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Feasibility of curtain weir installation for water quality management in Daecheong Reservoir

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ABSTRACT

The study was aimed to determine the optimal location of a vertically moveable curtain weir in Daecheong Reservoir (Korea) and to assess its effectiveness for the control of algal bloom in the reservoir. A laterally averaged two-dimensional hydrodynamic and eutrophication model (CE-QUAL-W2) was used to simulate water quality variables and the effect of curtain weir. The original model was modified to accommodate vertical displacement of the weir according to the water surface fluctuation. The model calibrated in a previous study was validated for different hydrological conditions representing drought year (2008) and normal year (2006) for the study, and adequately reproduced the temporal and spatial variations of temperature, nutrients and phytoplankton concentrations. The performance of curtain weir on the control of algal bloom was assessed by applying the validated model to 2001 when an abnormal mono-specific bloom of the *Microcystis aeruginosa* had developed and 2006 based on 9 different installation scenarios. The reduction rates of algal concentration (Re) were placed in the range of 11.2–40.3% and 20.3–56.7% for 2001 and 2006, respectively. The performance of curtain weir was varied for different locations and different hydrological years. Overall, the performance was improved as the weir was installed further downstream.

Keywords: Algal bloom; Curtain weir; CE-QUAL-W2; Daecheong reservoir

1. Introduction

Algal bloom, an excessive growth of phytoplankton, is a major water quality issue for the management of many eutrophic reservoirs in Korea [1]. Daecheong Reservoir operated since 1981 has revealed serious eutrophication and algal blooming during summer [2]. In the end of July and early August of 2001, an abnormal mono-specific bloom of the cyanobacterium *Microcystis aeruginosa* had developed in the reservoir. The cell counts during the peak bloom were about 1,477,500 cells/mL. *Microcystis aeruginosa* contain gas vesicles in cells and are able to control their buoyancy with intracellular carbohydrate concentrations and colony formation, which is beneficial for dominance against other species in the strongly stratified Daecheong Reservoir [3–5].

The algal bloom events incurred the concern over the effectiveness of the water treatment system and outbreak of disinfection by-products. To cope with the negative impact of algal blooming on the reservoir and drinking water quality, installation of a float-type curtain weir has been suggested by the reservoir management institute (K-water) [2]. Important factors

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regulating algal growth include light, temperature, inorganic nutrients, and organic micronutrient factors [4, 6], thus limiting of these factors can mitigate the algal bloom. Previous studies [7–10] have shown that the manipulation of hydrodynamic flow regimes at riverine and transitional zones could partially control the algal blooming in lacustrine zones by reducing allocthonous nutrient load. Asaeda *et al*. (2001) reported how a curtain weir installed in Terauchi Dam Reservoir effectively controlled algal blooms in the main reservoir. The curtain weir markedly reduced algal blooming by curtailing the dispersion of nutrients from the riverine zone to the lacustrine downstream epilimnion and enhancing the biological uptake of nutrients by the upstream algal population [11].

The objective of the study was to assess the effectiveness and optimal location of a vertically moveable curtain weir as a cost-effective and ecologically sound control measure to lessen the negative impact of algal blooming on the reservoir. A new computational algorithm was incorporated into a laterally averaged two-dimensional (2D) hydrodynamic and eutrophication model (CE-QUAL-W2) for representing the float-type weir that moves vertically with the water surface fluctuations. The paper describes the detailed information on the model set-up, model validation, and model application processes for evaluating the effectiveness and optimal site of a curtain weir on the control of reservoir water quality with several different installation scenarios.

2. Materials and methods

2.1. Study site description

Daecheong Reservoir has a watershed area of 3204 km^2 and an effective storage volume of 790×10^6 m^3. It is an important reservoir supplying 922,000 m^3 of drinking water per day to 2 million people dwelling in surrounding cities, and also used for flood control, irrigation, and hydropower. It is a deep, narrow and warm monomictic reservoir, completely mixed once a year in the winter and stably stratified for the remainder of the year, with a maximum depth of 50 m. A regular sampling has been performed at 4 monitoring sits (R1, R2, R3, R4) located in the main reservoir and 2 sites (A1, A2) located near two drinking water withdrawal structures (Fig. 1(a)).

Currently a 7 m deep curtain weir (1 in Fig. 1(a)) is installed at the confluence of So-oak river and the reservoir to prevent the transport of nutrient-rich inflow and algae to the surface of the main reservoir from the river, which is most contaminated tributary. In this study, the optimal location and effect of an additional curtain weir along the transitional zone of the reservoir is assessed with nine different installation scenarios as shown in Fig. 1(a) and Table 1.

