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Application of three-dimensional hydrodynamics and water quality model of the Youngsan River, Korea

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ABSTRACT

There have been major changes in flow pattern in the Youngsan River due to construction in-stream structures including newly built Seungchon Weir and Juksan Weir in the middle of the river in addition to existing estuarine dam. Increased nutrient load from basin area has been a major cause of repetitive algal blooms in the river. And increased residence time due to the construction may affect growth dynamics of phytoplankton in the river. This paper reports the construction of a mathematical model to predict phytoplankton dynamics in the area for evaluation of various future management scenarios. The Environmental Fluid Dynamics Code model was chosen as a three-dimensional hydrodynamics and water quality model. Hydrodynamics model and water quality model were successfully calibrated using observed water level data and water quality data, respectively, in selected locations in the river. It is expected that the developed model can be successfully applied to select appropriate water quality management alternatives.

Keywords: The Youngsan River; EFDC; Chl-a; Algal bloom; Water quality modeling

1. Introduction

The four major river restoration project [1–3] that deepened the river depth by dredging and changed flow pattern by in-stream weirs was completed in 2012. There have been many different opinions and analysis for what has happened in the rivers including the Youngsan River. Water quality models are effective tools for the cause and effect analysis of various qualitative phenomena in water bodies [4–6]. Many water quality models [7–9] have been applied to surface waters in Korea but most of application had not included information on transport of water properly. [10] developed a comprehensive code to predict three-dimensional movement of water, dynamics of water quality, and sediment transport. Since the initial development, the Environmental Fluid Dynamics Code (EFDC) has been applied in many water bodies including freshwater systems. USEPA developed a special version of EFDC program [11] to support WASP water quality model [12]. Wool et al. [13] applied this approach in TMDL (total maximum daily loads) [14] analysis of the Neuse River, NC USA. Seo

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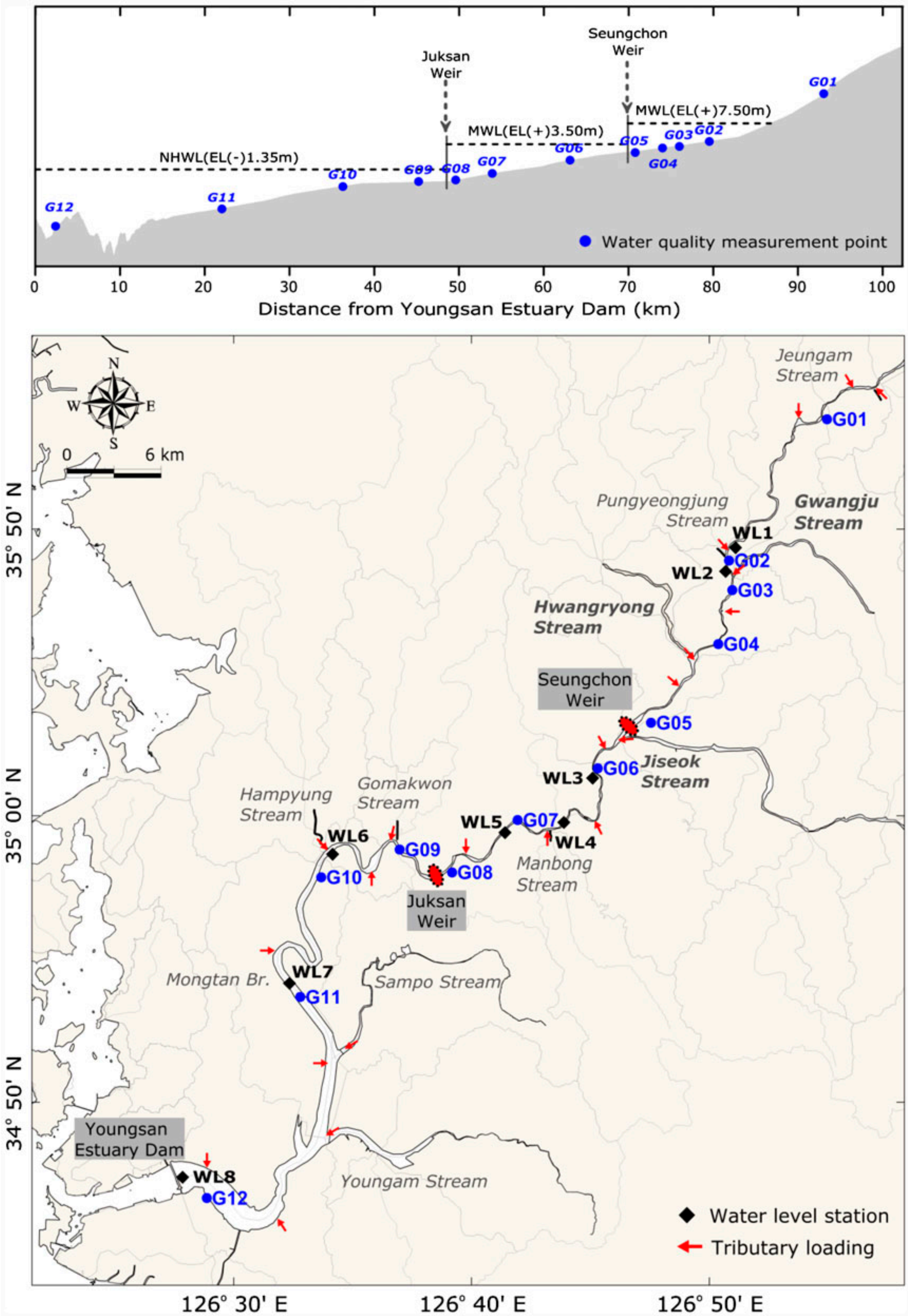

