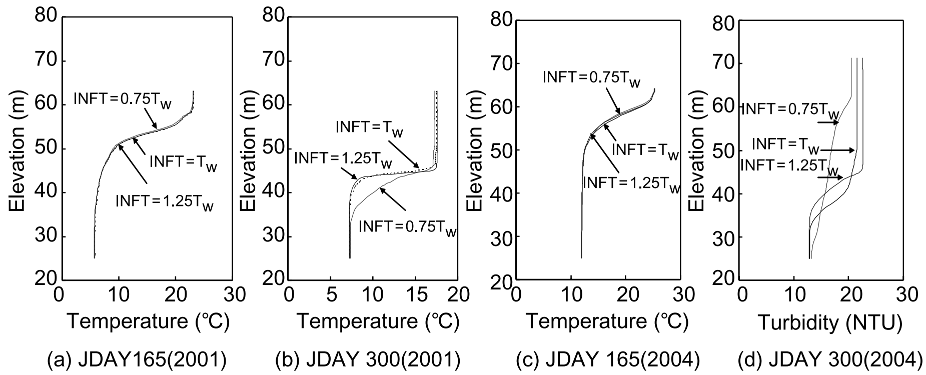

Figure 7 Sensitivity of inflow water temperature on reservoir water temperature profiles

September 2004. The regression model reasonably replicated the drop in water temperature during precipitation events. The absolute mean error (AME) and coefficient of determination (r^2) were 1.277 °C and 0.822, respectively. The daily inflow and outflow data obtained from the hydrologic database of the Korea Water Resources Corporation was used as boundary flow conditions.

$$T_w = 1.3109 + 0.8828T_a + 0.1479T_d - 0.0021Q \tag{1}$$

The most significant parameters affecting the reservoir thermal structure were found to be WSC, FRICC, and CBHE in order (Figures 5 and 6). The WSC, which is multiplied with wind speed to reduce the effect of wind considering the surrounding terrain, significantly affected the thermocline depth and water temperature profile during the stratification period, and accelerated vertical mixing during the turnover period. The increase in FRICC, which represents the degree of boundary roughness between water column and reservoir bottom, resulted in additional vertical heat exchange, and acceleration of turnover. The effect of heat exchange coefficient between overlying water column and bottom

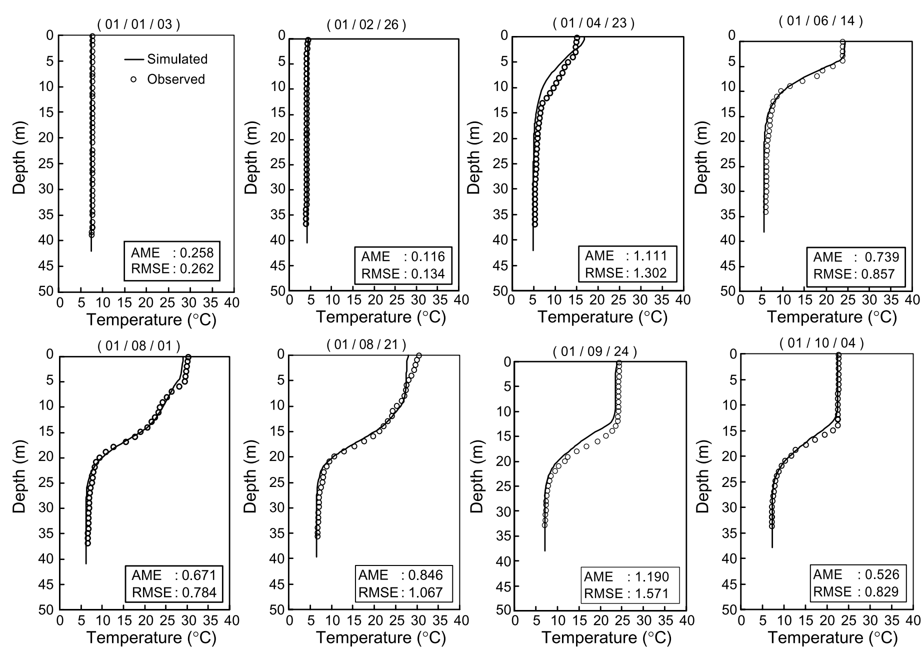

Figure 8 Observed and simulated water temperature profiles at Sta. 2 after calibration

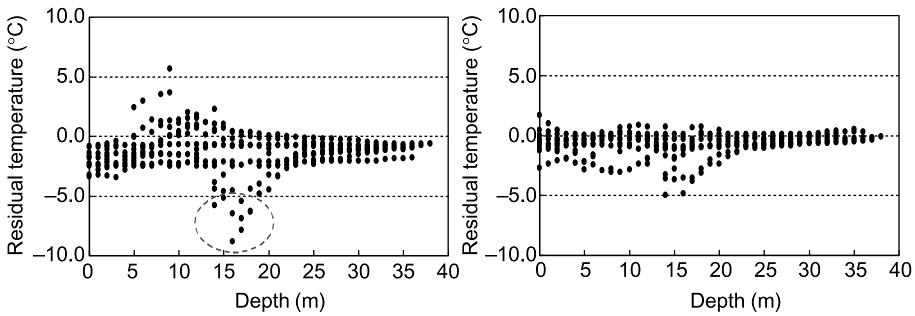

Figure 9 Residual analysis between observed and simulated water temperatures before (left) and after (right) calibration

sediment (CBHE) was only significant in the hypolimnion zone because of the stratification barrier. The other parameters including AX, DX, BETA, and EXH20 were found to be not significant. The effect of inflow water temperature was not significant in 2001 because there was no considerable rainfall and runoff event (Figure 7). This is because thermal energy mixing in the reservoir was controlled mostly by solar radiation and wind mixing at that time. However, it was very sensitive to simulated water temperature profiles in 2004 when normal rainfall events occurred during the flood season. This implies that a real-time monitoring of inflow water temperature is vital to simulate the transport and mixing processes of the turbidity plume accurately and to improve the capability of RTMMS.