The model parameters were calibrated using the field data obtained in 2001 in a previous study [2, 12], thus the results are not presented in this paper. In this study, the model was verified with independent sets of data obtained recently in 2006 and 2008. The amounts

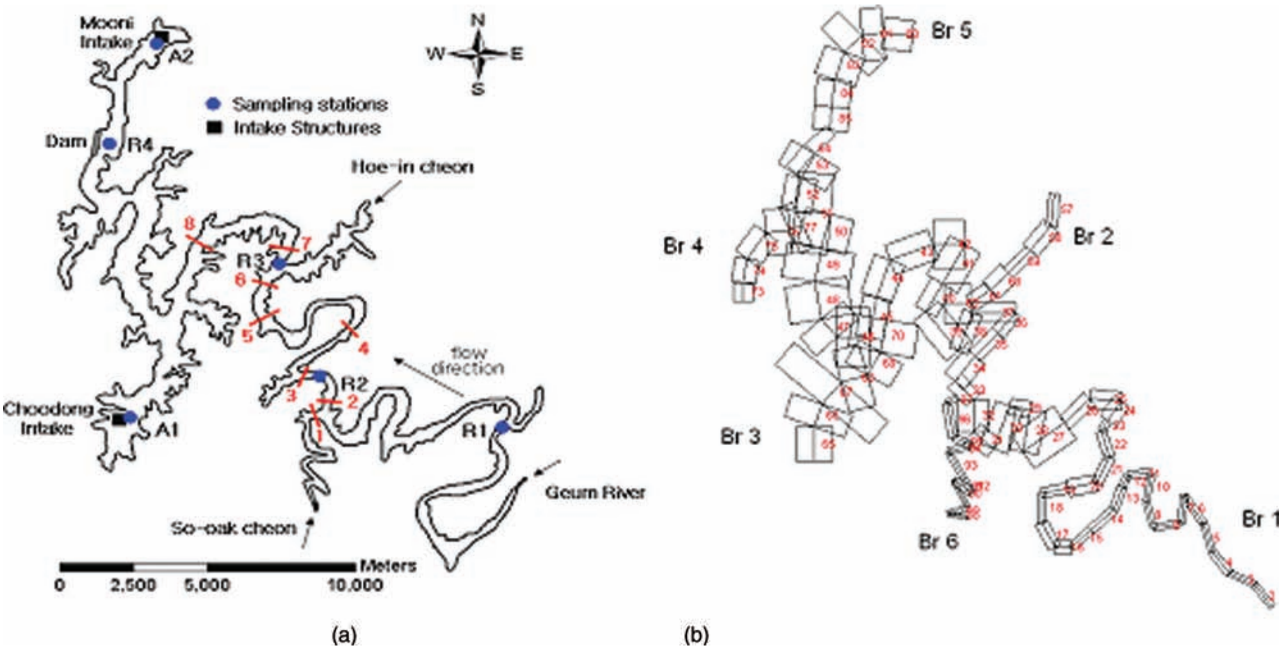

Fig. 1. Locations of monitoring stations and potential curtain weir sites (a), and model segments (b).

of total precipitation during the verification periods were 1235.9 and 782.4 mm, respectively. Meanwhile, the amounts of precipitation during flood season (June–September) were 868.3 mm (70.3%) and 565.5 mm (72.3%), respectively. The amounts of averaged daily inflow to the reservoir were 86.7 m^3/s in 2006 and 34.8 m^3/s in 2008. The maximum and minimum water surface elevations were EL. 75.2 m and EL. 64.1 m in 2006, EL. 72.6 m and EL. 64.5 m in 2008 (Table 2). 2006 was normal flood year, so there were spillway discharges for flood control of the reservoir. The first discharge was 6701.0 m^3/s from July 14 to July 24, and second one was 1420.4 m^3/s from July 26 to July 28 in 2006. In contrast to 2006, 2008 was dry year and hydrological conditions were similar to 2001.

2.2. Simulation model

A 2D, laterally averaged hydrodynamic and water quality model (CE-QUAL-W2) was used for the reservoir. The model is appropriate for water bodies where lateral variations in velocity, temperature, and water quality are insignificant [13]. The model uses a numerical scheme for a direct coupling between hydrodynamic and water quality simulations, and solves six governing equations including horizontal momentum, water surface elevation, hydrostatic pressure, continuity, water density, and constituent transport to laterally averaged fluid motion and heat transport using finite difference methods [14].

The placement of curtain weir is updated every time-step and moves vertically according to water surface changes, and effectively acts as a barrier to flow and diffusion of mass and heat across the width of the water body. A finite difference grid consisting of six branches with 98 segments and 69 layers (at 0.5–1.0 m intervals), was created based on the surveyed reservoir bathymetry (Fig. 1(b)).

The accuracy of model bathymetry and water balance was examined by comparing the observed and simulated reservoir water surface elevations based on the measured inflow and outflow data for 2006 and 2008 (Fig. 2). The goodness of fit and errors between the observed and simulated water surface elevations were quantitatively estimated using statistical indices including coefficient of determination (R^2), the absolute mean errors (AME), and root mean square errors (RMSE) that the formulations are presented in Table 3. The model showed good agreement with the observation and the magnitude of AME was less than 0.1 m.

Table 1
Simulation scenarios for the evaluation of curtain weir installation.