Fig. 1. Monitoring stations, tributaries, and important locations in the Youngsan River.

et al. [2] applied the same USEPA's approach to the Geum River for the first time in freshwater system in Korea. Seo et al. applied the same approach in the modeling of other surface waters in Korea [15,16]. On the other hand, Park et al. [17] applied the full EFDC model in the modeling of Kwangyang Bay in Korea.

During the four major river restoration project, two in-stream weirs were constructed and bottom areas were dredged to enlarge the storage capacity in the river. This study reports the development of water quality modeling system in the Youngsan River to evaluate the effect of the project and to assist in the development of future management options.

2. Materials and methods

2.1. Study area

The Youngsan River, Korea, is the fourth largest river in the country with basin area of 3,468 km^2 and length of 135.7 km. Fig. 1 shows locations of tributaries and important monitoring stations in the Youngsan

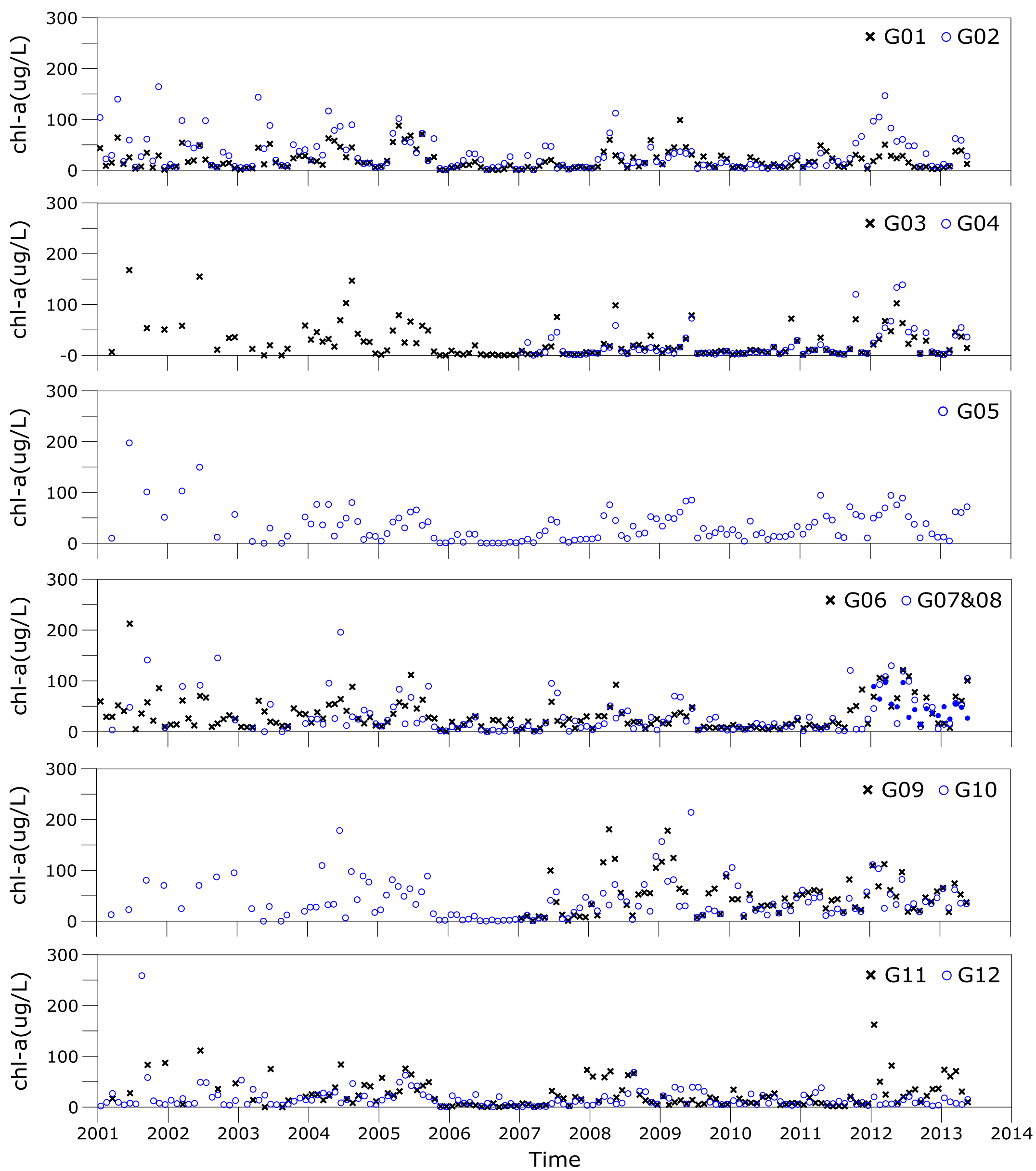

Fig. 2. Chl-a dynamics in the Youngsan River during 2001–2013.

River and the Youngsan Estuarine Lake. As shown in the figure, Juksan Weir and Seungchon Weir were constructed at locations 50 and 70 km away from the mouth of the river, respectively.

2.2. Chl-a dynamics in the study site during 2001–2013

Fig. 2 shows the time series of Chl-a data in the Youngsan River area [18] between 2000 and 2013. In general, Chl-a concentrations of greater than 0.1 mg/L are observed often in the entire river while higher Chl-a concentrations are observed during winter and spring. Song et al. [19] reported that diatoms are dominant in those cooler periods in the river. It seems there has not been sufficient nutrient removal before 2006. It is notable that Chl-a concentrations were higher until 2006 and another concentration peaks are found in 2008 and 2009. There had been less than 1,000 mm/year of precipitation in 2008 while average rainfall of the area ranges between 1,000 and 1,700 mm/year (www.wamis.go.kr). The four major restoration project began in 2009, and it was possible internal nutrient loading would have been increased in 2009. Therefore, excessive growth in 2008 and 2009 would have been caused by increased nutrient concentrations in the river due to less dilution water and more

