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Application of CE-QUAL-W2 Model to Eutrophication Simulation in Daecheong Reservoir Stratified by Turbidity Storms

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ABSTRACT

This paper aims to understand the effect of a turbidity flow intrusion on the eutrophication in Daecheong Dam Reservoir. CE-QUAL-W2, two-dimensional hydrodynamic and water quality model, is applied. The elevation of the reservoir water surface is used to validate the hydrodynamic model parameters and maximum fluctuations in water surface elevations reache about 1 m in the reservoir. Stratification is well reproduced with the correct predictions of the depths in terms of not only the thermo cline but also turbidity cline. Although complete mixing dominates in cold winter season, from May to June, the thickness of the thermo cline becomes the maximum state and transient layer reaches to about 40 m below the surface. By entering into the heavy storm season, July, the thermo cline submerged in deeper lower than 30 m below and the thickness of it is also reduced down to 10 to 15 m. While average TSS in June, an entrance of monsoon is still low but it reaches to peak in July with heavy rainfall. Vertical profiles of TSS regime in July indicates higher concentration in upper water layers and then the regime moves gradually downward in accordance with lapse of time. By the dam spillway opening, high concentration of TSS attributed to storm turbidity ascends to the upper water layer by following the upward current movement and then, the regime precipitates to the layer below 30 to 40 m after September. Model validation for water quality constituents shows good consistency with observed data for last 5 years. The effect of passive operation of discharge gates on the dynamics of TP spatially as well as temporally in the reservoir is also well depicted by model. In spite of comparatively small rainfall accompanied with low concentration of TP, high concentration of TP for entire depth in June appears apparently after monsoon period due to taking nonintervention against the turbidity regime in 2005. And then it sustains the higher TP concentration in the water column after monsoon. And the average TP after monsoon season in 2005 is higher than it in 2003 in which active gate control was established and shorten the duration time of the turbidity regime stagnation in the reservoir.

Keywords: CE-QUAL-W2, reservoir, validation, stratification, turbidity, eutrophication, gate control

INTRODUCTION

Eutrophication has been one of the major water quality problems in lakes and reservoirs in many parts of the world. High phytoplankton biomass levels in a reservoir primarily result from point and nonpoint nutrient loads to the reservoirs. An overabundance of algae biomass may cause water quality problems such as diurnal oxygen variation, oxygen depletion in the bottom waters, taste and odor in water supply, filter clogging in water treatment plants, and affecting water-contact sports and recreation. Phytoplankton dynamics are influenced by mass transport, exogenous environmental factors, and interactive biochemical kinetics (James 2002; Hartnett and Nash, 2004; Beck, 2005). The spatial and temporal variations of water quality constituents in lakes and reservoirs are also influenced by the complex mass transport and biochemical kinetics in the water column. Mass transport includes advection and dispersion. Advection transport represents the bulk movement of water and dispersion is caused by the velocity gradients and turbulent mixing in the water column. The circulation of water (or hydrodynamics) in lakes and reservoirs is driven by the combined influence of wind stress, current, topography, density distribution, inflow, and outflow. The biochemical or physical kinetics is composed of settling, interactive reactions with other constituents, light effect, and other physicochemical processes. Because the water movement and mixing processes is closely related to biochemical kinetics in the water column, the ability to couple multidimensional hydrodynamic and mass transport simulations with algorithms to predict constituent kinetics may be critical to many water quality modeling studies. With improved understanding of the eutrophication processes and hydrodynamics as well as more advanced computing capability, multidimensional lake and reservoir hydrodynamic and water quality models have been developed and applied to study water quality problems (Lung, 2001; Leon et al., 2003; Liu et al., 2005; Pastres and Ciavatta, 2005: Ha et al., 2005). The purpose of this study is to understand the effect of a turbidity flow intrusion on the eutrophication in Daecheong Dam Reservoir. CE-QUAL-W2 model is applied to quantify the mass transport, density stratification, and water quality variations in the reservoir.

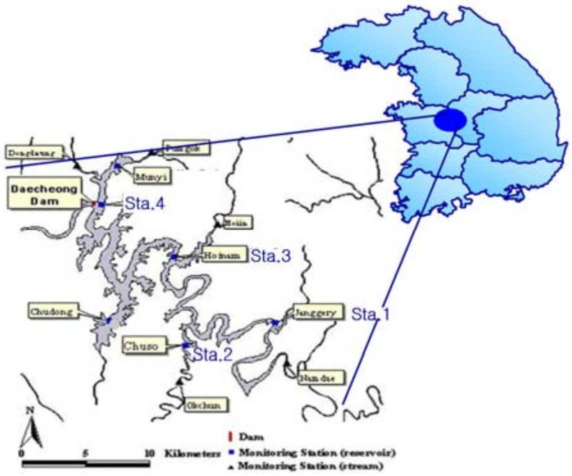


Figure 1. Study area of Daecheong Dam Reservoir and its watershed with major tributaries

Study Area and Field Data Collection

Figure 1 shows that Daecheong Reservoir in South Korea is selected in this study. It locates in the upstream part of the Kum River. The reservoir had been constructed as a multi-purpose high dam reservoir on the Kum River in 1980 and has a total watershed area of 4,166sq.km with effective storage area of 72 sq.km. It is being operated by the Korea Water Resources Corporation for hydro-power generation and water supplying. There are five major tributaries in the river. The reservoir backwater is roughly 86sq.km long and the water depth at the dam can reach 78m under normal operating conditions. In addition, the land cover of the reservoir watershed consists mainly as 70% of mountain forest, about 20% of agricultural cultivation land including paddy and upland crops and small towns with urban facilities and rural villages. Table 1 is a summary of the details of the reservoir.