Scenarios	Curtain weir 1	Curtain weir 2	Curtain weir 3	Curtain weir 4	Curtain weir 5	Curtain weir 6	Curtain weir 7	Curtain weir 8
S-1	×	×	×	×	×	×	×	×
S-2	○	×	×	×	×	×	×	×
S-3	○	○	×	×	×	×	×	×
S-4	○	×	○	×	×	×	×	×
S-5	○	×	×	○	×	×	×	×
S-6	○	×	×	×	○	×	×	×
S-7	○	×	×	×	×	○	×	×
S-8	○	×	×	×	×	×	○	×
S-9	○	×	×	×	×	×	×	○

Table 2
Hydrological conditions of daecheong reservoir in 2001, 2006 and 2008.

Years/ factors	Precipitation (mm)		Average inflow (m^3/sec)		Water level (EL. m)		
	Annual	Flood season*	Annual	Flood season*	Max	Min	Difference
2001	794.6	500.6	34.6	52.1	68.1	62.8	5.3
2006	1235.9	868.3	86.7	204.1	75.2	64.1	11.1
2008	782.4	565.5	34.8	67.8	72.6	64.5	8.1

*Flood season: June–September.

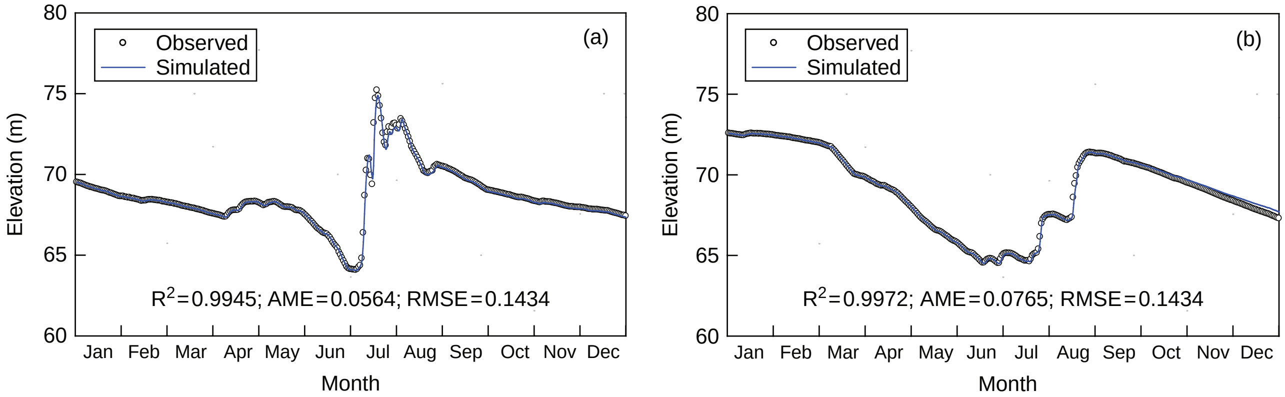

Fig. 2. Comparison of observed and simulated water surface elevations in 2006 (a) and 2008 (b).

Table 3
Statistical indices used to evaluate the model accuracy.

Statistical index	Equation	Desired value
Absolute Mean Error	$AME = \frac{1}{N}\sum_{i=1}^{N}\lvert Q_s - Q_o\rvert$	0
Root Mean Square Error	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[Q_s - Q_o]^2}$	0

Q_o = observations, Q_S = simulations, N = total number of observations

3. Results and discussions

3.1. Validation of the model for temperature simulations

The performance of the 2D model for the simulation of water temperature and seasonal stratification processes was validated by comparisons of the observed and simulated water temperature profiles at R4 for different times during 2006 and 2008 (Figs. 3–4). Overall the model satisfactorily reproduced the temporal changes of seasonal stratification structure of the reservoir for both years. Averages of the AME and RMSE were placed within the range of 0.844–1.961°C and 1.010–2.762°C in 2006 and within the range of 0.485–1.162°C and 0.618–1.415°C, respectively in 2008. However, the model showed a significant error in the simulation of water temperature near the thermocline zone where water temperature declines rapidly due to light extinction and penetration of turbid inflow in 2006. The errors might be associated with the uncertainty of inflow temperature that was estimated with weather data, and some influencing parameters affecting the reservoir thermal structure including wind sheltering coefficient (WSC). The WSC, which is multiplied by wind speed to reduce the effect of wind considering the surrounding terrain and vegetation, can significantly affect the thermocline depth and water temperature profile during the stratification period, and accelerated vertical mixing during the turnover period.

3.2. Validation of the model for nutrient and algal simulations

The comparisons of observed and simulated time series of total nitrogen (T-N), total phosphorus (T-P), and Chlorophyll-a (Chl-a) concentrations at the surface layer of water quality monitoring stations are presented in Figs. 5–7. The AME and RMSE of T-N concentrations were placed within the range of 0.364–0.598 and 0.477–0.872 mg/L in 2006 and within the range of 0.193–0.347 and 0.259–0.384 mg/L, respectively in 2008. Meanwhile, the AME and RMSE of T-P concentrations were placed within the range of 0.013–0.027 and 0.018–0.030 mg/L in 2006 and within the range of 0.007–0.012 and 0.008–0.013 mg/L, respectively in 2008. The simulation results reasonably agree with the temporal variations of T-N and T-P at all monitoring stations both in 2006 and 2008, although some deviations were noticed for T-P after August of 2006. The overestimation of T-P in the reservoir maybe attributed to the missing of the