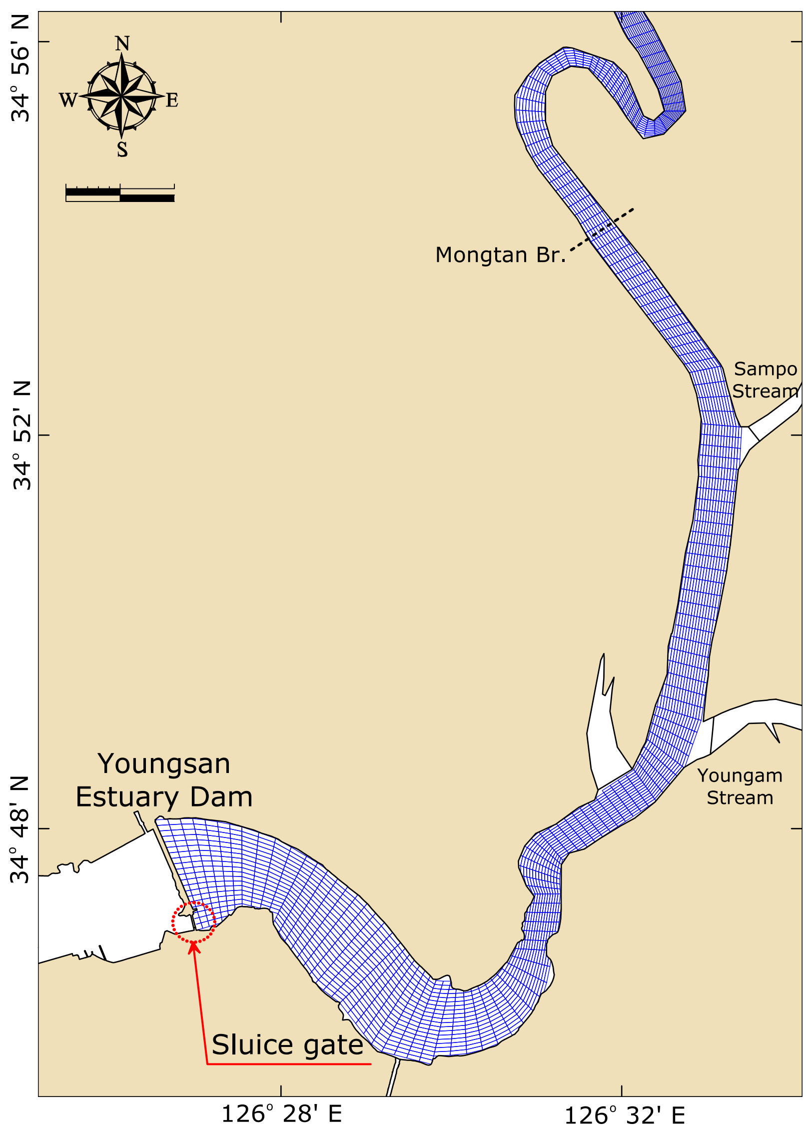

Fig. 3. Horizontal grid developed for the Youngsan River for this study (only downstream areas are shown in this figure).

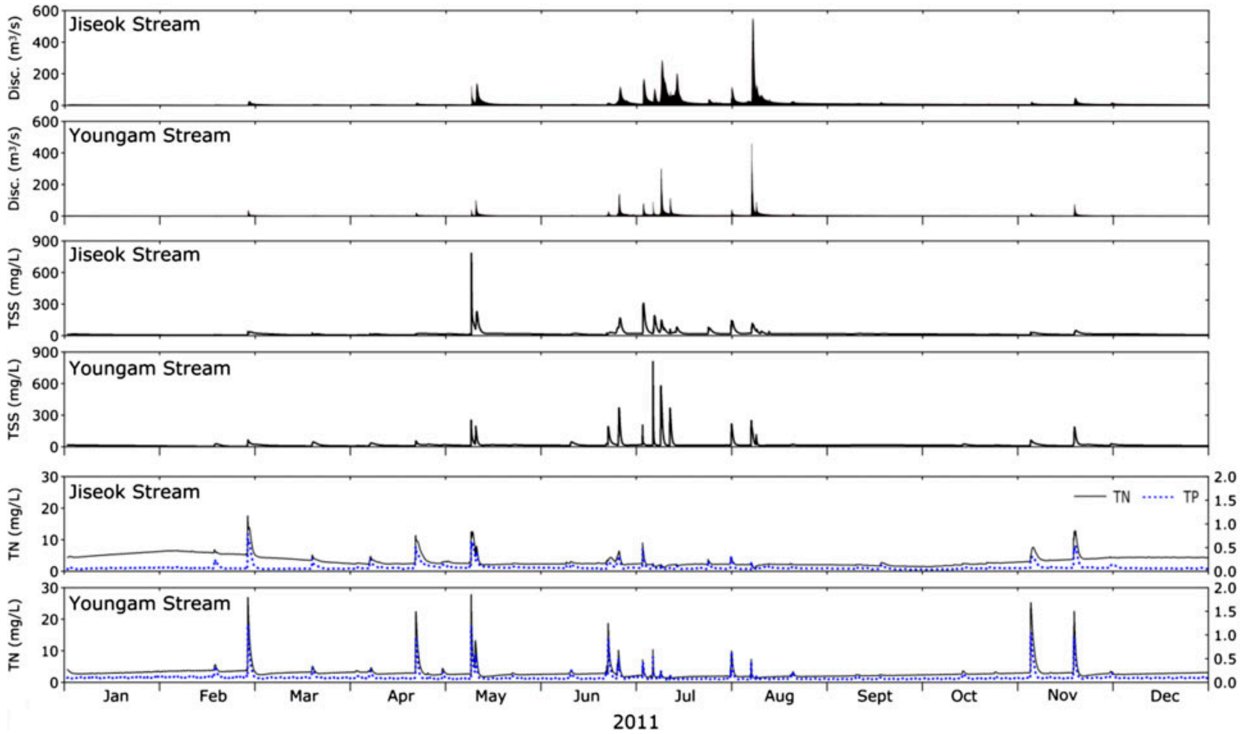

Fig. 4. Inflow and external loads from major tributaries of the Youngsan River generated from HSPF watershed model (only Jiseok stream and Youngam stream cases are shown here).