Table1. Summary of Daecheong Reservoir characteristics

Item	Value	Item	Value
Watershed area(□)	3,204	mean depth(m)	20
Water surface area(□)	72.8	Annual inflow(10^6□)	2,451
Annual mean precipitation(□)	1,230	Mean residence time(day)	180
Total storage(10^6□)	1,490	Flood water level(EL.m)	80.0
Effective storage(10^6□)	790	Normal water level(EL.m)	76.5

Collection of Water Quality Data of the Reservoir

Figure 2 shows the chronically varied water quality variation in the study reservoir for five years from 2001 to 2005. We selected four locations as a calibration data collection sites, site 1 (upper reach of main reservoir branch), site 2 and 3 (confluences with two tributaries) and site 4 (dam location with discharge dam gates) as shown in Figure 1. Monitoring items are dissolved oxygen (DO), biochemical oxygen demand (BOD5), chemical oxygen demand (CODcr), total suspended solid (TSS), total phosphorus (TP), total nitrogen (TN) and pH. From the view stand of significant difference in terms of hydrologic and water quality, we selected two typical years, 2003 in which heavy precipitations with high turbidity storm inflows were recorded and very sensitive discharge gate operations was conducted and 2005 in which due to comparatively light precipitation, discharge gate operation was moderated. In the Figure 2, the data boxed with blue dashed line and red one-point dashed one indicate the data in 2003 and 2005, respectively. By comparing water quality variations in 2003 and 2005, it was clear that annual DO concentration in 2003 was higher than that in 2005.

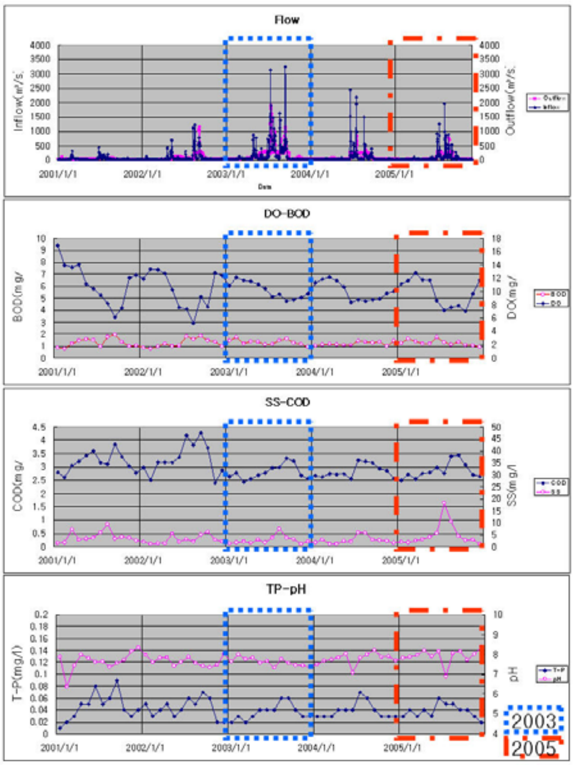


Figure 2. Watershed flows and water quality for Daecheong Reservoir

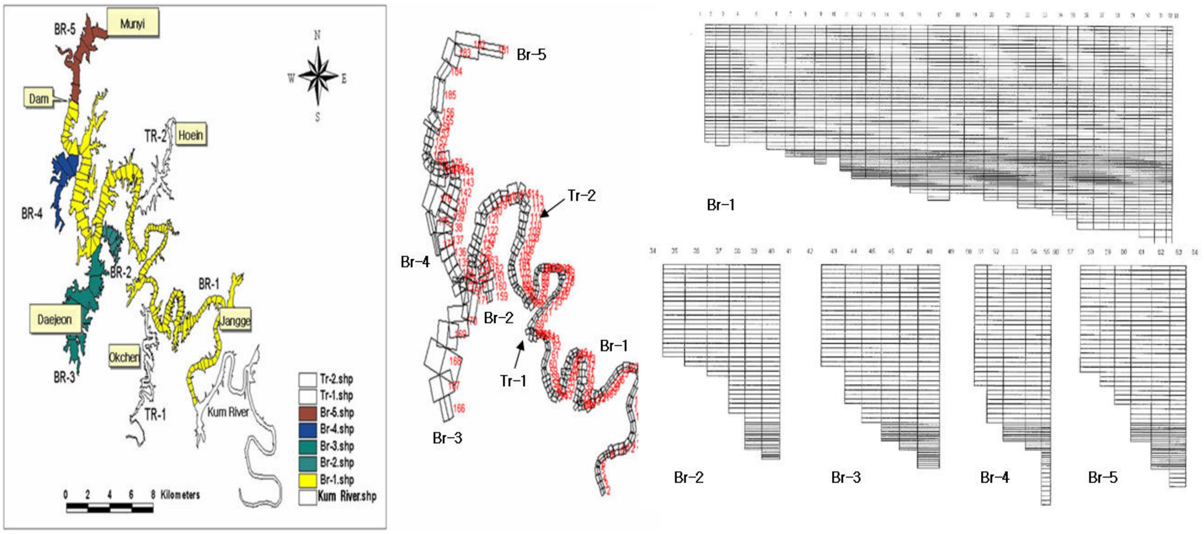
In the other hand, TSS concentration in 2003 was very low in spite of very heavy storm inflow with higher TSS concentration as a turbidity storm regime in that year. Reversely, in 2005 the concentration of TSS at the site 4 (Dam location) during storm season was very high even though precipitation and storm inflows in the 2005 was not strong. It could be convinced that low concentration of TSS as a turbidity indicator was attributed to a sensitive discharge gate operation responding to the inflowing of turbidity storm migration into the reservoir in 2005. In this paper, observed data for these two years, 2003 and 2005 were used to calibrate and verify the CE-QUAL-W2 model parameters.