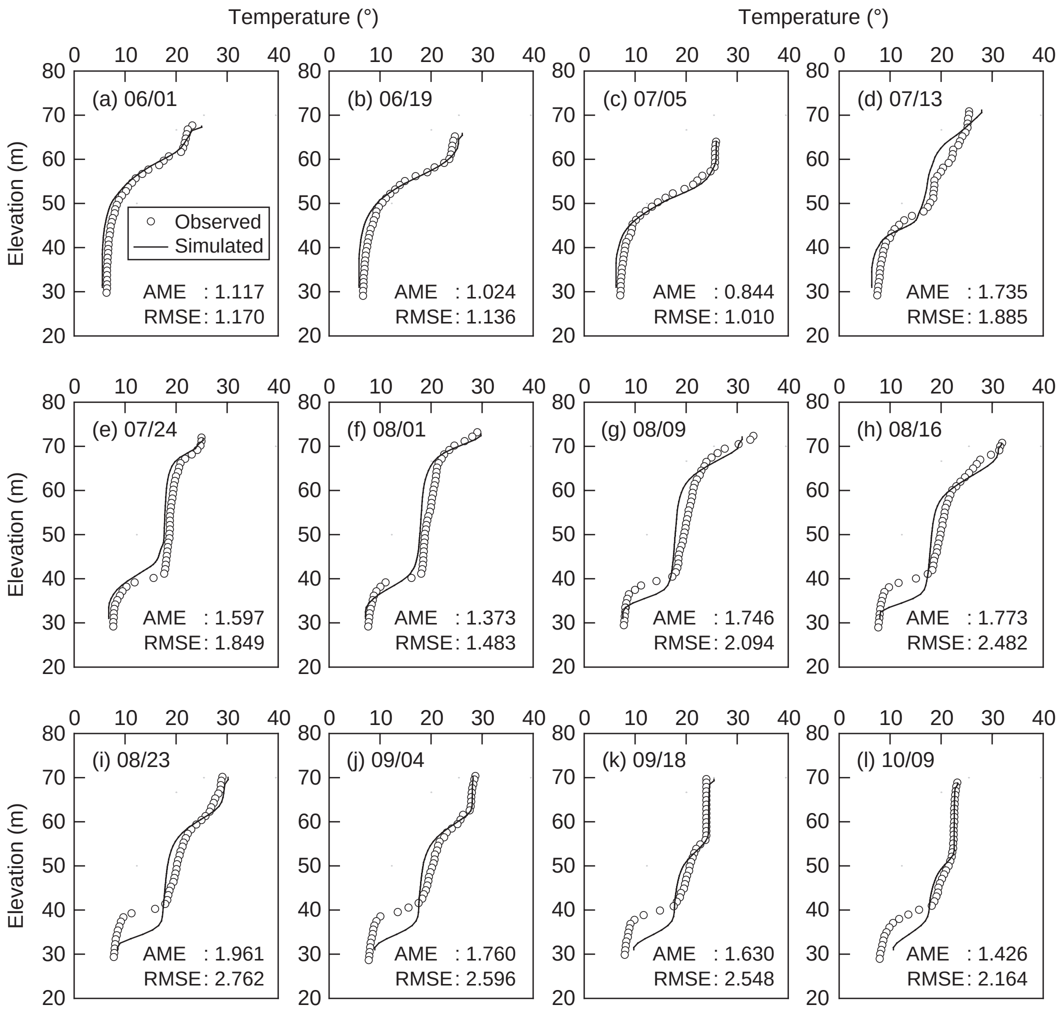

Fig. 3. Comparison of observed and simulated profiles of water temperature at R4 in 2006.

adsorption processes of inorganic phosphorus with iron, manganese, and suspended solids, which can be important processes that reduce the inorganic phosphorus concentration during turn over period.

The AME and RMSE for Chl-a simulation were placed within the range of 0.004–0.011 and 0.005–0.024 mg/L in 2006 and within the range of 0.004–0.006 and 0.005–0.009 mg/L, respectively in 2008. The simulated Chl-a concentrations were also well consistent with the measured data both spatially and temporally in the reservoir as shown in Fig. 7. Both the observed and simulated results showed higher algal concentrations in the transitional zone (R1 and R2) of the reservoir where more nutrients are available. Meanwhile, one large flood event occurred in 2006 transported nutrients and algae that were built at upstream of the reservoir to the downstream euphotic zone, and resulted in increase of algal biomass at all stations.