Table 1
Summary of kinetic coefficients employed in the present model application

Coefficient	Value
Maximum algal growth rate (d^{-1})	2.0, 2.23, 2.0[a]
Optimum temperature for algal growth (℃)	23–27.5, 12.0–13.0, 20.0–27.0[a]
Effect of temp. on algal growth below optimum temp. ($℃^{-2}$)	0.004, 0.004, 0.001[a]
Effect of temp. on algal growth above optimum temp. ($℃^{-2}$)	0.01, 0.1, 0.1[a]
Algal basal metabolism rate at 20℃ (d^{-1})	0.05, 0.03, 0.03[a]
Half-saturation constant for:	
Nitrogen uptake of algae (g N m^3)	0.05, 0.05, 0.05[a]
Phosphorus uptake of algae (g P m^3)	0.003, 0.005, 0.005[a]
Silica uptake of diatoms (g Si m^3)	0.1[a]
Algal predation rate at 20℃ (d^{-1})	0.1, 0.08, 0.1[a]
Algal settling rate (m d^{-1})	0.015, 0.06, 0.03[a]
Decay rate of:	
Organic carbon at 20℃ (d^{-1})	0.005, 0.075, 0.01[b]
Organic phosphorus at 20℃ (d^{-1})	0.005, 0.075, 0.1[b]
Organic nitrogen at 20℃ (d^{-1})	0.005, 0.075, 0.15[b]
Settling velocity of particulate organic matter (m d^{-1})	0.5
Maximum nitrification rate at 20℃ (g N m^3 d^{-1})	0.07
Dissolution rate of particulate silica at 20℃ (d^{-1})	0.03
Sediment oxygen demand (g O_2 m^2 d^{-1})	0.444
Benthic flux of:	
Ammonia (g N m^{-2} d^{-1})	0.0784
Nitrate (g N m^{-2} d^{-1})	0.0392
Phosphate (g P m^{-2} d^{-1})	0.0018

[a]For cyanobacteria, diatoms, and other algae, respectively.

[b]For refractory particulate, labile particulate, and dissolved organic matter, respectively.

internal nutrient loading, respectively. Excessive growth of phytoplankton is found again after 2012 after the four major river restoration project was completed. It seems increased hydraulic residence time may have been responsible for this. Water quality model can be used effectively to explain concentration dynamics in water systems.

2.3. Model development

The full EFDC [10] model was used to develop three-dimensional hydrodynamics and water quality model to analyze water quality dynamics in the study sites.

Varying orthogonal curvilinear grid sizes between 30 and 250 m were used for 101.7 km river area and total number of horizontal grid was 27,773 with 11 vertical layers. Wet and dry conditions were considered and 10 s of time step was used to satisfy CFL (Courant–Friedrichs–Lewy) condition [20]. Fig. 3 shows the developed grid for the study sites. Modeling period was chosen as one year in 2011. Initial conditions for water quality modeling were specified using the January observation data for stations as shown in Fig. 1.