Ce-Qual-W2 Model Description

CE-QUAL-W2 model that is a two-dimensional (longitudinal-vertical) hydrodynamic and water quality model and developed by U.S. Army Corps of Engineers' Waterways Experiment Station is used a computer simulator in this paper. Because the model assumes lateral homogeneity, it is particularly suited for water systems with little lateral variations of water quality constituents in long and narrow water bodies. The topography of the Daecheong Reservoir is especially suited for the model applications. The model uses a numerical scheme for a direct coupling between hydrodynamic and water quality simulations and also it uses the same step and spatial grid for concurrent hydrodynamic and water quality simulations. There have been many application examples of CE-QUAL-W2 to stratified water systems, including lakes, reservoirs, and estuarine environments in the world (Kurup et al., 2000; Kuo et al., 2003; Lung and Bai, 2003). In the model applications, the hydrodynamic runs provide real-time simulations of velocities, temperature, and a conservative tracer such as salinity prior to the water quality calculations. Its water quality module can simulate twenty one constituents ranging from a conservative tracer, suspended soils (SS), coli form bacteria, total dissolved solids (or salinity), labile and refractory dissolved organic matters (RDOM), algae, detritus, total phosphorus (TP), ammonia, nitrite/nitrate, DO, sediment, total inorganic carbon, alkalinity, pH, carbon dioxide, bicarbonate, carbonate, iron, and carbonaceous BOD (CBOD). Users have the option to select a subset of interrelated constituents in the simulation. A predominant feature of the model is its ability to compute the two-dimensional velocity field for narrow systems that stratify.

Segmentation of Control Water Body The Reservoir

Applying the CE-QUAL-W2 modeling framework requires that a reservoir water body should be segmented into a number of completely mixed water cells. An iterative process has been implemented to determine the proper segmentation of the reservoir based on the bottom bathymetry. In this paper, the reservoir is schematized to consist of five reservoir branches, which are one main reservoir water body, two subsidiary water bodies around water intake towers, and two more subsidiary water bodies, and three stream water bodies, which are one main upstream and two tributaries as shown in Figure 3 (a). And then, each reservoir water body is segmented along longitudinal direction as well as water depth direction. The main reservoir water body is divided to consist of 156 longitudinal segments at the surface with a length from 300m to 500m as shown in Figure 3(b). Each segment is then divided into 2-m layers in the water column as shown as Figure 3(c).



(a) (b) (c)

Figure 3. Segmentation of Daecheong Reservoir

Hydrodynamic Modeling

The hydrodynamic model is calibrated with the 2003 data. The comprehensive input data for CE-QUAL-W2 hydrodynamic modeling include reservoir topography, meteorological, inflow and outflow of reservoir, flow and temperature of stream information. The driving force of this model includes: (1) boundary conditions: time-variable main inflows and temperatures at main upstream and two tributaries, and (2) meteorological data: air temperature, dew point temperature, wind speed, wind direction, and percent of cloud cover. Stream flows from small tributaries are calculated based on their watershed areas. According to hydrodynamic model calibration analysis, the time-variable water surface elevation data are used to estimate the reservoir outflow through a water mass balance. Figure 4 shows a close match between the simulated and measured water surface elevations in the reservoir. The time series data of one year indicate that the water surface elevation decreases gradually and reaches the lowest in early summer months, then gradually raised and reached a peak in late summer and autumn periods of a typhoon and thunderstorms.

Result of Model Calibration and Verification

Water quality calibration is conducted with the field data obtained in 2003 year. Figure 6 presents the concentration of BOD, TN, TP, and Chl.a at four monitoring stations as indicated in Figure 1 and it consists of four groups of charts: the group at left top represents BOD calibration results and the one at right top is TN results. Another at left down and the one at right down show the results in terms of TP and Chl. a concentration, respectively. In addition, each group consists of three columns and four rows. In each group, very left column represents the averaged concentration of water quality constituents simulated in the surface water layers less than 15 m below the water surface. And the second left one is the averaged water quality in the middle water layers (between 15 m to 25 m of water depth) and the last one is the calculation for the bottom layers deeper than 25 m below. On the other hand, four rows of each group represent the water quality variation for a year at monitoring station 1, station 2, station 3 and station 4 in the order from top of the rows. The calibration of the model parameters has been done with the data in 2003. In the model verification, the

In the winter months, the water surface elevation remains relatively constant. Maximum fluctuations in water surface elevations reached about 1 m in the reservoir. Water temperature data are used to evaluate the hydrodynamic results from one-year model runs. Figure 5 shows the vertical profiles of simulated and measured temperature levels in the water column for period of 2003 in the reservoir. Note the model simulation results closely mimic the measured vertical temperature profiles and the seasonal variation of temperature in the water column. Stratification in the reservoir was also reproduced with the correct predictions of the depths in terms of not only the thermo cline but also turbidity cline in each year selected. The difference in water temperature between the upper layers and lower layers reached about 15℃, and the thermo cline penetrated from 10 to 20 m below the water surface in the reservoir. The fall overturn (by the end of October) in the Daecheong Reservoir is caused by surface cooling.

