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Hydrodynamic and Water Quality Modeling for Gate Operation: A Case Study for the Seonakdong River Basin in Korea

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Abstract

The Seonakdong River is an impound stream whose flowrate is controlled by the Daejeo and Noksan gates. Therefore, constant natural flow of the Seonakdong River does not occur. In contrast, pollutant loadings occur constantly occurring as water flows into the river from the watershed. The Daejeo gate is located at the upstream head and the Noksan gate is at the downstream end of the Seonakdong River. The Seonakdong River is an estuarine tributary of the Nakdong River. It is a reservoir-like river used for agricultural irrigation, with the Noksan gate at the river mouth serving to prevent the intrusion of saline water. In this study, a steady-state model, QUAL2E, and an unsteady-state model, CE-QUAL-RIV1, were chosen for comparative simulations. The results of the simulations of river water quality changes were verified with respect to short-term variations of water quality due to the increasing water flow from the Daejeo gate and the discharging flow from the Noksan gate. Field measurements were performed to monitor the flowrate and water quality during the operation of the Daejeo and Noksan gates in the Seonakdong River. The general trend observed is that the water quality worsens after the opening of the gates. The reduction in water quality ranges from 3% to 38%. These results show that the gate operators should carefully select the most appropriate operating plan to obtain better water quality in the Seonakdong River. The numerical simulation shows that a discharge of 300 CMS, which is a peak inflow from the Daejeo water gate to the river, can make it possible to achieve the target water quality of the Seonakdong River if the Daejeo water gate can remain open in connection with the Noksan water gate operation.

Keywords: *Seonakdong River, reservoir-like river, gate operation, QUAL2E, CE-QUAL-RIV1*

1. Introduction

Regulated stream systems may include complicated physical features, such as multiple run-of-the-river dams, locks and dams, and regulated dams. In addition, highly unsteady flows may exist or may be expected, as in the planning for peak hydropower releases (USACE, 1995). Numerous water quality models exist, but most of them are developed for steady flow conditions and are not appropriate when time-varying flows are to be considered (Zhang and Tang, 2009). The Seonakdong River is an impound stream whose flowrate is controlled by the Daejeo and Noksan water gates. As a result, the flowrate of the Seonakdong River is not constant (Lee *et al*., 2007). The Daejeo gate is located at the upstream head of the Seonakdong River, and the Noksan gate is located at the downstream end. The Seonakdong River is an estuarine tributary of the Nakdong River. It is a reservoir-like river used for agricultural irrigation, with the Noksan gate at the river mouth serving to prevent the intrusion of saline. After the construction of the water gates, the water quality of the river became worse. This could have been due to the internal loading of pollutants, especially nutrients, from the sediments of the river due to the detention time being increased by the water gates. To resolve these problems and to improve the water quality of the Seonakdong River, it is necessary to control the flowrate and the velocity by optimizing the gate operations.

The mixing behavior of the inflow from the Daejeo gate and the variation of the water quality during the operation of the Daejeo and Noksan gates were investigated in this study. A representative steady-state water quality model, QUAL2E (Linfield and Barnwell, 1987; EPA, 1995), and unsteady-state water quality and hydrodynamic model, CE-QUAL-RIV1 (USACE, 1995) were compared in this study. For the same reaction coefficients and

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Fig. 1. Watershed of the Seonakdong River

boundary conditions, the water quality of the Seonakdong River was simulated using the two different models, and the governing equations for the water quality reactions were compared with each other. This study was focused on verifying the variations in the water quality associated with the increase in inflow from the Nakdong River to Seonakdong River. The objective of this study was to use numerical simulations to determine the flowrate required to improve the water quality of the Seonakdong River. Fig. 1 shows the watershed of the Seonakdong River and the four sites where field measurements were taken for this study.

2. Field Survey

Field measurements were obtained to monitor the flowrate and water quality during the operation of the Daejeo and Noksan gates in the Seonakdong River for a period of six months-from