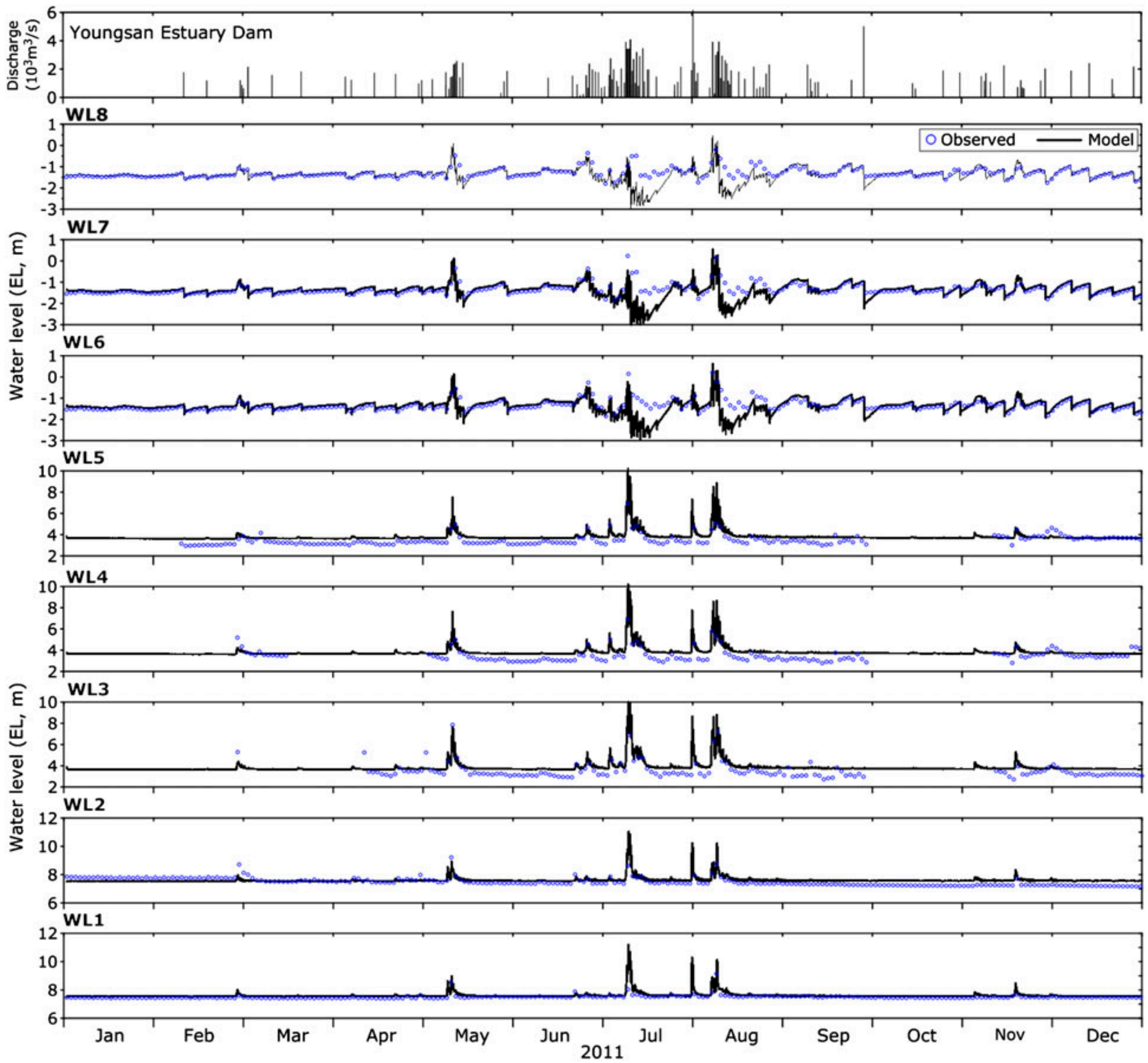

Fig. 5. Water level calibration results in selected locations (Fig. 1) of the Youngsan River.

2.4. Boundary conditions

Though there are number of tributaries flowing into the Youngsan River, only 20 tributaries have been regularly monitored by the Ministry of Environment, Korea. The entire watershed was dived into 20 sub watersheds and the HSPF [21] model was used to generate flow and dynamic external loads to the Youngsan River as shown in Fig. 4.

Although the EFDC model incorporates a sediment process model, it was not activated in the present application due to the relatively short modeling period and constant values for benthic nutrient release were used based on field measurements of this study as shown in Table 1.

3. Results

3.1. Hydrodynamic model calibration

Hydrodynamic calibrations were performed using water level and water temperature data of the Youngsan River. Fig. 5 shows the calibration results of water level of the selected stations along with discharge data from the Youngsan Estuarine Dam. Calibration results seem to reflect field measurement successfully.