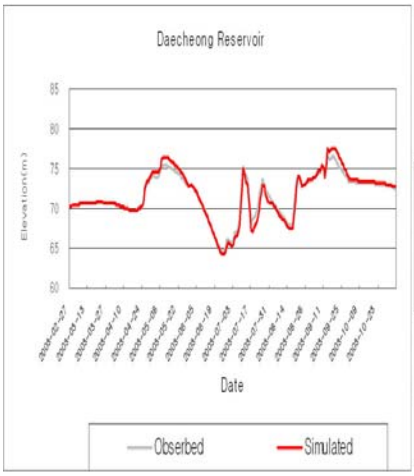


Figure 4 Water surface elevation of model calculated and observed

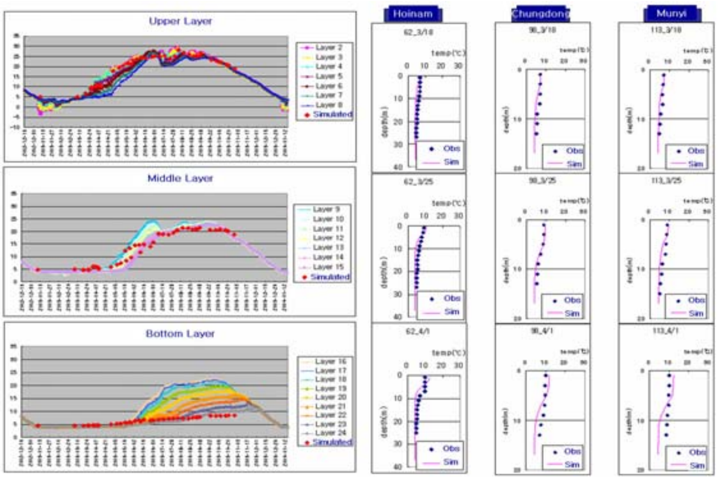


Figure 5 Vertical profiles of model calculated temperature and observed data

Table 2. Kinetic coefficients and values applied to the simulation of Daecheong Reservoir .

Parameters	abb.	value	parameters	abb.	value
Dissolved Organic Matter/ Labile DOM decay rate, 1/day	LDOMDK	1	OrganicMatter Stoichiometry/ Fraction C	ORGC	0.45
Dissolved Organic Matter /Labile to refractory decay rate, 1/day	RDOMDK	0.01	Organic Matter Stoichiometry /Fraction Si	ORGSI	0.18
Dissolved Organic Matter /Maximum refractory decay rate, 1/day	LRDDK	0	Organic Rate Multiplier /Lower temperature for Organic mater decay	OMT1	4
Particulate Organic Matter /Labile POM decay rate, 1/day	LPOMDK	0.08	Organic Rate Multiplier /Upper temperature for Organic mater decay	OMT2	25
Particulate Organic Matter /Labile to refractory decay rate, 1/day	RPOMDK	0.001	Organic Rate Multiplier /Fraction of Organic Mater decay rate at OMT1	OMK1	0.1
Particulate Organic Matter /Max. refractory decay rate, 1/day	LRPDK	0.001	Organic Rate Multiplier /Fraction of Organic Mater decay rate at OMT2	OMK2	0.99
Particulate Organic Matter /Settling rate, m/day	POMS	0.05	Carbonaceous BOD / 5 day decay rate at 20 deg C, 1/day	KBOD	0.05
Particulate Organic Matter /Fraction algae lost by mortality to POM	APOM	0.8	Carbonaceous BOD / Temperature coefficient	TBOD	1.01
Organic Matter Stoichiometry /Fraction P	ORGP	0.005	Carbonaceous BOD / Ratio of BOD5 to ultimate BOD	RBOD	3
Organic Matter Stoichiometry /Fraction N	ORGN	0.08			

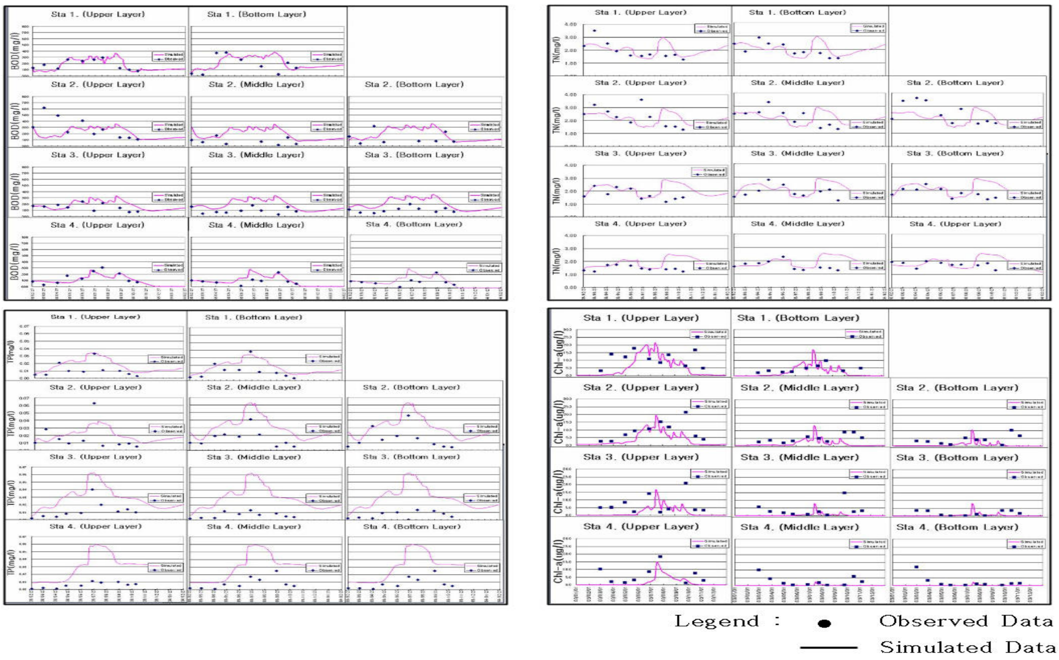


Figure 6. Model calculation result in terms of BOD, TN, TP and Chl.a concentrations during January to December in 2003

Water Quality Model Configuration

The boundary conditions for the water quality model include the dissolved oxygen, chlorophyll a (Chl.a), and nutrient concentrations at the upstream ends of the main stem of the river. In addition, concentrations of DO, chlorophyll a, and nutrients in the tributaries are also incorporated. Through numerous model runs, the calibrated kinetic coefficients and constants for the water quality simulation are determined and listed in Table 2. In general, they are consistent with literature values.