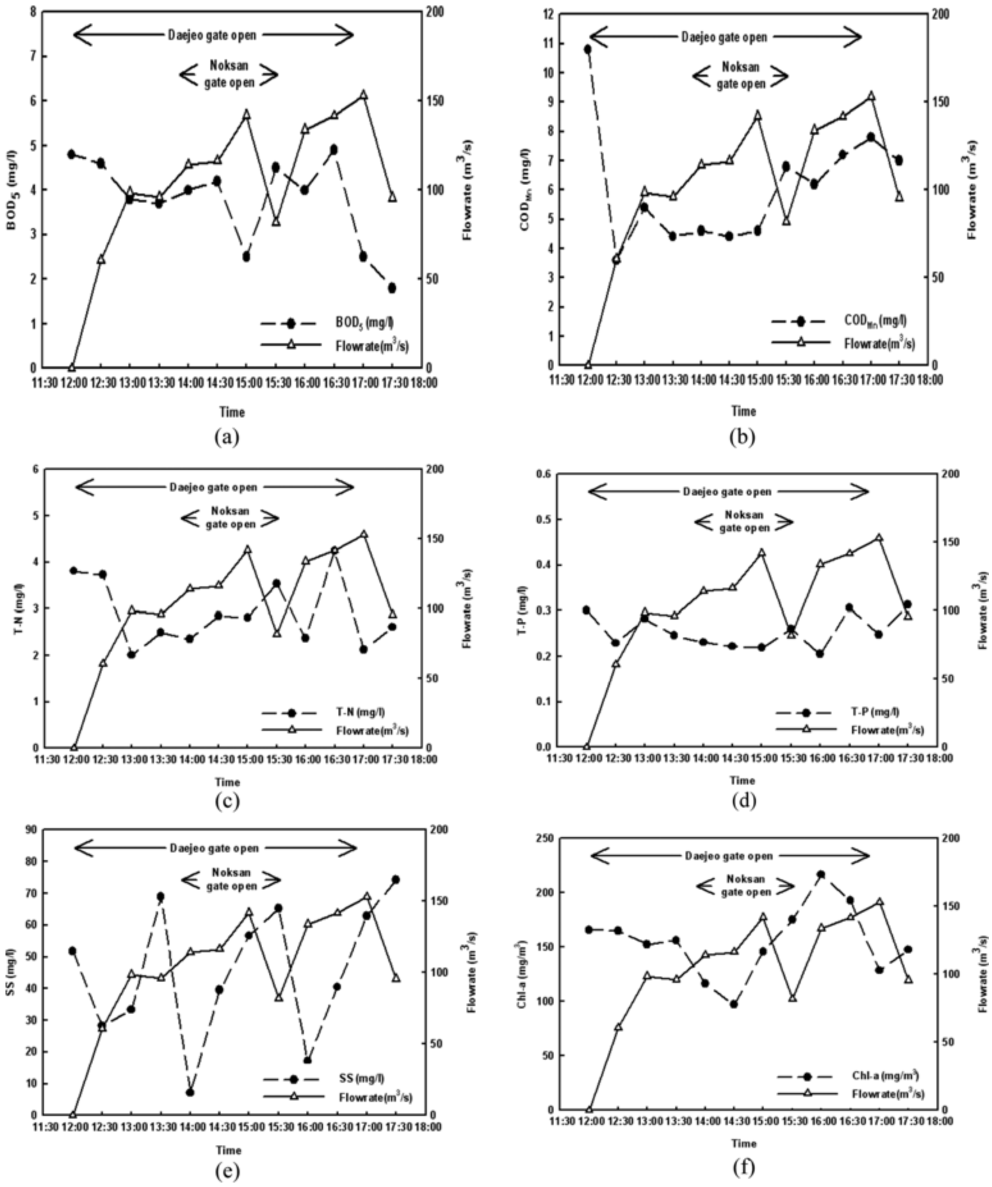

Fig. 2. Water Quality Change with Flowrate Increase: (a) BOD, (b) COD, (c) T-N, (d) T-P, (e) SS, (f) Chl-a

July to December 2006 (Kim *et al*., 2007). Fig. 1 shows the four measuring sites, which are located at the Daejeo gate (Site 1), the Gimhae bridge (Site 2), the Gangdong bridge (Site 3), and the Noksan gate (Site 4). The water quality was analyzed for nitrogen and phosphorous compounds, Suspended Solids (SS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and chlorophyll-a. Fig. 2 shows the changes in the BOD, COD, T-N, and T-P concentrations and the flowrate at the Gimhae Bridge (Site 2) due to the operation of Daejeo and Noksan gates in the Seonakdong River. After the opening of the gates, the BOD and COD values for the river tend to decrease. The patterns of the T-N and T-P concentrations are similar to those of the BOD. The average results of all measurements, which include five individual investigations, are listed in Table 1. A comparison between these results is unlikely to provide a good estimate because of T-P. This is most likely due to the effect of inadequate inflow from the Joman River, which is the largest tributary of the Seonakdong River. A wastewater treatment plant is located at the downstream of the Joman River, and because the Seonakdong River is generally stagnant unless the gates are opened, the effluents from the wastewater treatment plants usually settle down. When the gates are opened, the sediments from the Joman River are transported into the Seonakdong River. The general trend is that the water quality is reduced after the opening of the gates. The reduction ranges from 3% to 38%. These results suggest that the gate operators should carefully select the most appropriate operating plan, considering possible water shortages and available water resources. It is hoped that the results of this study will help the researchers who are interested in evaluation of uncertainties in water quality management. The field data can also be used to decide on the frequency and duration of gate opening. Monitoring schemes were developed in this study to achieve sufficient accuracy in unsteady-state water quality modeling.