3.2. Water quality model calibration

The water quality modeling results were calibrated using observed data collected from Korean governmental database [18]. Table 1 shows a summary of the kinetic coefficients employed in the present application. Figs. 6 and 7 compare the model results with the data of stations G09 and G12 for Chl-a, total nitrogen, nitrate plus nitrite nitrogen (NO_3), total suspended solid, total phosphorus, dissolved oxygen, dissolved phosphate (PO_4), total organic carbon, and water temperature. It seems the overall model calibration was successful. Previous monitoring studies reported that the growth of phytoplankton in the Youngsan River is limited by the availability of light [19,22] and increased depth due to the dredging of the area which may affect the growth of phytoplankton in the study area.

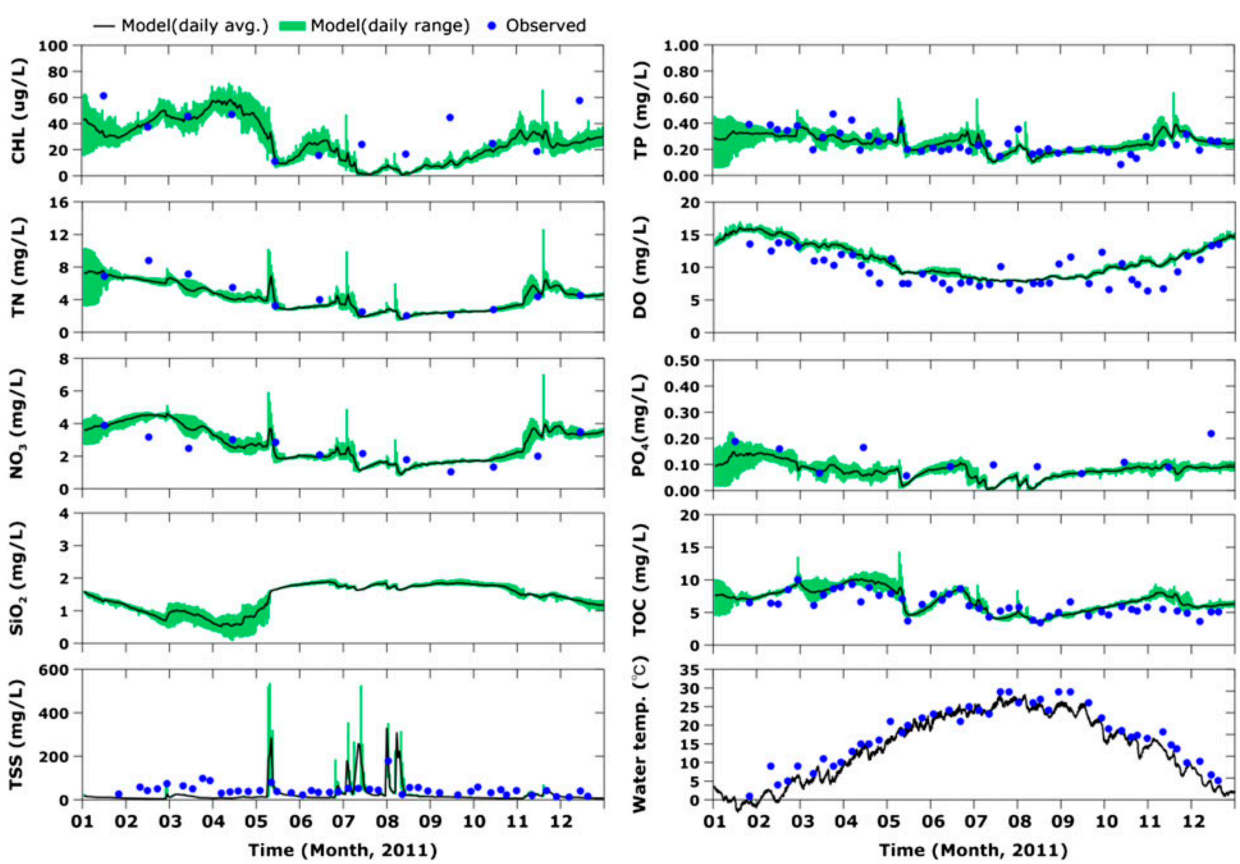

Fig. 6. Daily range and average model predictions of G09 station (Fig. 1).