3.3. Effect of curtain weir

The performance of curtain weir on the control of algal bloom was assessed by applying the validated model to the hydrological years of 2001 and 2006 for nine different scenarios as presented in Fig. 1(a) and Table 1. 2001 is selected because it is the year when an abnormal mono-specific bloom of the *Microcystis aeruginosa* had developed in the reservoir. The time series of Chl-a concentrations simulated in the top layer of the reservoir at sites of R3, R4, A1 and A2 for all scenarios are compared in Fig. 8. The results showed that the proposed weir can be very an effective method to control algal blooming by curtailing the transport of algae and nutrients from riverine zone to lacustrine zone in the reservoir. Spatially, the effect of curtain weir on the control of algal growth was found to be more significant at R3 and A1 compared to R4 and A2. It is because that the pollutant loading

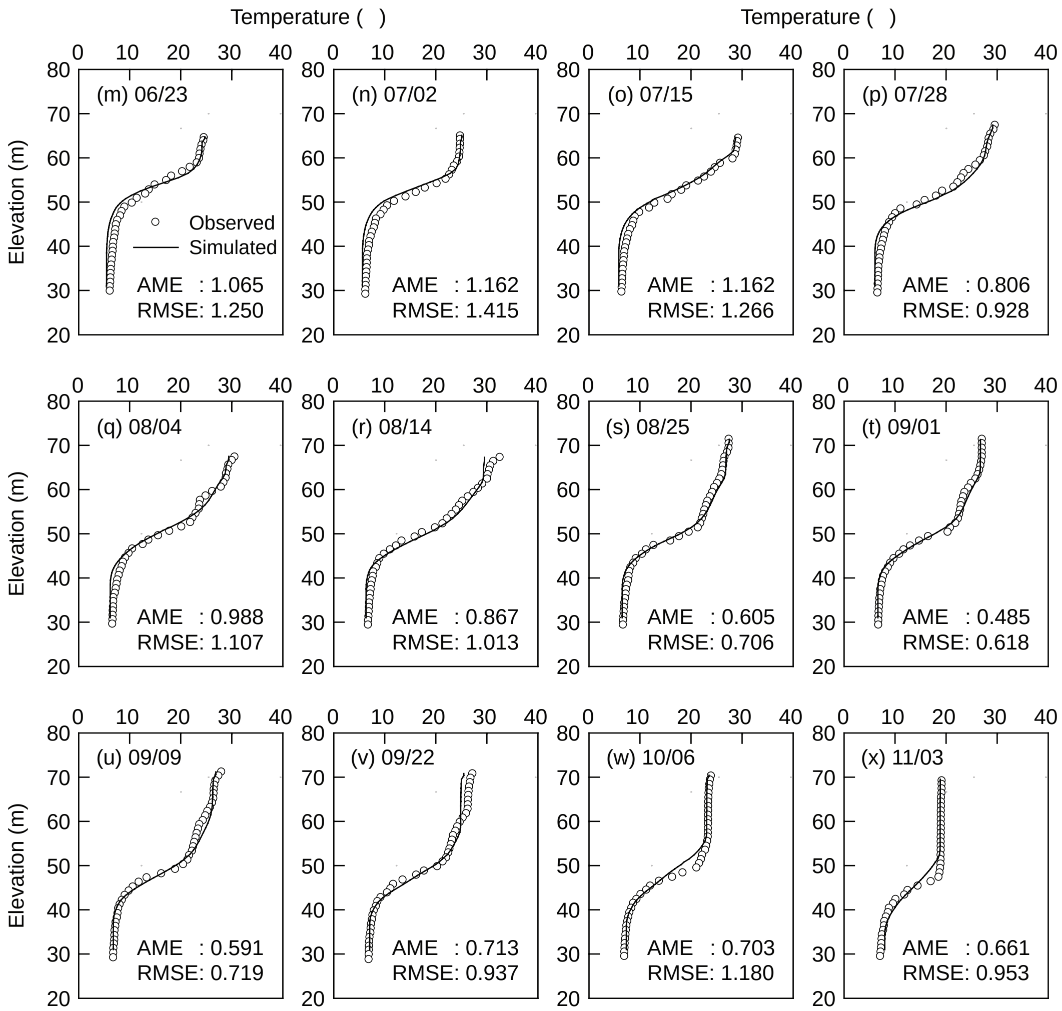

Fig. 4. Comparison of observed and simulated profiles of water temperature at R4 in 2008.

from inflow affects R3 and A1 sites directly due to hydrodynamic and geomorphologic features of the reservoir. It is also noteworthy that the performance of curtain weir was effective until September but became marginal from October when the autumn vertical mixing and turn-over starts. However, it may be not a great concern for selecting curtain weir as a solution for the reservoir water quality management because algal biomass naturally declines from that time because of temperature limitation.

The effectiveness of curtain weir to reduce the algal concentrations in the reservoir was quantitatively examined using the normalized reduction rate of Chl-a concentration (R_e), defined as Eq. (1), for nine different scenarios and two hydrological years in Table 4.

$$R_e = (C_{nw} - C_w)/C_{nw} * 100 \quad (1)$$

where C_{nw} and C_w are mean Chl-a concentrations without weir and with weir in top layer, respectively.

The results indicate that the performance of curtain weir varies for different locations and different hydrological years. The values of reduction rate R_e were placed in the range of 11.2–40.3% and 20.3–56.7% for the drought year (2001) and normal year (2006), respectively. However, it should be addressed that there was only one flood event on July in 2006. According to the previous study [2], frequent flood events may reduce the performance of the curtain weir by transporting nutrients and algae built at upstream of the weir into the downstream euphotic zone through entrainment process.