Calibration and residual analysis of the model

Based on the information obtained from the sensitivity analysis, some parameters were calibrated to minimize the errors between observed and simulated values. The WSC values decreased to 0.1 to 0.5 depending on the season, which indicated strong wind

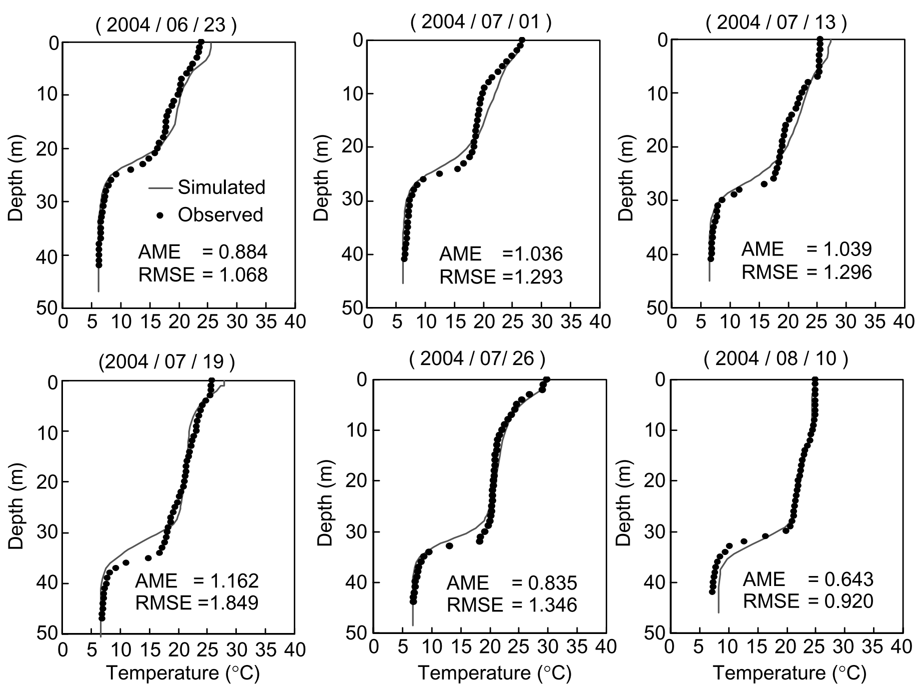

Figure 10 Verification of model using field data obtained in normal precipitation year, 2004

sheltering by the surrounding mountainous terrain. The FRICC, CBHE, EXH20 values of 70 m^2/sec, 0.5, 0.3 were found to be optimal for the reservoir. The AME and root mean square (RMSE) between the observed and simulated water temperatures were placed within 0.116–1.190 °C and 0.134–1.571 °C, respectively, after calibration (Figure 8).

A residual (observed minus simulated) analysis was implemented to identify the weakness of the model (Figure 9). It revealed that the model has shortcomings in the simulation of water temperature at the metalimnetic zone where water temperature declines rapidly due to light extinction and penetration of turbidity inflow. The degree of error ranged from −10 to 5 °C before calibration, and tended to underestimate the water temperature overall. However, after calibration, the residuals were reduced to less than −5 to 1 °C. To verify model performance, the same parameter values were applied for simulating other independent field data obtained in 2004 when considerable disruption of stratification occurred due to three flood events. As the results show in Figure 10, the model still showed satisfactory performance by maintaining the AME and RMSE values less than 1.162 °C and 1.849 °C, respectively.

Conclusions

In this study, a systematic calibration process of a W2 model was suggested for a warm, monomictic reservoir located in a monsoon climate area where the stratification structure is significantly influenced by inflow mixing. According to the sensitivity analysis results, the most sensitive model parameters affecting the thermal structure of the reservoir were wind sheltering coefficient, Chezy roughness coefficient, and sediment heat exchange coefficient in order. The boundary inflow water temperature was sensitive to the thermal structure during a year of normal precipitation, although it was not significant during a year of drought. Therefore, real-time monitoring of inflow water temperature is very important for better simulation of reservoir hydrodynamics and turbidity plume, and to improve the reliability of RTMMS. Residual analysis revealed that the model has shortcomings in the simulation of water temperature near the metalimnetic zone without calibration. After calibration, however, the AMEs between observed and simulated water temperatures were placed within 0.116–1.190 °C. Its performance was maintained under flood events during the verification stage, which implies that the model is ready to use for the simulation of turbidity plume in the RTMMS under various hydrologic conditions. The suggested model calibration strategy and relevant results may be adopted for other reservoirs located in monsoon climate areas.

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