Model parameters calibrated have been run with the data collected in 2005. The water quality results compared with observed field data at the surface layer at Station 4 (at the Daecheong Dam Reservoir location) in 2005 are presented in Figure 7. The seasonal trend of temperature at Station 4 is well reproduced by the model. A summer chlorophyll a peak is calculated by the model, followed by a sharp decline in the rest of the year. Dissolved oxygen levels in the surface strongly depend on the water temperature. The seasonal variation of BOD, DO and T-N in the reservoir is well simulated and the results match those data well. But the seasonal variation of T-P and Chlorophyll.a is simulated with relatively poor match. Especially, Station 2 represents lower simulated data than the observed ones. It seems to be weak point about validation accuracy in this occasion. It is also clear that the concentration of TSS by a turbidity flow intrusion is well predicted and the staying time of it in the reservoir can be controllable by appropriate operation of the dam discharging gates installed at the Dam body for discharging of hydro-power generation as well as spill out the peak flood to protect the dam safety. These conclusions are delivered by comparing two selected runoff years, 2003 and 2005.

DISCUSSIONS

Figure 8 shows the simulated water temperature distributions in water depth for cold season (very left), spring and fall seasons (mid), and monsoon season (very right), respectively. In each figure, there are several groups of curves with same color. Each group indicates the temperature of the water column during same month so that each curve denotes the average thermo situation in a certain day. It can be read that complete mixing dominates in the water column during cold winter season. In transient period, surface water temperature is rising so that the development of thermo cline in the reservoir is observed clearly from the figure (mid). In particular from May to June, the thickness of the thermo cline becomes the maximum state and transient layer reaches to about 40 m below the surface. And by entering into the heavy storm season, July, the thermo cline submerged in deeper lower than 30 m below and the thickness of it is also reduced down to 10 to 15 m.

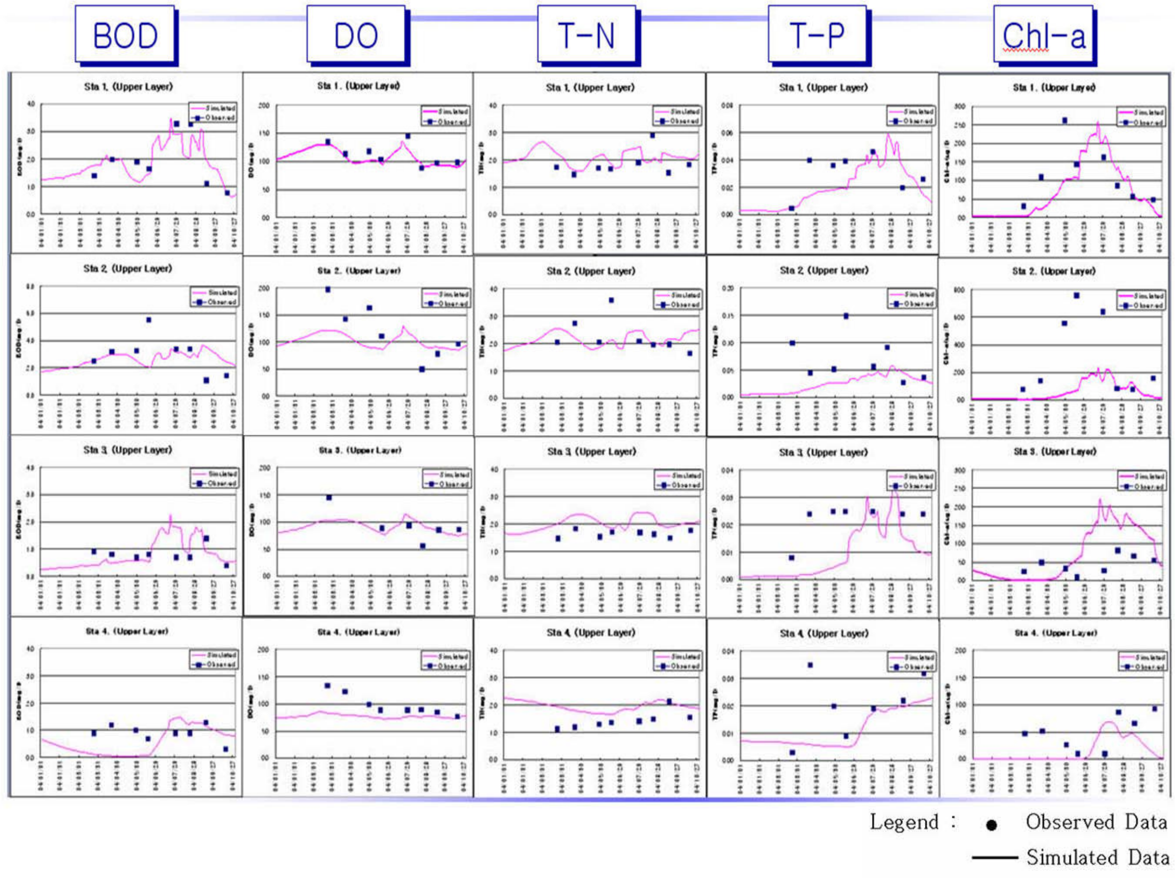


Figure 7. Model verification results in terms of BOD, DO, TN, TP and Chl.a concentrations during January to December in 2005