For the control of algal blooming occurred during the drought year, the optimal location of the weir can be one of S-6, S-7, and S-8 scenarios. Meanwhile, for the normal year (2006), S-9 showed slightly higher efficiency at R4 and A1 than other scenarios. Overall, the curtain weir showed a higher efficiency when it was installed further downstream of the reservoir.

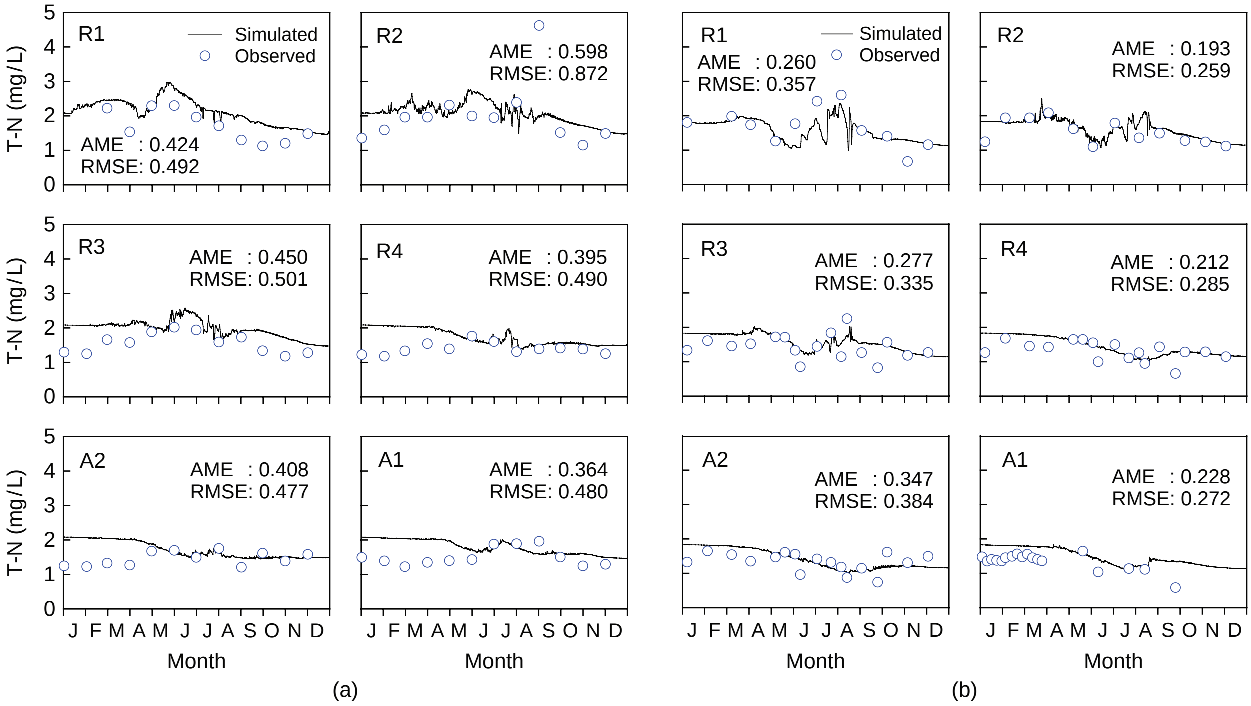

Fig. 5. Observed and simulated T-N concentrations at the surface layer in 2006 (a) and 2008 (b).