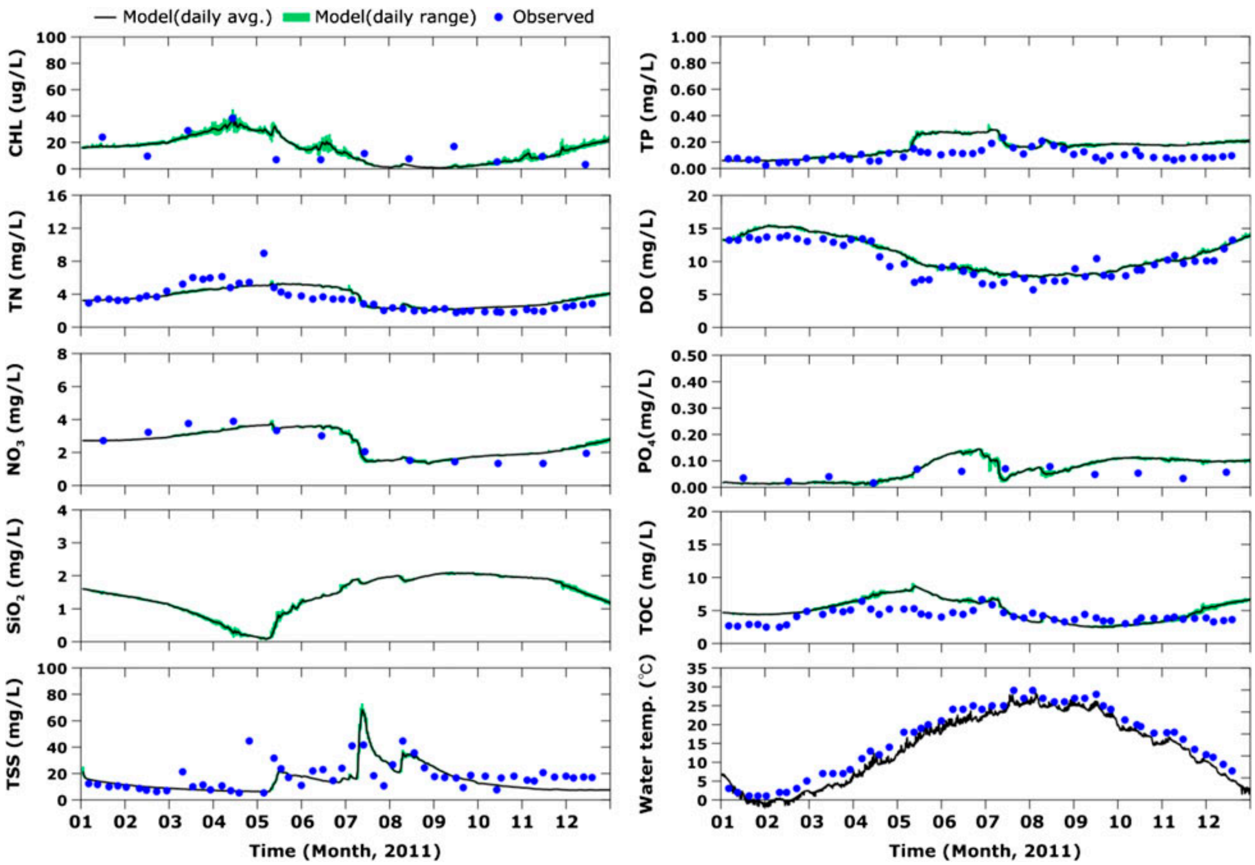

Fig. 7. Daily range and average model predictions of G12 station (Fig. 1).

4. Conclusions

Phytoplankton growth dynamics in the Youngsan River between 2001 and 2013 was analyzed. And it seems that appropriate water quality model is necessary to explain complex interactions among various factors that affect water quality dynamics especially for phytoplanktons. The EFDC model [23] was chosen as a three-dimensional hydrodynamic and water quality model in this study for this purpose. Approximately 0.3 million orthogonal curvilinear cells were developed including 11 vertical layers. Boundary conditions were developed using Korean governmental database system including the Ministry of Land and Transportation, K-water, the Korean Meteorological Agency, and the Ministry of Environment. Field measurements data were used for benthic nutrient releases.

Hydrodynamic calibration results were verified against field measurements in eight different stations along the Youngsan River. It seems model predictions successfully reflect field observations. Water quality model also was calibrated for various water quality variables in selected stations of the study site.

Excessive growth of phytoplankton pattern was found after the four major river restoration project though it had appeared in the past as well. Many methods have been suggested to enhance water quality in the river including source control from watershed areas and introduction of saline water from the sea. However, care must be taken before implementing major investment. It is expected that his model development will serve effectively to provide predictions for possible water quality management scenarios.

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