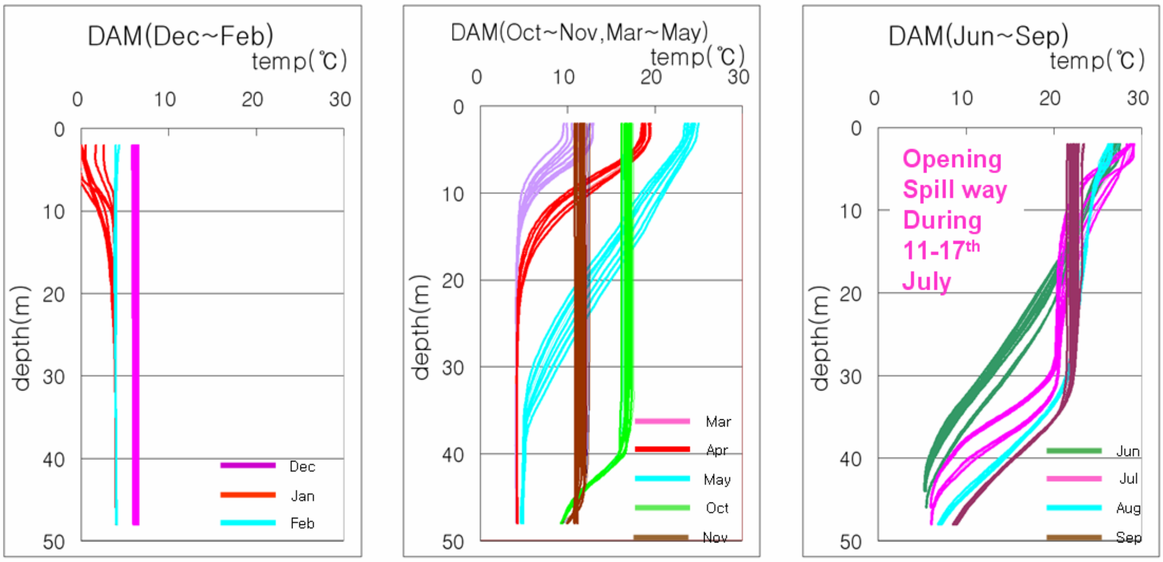


Figure 8. Development of thermo cline and stratification at Dam location in 2003

On the other hand, the effect of turbidity storm intrusion on the TSS concentration in the reservoir is depicted in Figure 9. Upper figures show the seasonal change of TSS concentration distribution in water depth in 2003: very left one for monsoon period, mid for transient period, and very right side for cold season, respectively whereas lower ones represent the cases in 2005. In reality there are heavy storms with high concentration of turbidity substances in 2003. Dealing with the turbidity intrusion into the middle layer of water in the reservoir, the reservoir gate operator had actively manipulated the discharge gates including spillway and hydro-power generation. The purpose of the gate operation is to discharge of high turbidity regime from the reservoir as quick as possible for minimizing the quantity of turbidity substances accumulated or remained after storms. From the simulation results from either 2003 or 2005, it is clear that TSS concentration both before and after Monsoon period the reservoir is very low. As shown in Figure 9, the average concentration of TSS in June as an entrance of Monsoon is still low but it in July with heavy rainfall reaches to peak. And then the concentration turns to decrease and this trend is continued to next Monsoon in the reservoir studied. In particular, the vertical profiles of TSS in July indicates higher concentration in upper and middle water layers and then higher concentration regime moves gradually downward in accordance with lapse of time. For example, suspended particles that contributed to raise the concentration are submerged into deeper depth below 40 m after October in 2003. The temporally changing pattern of the vertical profile of TSS is similar regardless to the discharging gate operation difference in both 2003 and 2005. Another interesting point observed in the figure is that the dominant regime of turbidity at Dam location rises up to the surface water layer in 10 to 15 m from the middle layer in 20 to 25 m water depth by opening of spillway gate during 11 to 17th July in 2003. It means that active operation of spillway gates of the Dam reservoir drags the turbidity regime from the deeper depth to the surface water depth. It is explained that the turbidity regime ascended to the upper water layer by following the upward current movement occurred by the spillway opening as shown in the first figure at second row in Figure 10. And then the regime had been precipitated to the bottom layer below 30 to 40 m after September. Beside of the storm season, the stratification of turbidity regime in the reservoir is not found. On the other hand, as there is comparatively low intensity of rainfall precipitation as well as turbidity substance in 2005, the operational response taken by Dam gate operators is apparently passive. The storm regime with the highest TSS concentration of about 120 mg/l had stagnated in the vicinity of the discharge gate opening for hydro-power, 20 m below in 2005.