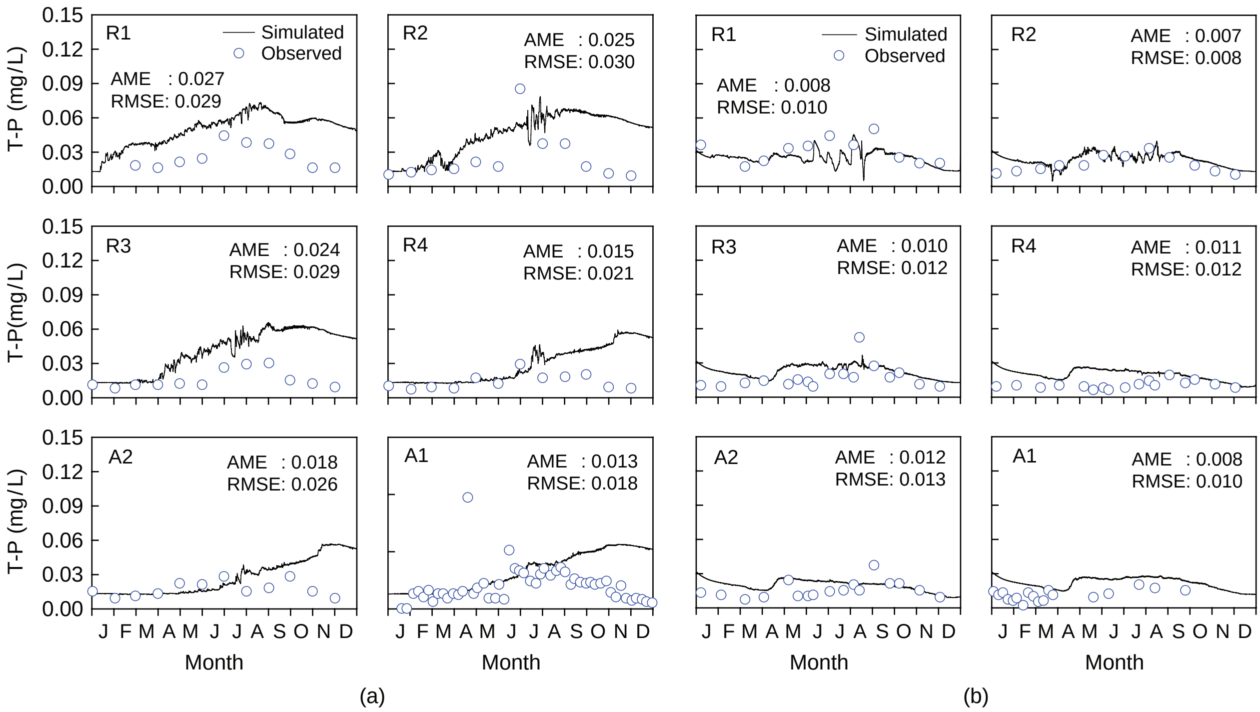

Fig. 6. Observed and simulated T-P concentrations at the surface layer in 2006 (a) and 2008 (b).

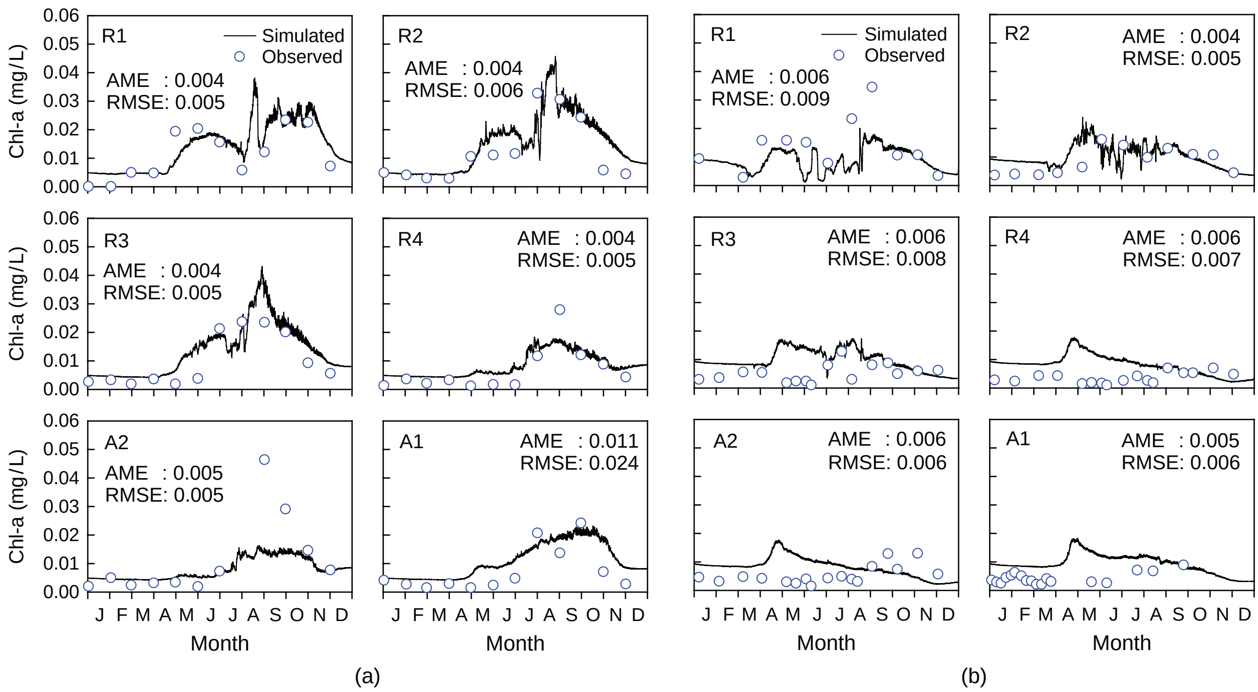

Fig. 7. Observed and simulated Chl-a concentrations at the surface layer in 2006 (a) and 2008 (b).