Table 1. Variation in Water Contaminant Concentrations and Average Flowrate at Four Sites

Quality resources	Site	Before opening	After opening	Conc. Variation	Average flowrate (CMS)
BOD (mg/L)	Site 1	2.9	2.8	3%▼	126.9
	Site 2	4.0	3.5	13%▼	108.0
	Site 3	3.6	3.9	8%▲	110.0
	Site 4	4.2	2.6	38%▼	1635.5
COD (mg/l)	Site 1	4.8	4.9	2%▲	126.9
	Site 2	7.0	6.2	11%▼	108.0
	Site 3	6.8	5.8	15%▼	110.0
	Site 4	6.8	5.2	24%▼	1635.5
T-N (mg/L)	Site 1	3.4	3.5	3%▲	126.9
	Site 2	3.1	2.6	16%▼	108.0
	Site 3	2.5	2.8	12%▲	110.0
	Site 4	2.5	2.1	16%▼	1635.5
T-P (mg/L)	Site 1	0.182	0.179	2%▼	126.9
	Site 2	0.265	0.380	43%▲	108.0
	Site 3	0.214	0.255	19%▲	110.0
	Site 4	0.141	0.175	24%▲	1635.5

3. Model Setup

In the case of the unsteady-state water quality model (CE-QUAL-RIV1), the node that represents the channel, divided into 18 elements, is defined in the same manner as in the steady-state water quality model (QUAL2E). The four major tributaries of the Seonakdong River are treated as point sources in this study. Fig. 3 shows schematic diagrams of the computational elements for QUAL2E and CE-QUAL-RIV1. The boundary conditions of the downstream in the hydraulic module are considered on the basis of the monitoring data of the Noksan water gate. For the

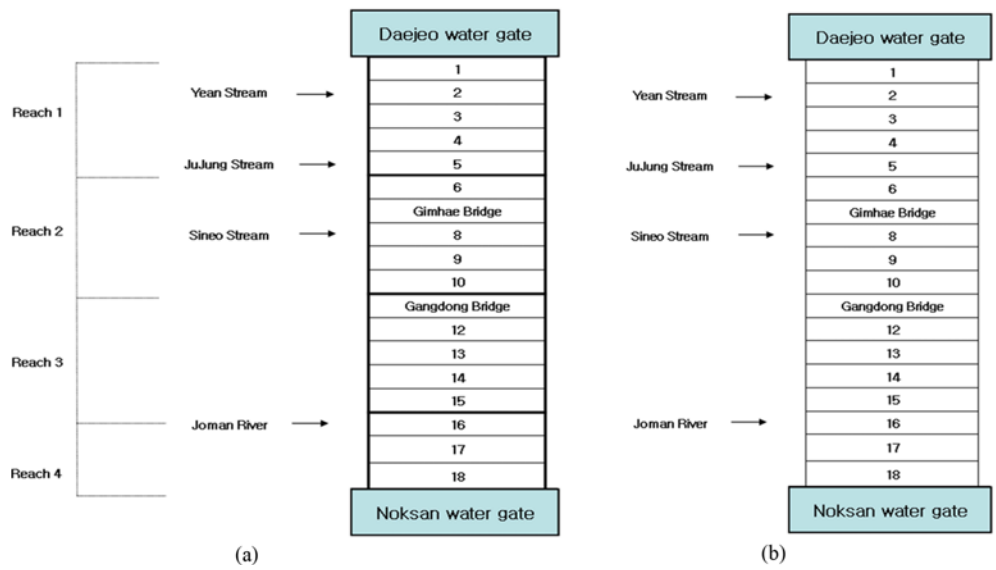

Fig. 3. Computational Elements for: (a) QUAL2E and (b) CE-QUAL-RIV1

Table 2. Water Quality Parameter Values used in QUAL2E and CE-QUAL-RIV1

Model	Parameters							
QUAL2E	K1	K3	K4/H	β3	σ4	β1	β4	σ5
RIV1	AK1	CBODSR/H	KSOD	ACK	KNSET/H	AKN	KPDK	KPSET
Value	0.08	-0.15	0.00	0.02	0.10	0.01	0.00	0.10