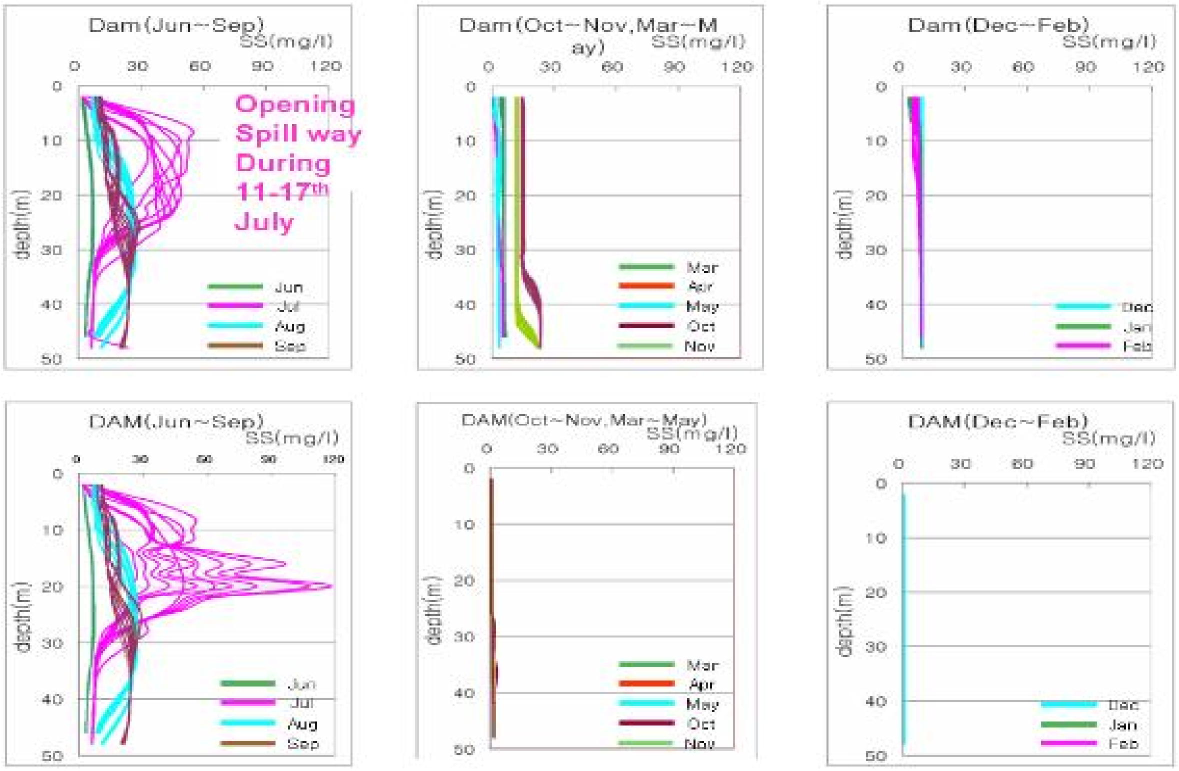


Figure 9. Impact of high turbidity flow intrusion on TSS concentration at Dam location on the basis of the model simulation results (Figures in upper and lower are for 2003 and 2005, respectively.)

Figure 10 is the result of model simulation in terms of TP as one of chemical indicators of the eutrophication of the reservoir water. Upper and lower ones represent the profiles of TP concentration for each month in 2003 and 2005, respectively. Before Monsoon, TP concentration is relatively low. The average TP concentration in August reaches to peak and then TP concentration turns to decrease. This trend is continued to next monsoon in the reservoir. Vertical profile of TP in August indicates the highest level in upper layers and then higher concentration regime moves gradually downward in accordance with lapse of time. Due to the simultaneous operation of the gates for hydro-power and spillway, in 2003, it is assumed that the dominant regime of TP in July is discharged from the reservoir by intensive opening of Gates. While in 2005, TP profiles are fluctuated and it reaches the peak in July. In contrast to the cases in 2003, the figures for 2005 placed lower in the Figure 10 indicate well the effect of passive operation of discharge gates on the dynamics of TP spatially as well as temporally in the reservoir. In spite of comparatively less rainfall accompanied with low TP concentration in 2005, higher TP concentration for entire depth of the reservoir is persistent after monsoon period due to taking nonintervention against the turbidity regime in 2005. It implies that the relatively short duration of turbid regime stagnation in the reservoir originated from the active gate control in 2003 whereas noninterference countermeasure in 2005. The effective measure to reduce the negative consequence of turbidity regime intrusion in the reservoir during Monsoon period is to operate the discharge gate of Dam appropriately. It should be paid an attention to open the spillway gate to discharge the turbidity regime because it may draw the upward flow movement and eventually result in the long term discharge of high turbid flows and higher TP from the reservoir.