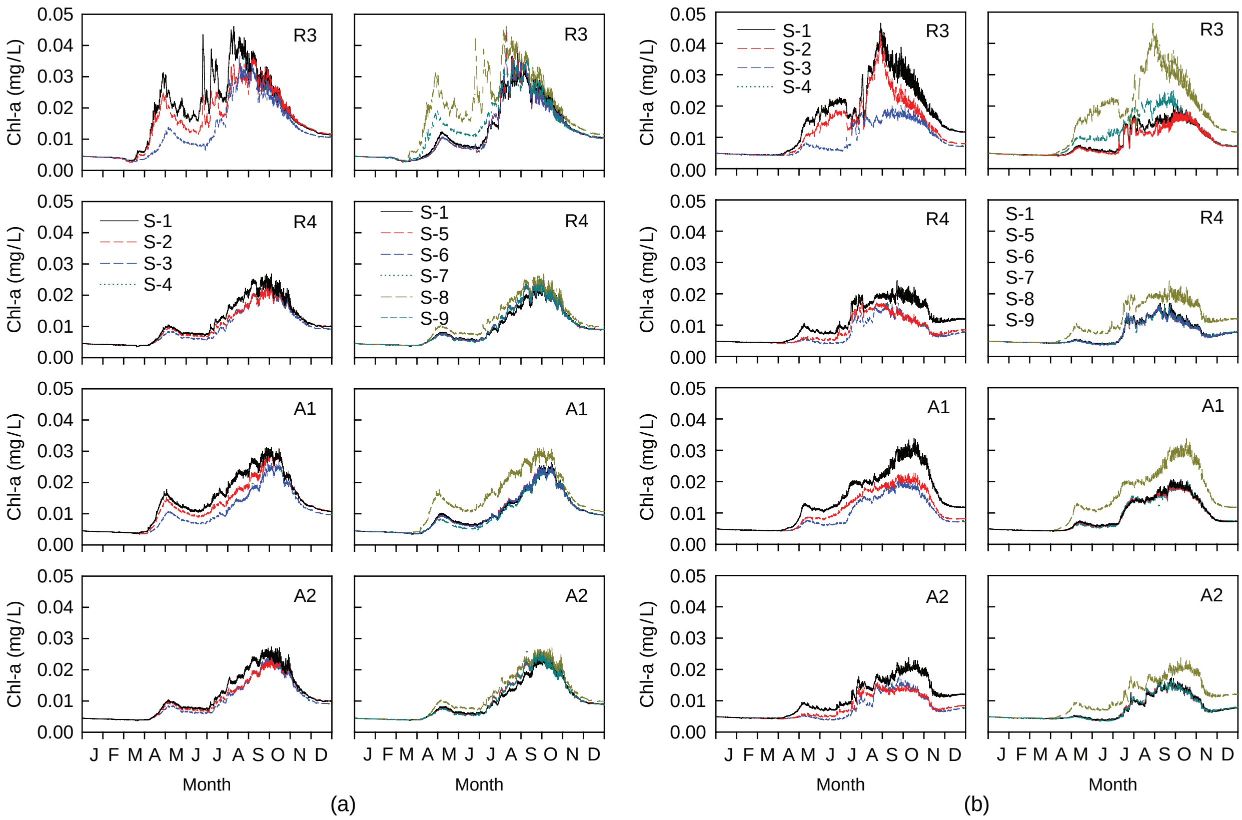

Fig. 8. Simulated time series of Chl-a concentrations for 9 different installation scenarios in years 2001 (a) and 2006 (b).

Table 4
Reduction rate of Chl-a concentration at R3, R4, A1 and A2 stations for the scenarios of curtain weir installation in 2001 and 2006 (May–October) Unit: %.

Stations/scenarios		S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9
	R3	16.8	33.0	32.9	35.6	**36.8**	**36.8**	24.6	–
2001	R4	11.4	18.5	16.9	**20.1**	17.7	17.7	19.8	16.8
	A1	13.7	31.0	30.3	34.0	34.9	34.9	**40.3**	39.9
	A2	11.2	17.4	15.5	18.8	15.6	15.6	17.6	14.0
	R3	20.3	49.6	49.0	52.9	**56.7**	**56.7**	36.4	–
2006	R4	26.6	36.6	36.0	38.6	40.6	40.6	41.4	**42.4**
	A1	24.4	37.8	37.4	39.5	41.1	41.1	42.1	**43.7**
	A2	27.3	34.8	34.4	36.5	37.0	37.0	**37.6**	37.5

4. Conclusions

Eutrophication and a periodic occurrence of cyanobacteria blooming during summer has been the most concerned problem for water quality management and water supply of Daecheong Reservoir. The effectiveness and optimal location of a vertically moveable curtain weir were assessed in this study as a cost-effective and ecologically sound control measure to deal with the negative impact of algal blooming on the reservoir. A modified CE-QUAL-W2 model to accommodate vertical displacement of the weir according to the water surface fluctuation was used to simulate the reservoir water quality variables and the effect of curtain weir. The model was validated for different hydrological conditions representing drought year (2008) and normal year (2006) for the study.

The model adequately reproduced the temporal and spatial variations of temperature, nutrients and phytoplankton concentrations in the reservoir. The performance of curtain weir on the control of algal bloom was assessed by applying the validated model to 2001 when an atypical mono-specific bloom of the *Microcystis aeruginosa* had developed and 2006 with nine different installation scenarios. The reduction rates of algal concentration (Re) at four monitoring stations for all scenarios were placed in the range of 11.2–40.3% and 20.3–56.7% for 2001 and 2006, respectively. The performance of curtain weir was varied for different locations and different hydrological years. The performance in limiting algal growth by the curtain weir was improved as the weir was located further downstream.

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