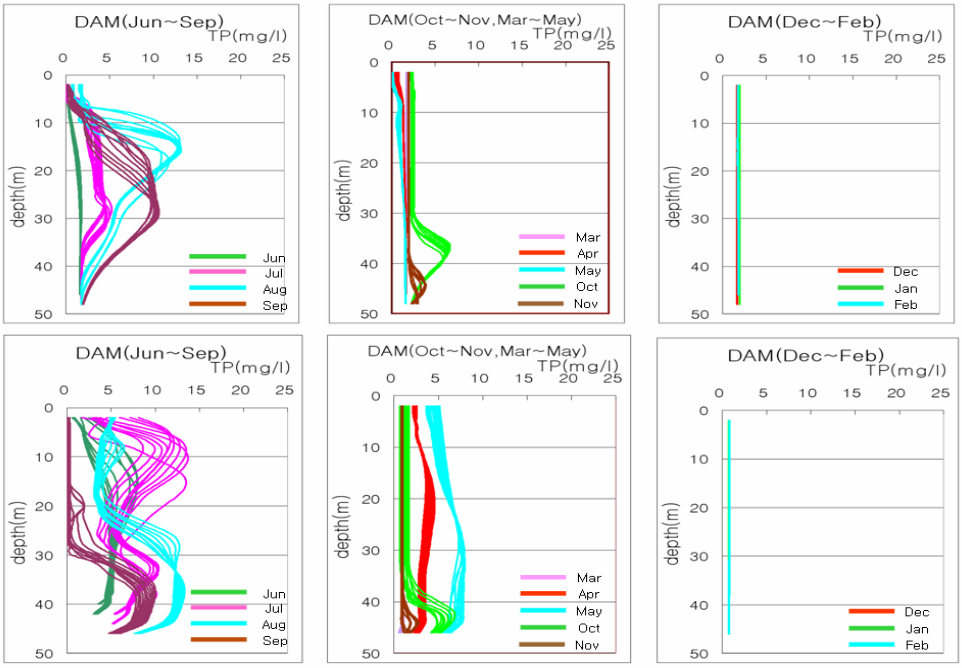


Figure 10. Impact of gate opening to discharge turbidity regimes on TP profile during Monsoon at Dam location (upper for 2003, Gate of spill ways as well as discharge gate for hydro-electricity generation are operated actively during this period whereas, lower for 2005, inactive operation of gate.)

Figure 11 is the spatial distributions of TP and Chl.a concentration averaged for eight days from 11-17th July in 2003 for which the discharge gates are opened actively whereas passive operation in 2005. It is possible to read the spatial distribution of TSS and TP in not only longitudinal direction but also vertical profile in the reservoir. Storms approach to the dam location from upstream of the reservoir. The dam with controllable discharge gates are located on very left side on the figure whereas branch of main reservoir comes from right side on the map of reservoir in Figure 11. Flowing direction is from right to left so that the destination of the storm with pollutants is the vicinity of the dam location and other bays. As previously mentioned there are two intake towers for drinking water, Munyi for Cheongju city area and Chudong for Daejeon metropolitan area in the reservoir as referred to Figure 1. As shown in Figure 1, two intake towers are located at bay areas and take water from surface layer of the bays. Therefore we are very concerned on the water quality change in these two water bays to maintain the quality of drinking water. In addition, the water quality of the water body in the vicinity of Dam impact on the down stream water quality after discharged from the reservoir. For instance, the high concentration of TSS during operation of gates at dam concentrates in the middle water layer between 12-24 m below the surface in both 2003 and 2005. It is attributed to the location of the discharge gate for hydro-power generation installed at about 20 to 25 m below water surface. During stagnation of high turbidity regime in the reservoir, not only TSS but also TP concentrations in the surface layer of the segments around two bays are relatively high as shown in Figure 11. In particular water quality of the surface layer in 2003 is affected by opening of spillway during the same period of this analysis as previously mentioned. In the case of nonintervention countermeasure established in 2005, major turbidity regime concentrated in the middle water layer and it skewed to the Munyi bay area following the current movement hydraulics in the dam reservoir. On the other hand, TP shows the concentration at the lower layer in 2005. It is also considered that it attributed to the gate control characteristics. From the figures in terms of chlorophyll a concentration, the movement of the Algae regime comes from upstream segment and it approaches to the bay segments discontinuously. In particular, by comparing two figures, it is possible to identify the effect of dam gates operation on the water quality distribution in the reservoir.

Figure 12 represents the spatial distribution of TSS and TP concentration in the reservoir after seven days by closing the gate operation during 11-17th July in 2003. It is clear that the turbidity regime including high concentration of TP concentrates in the middle layer during storm intrusion time and gradually precipitats to lower water layer after closing discharge gate operation. The nonintervention reaction against storm regime in 2005 results in the higher accumulation of TSS as well as TP constituents in the reservoir after monsoon period and it may make persistent effect on the nutrient balance of the reservoir ecosystem.

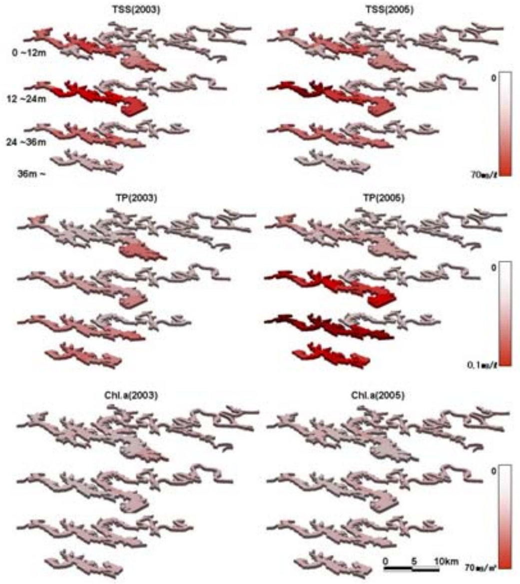


Figure 11. Spatial distribution of TP and Chl.a concentration averaged for eight days from 11-17th July in 2003 for which the discharge Gates are opened actively whereas passive operation is done in 2005.

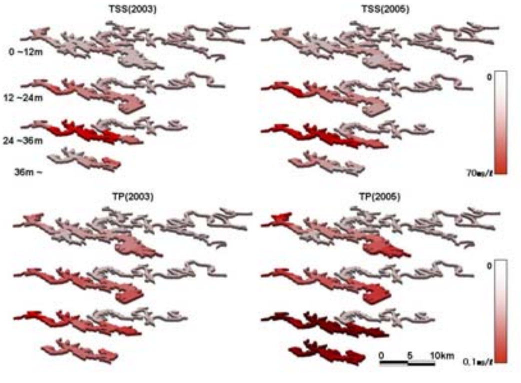


Figure 12. Effect of turbidity regime discharge on the spatial distribution of TSS and TP concentration in the reservoir after seven days from Gate opening date

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