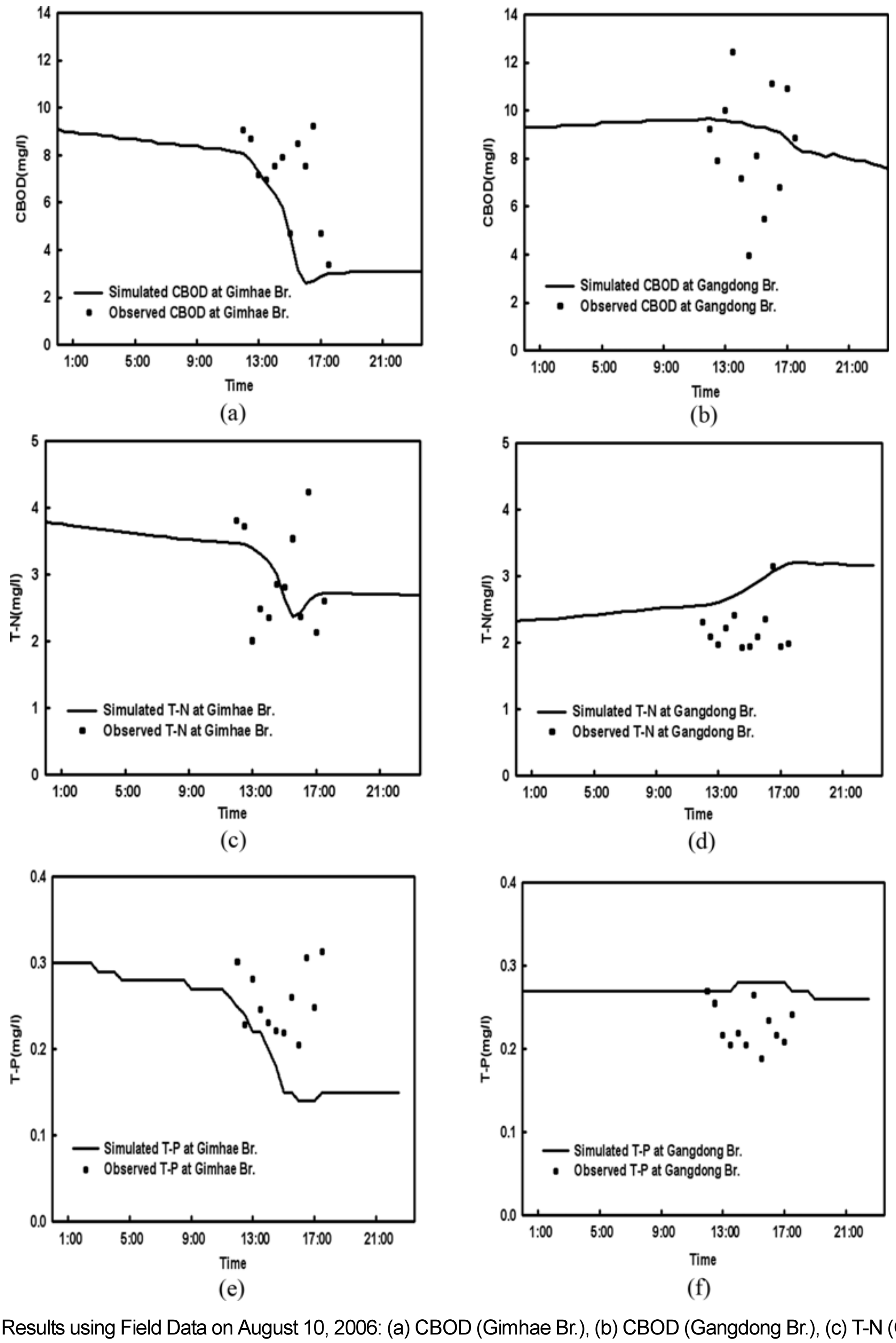

Fig. 4. Calibration Results using Field Data on August 10, 2006: (a) CBOD (Gimhae Br.), (b) CBOD (Gangdong Br.), (c) T-N (Gimhae Br.), (d) T-N (Gangdong Br.), (e) T-P (Gimhae Br.), (f) T-P (Gangdong Br.)

setup of QUAL2E, the hydraulic parameters were obtained from the results of the hydraulic simulations using HEC-RAS. The value of the water quality parameter for each model was entered in the same manner as in QUAL2E to compare the results of the water quality simulation from each model for the same conditions (Ko *et al*., 2005). The BOD reaction rate, K1; the sedimentation rate, K3; the sediment oxygen demand, K4; the organic N decay rate, β3; the organic N settling rate, σ4; the rate constant for the biological oxidation of NH_3 to NO_2, β1; the organic P decay rate, β4; and the organic P settling rate, σ5, are the parameters used to calibrate the QUAL2E model (Brown, 1986; Chapra, 1997). In the case of R1V1, the comparable parameters are AK1, CBODSR, KSOD, ACK, KNSET, AKN, KPDK, and KPSET. Table 2 shows the water quality parameter values for both

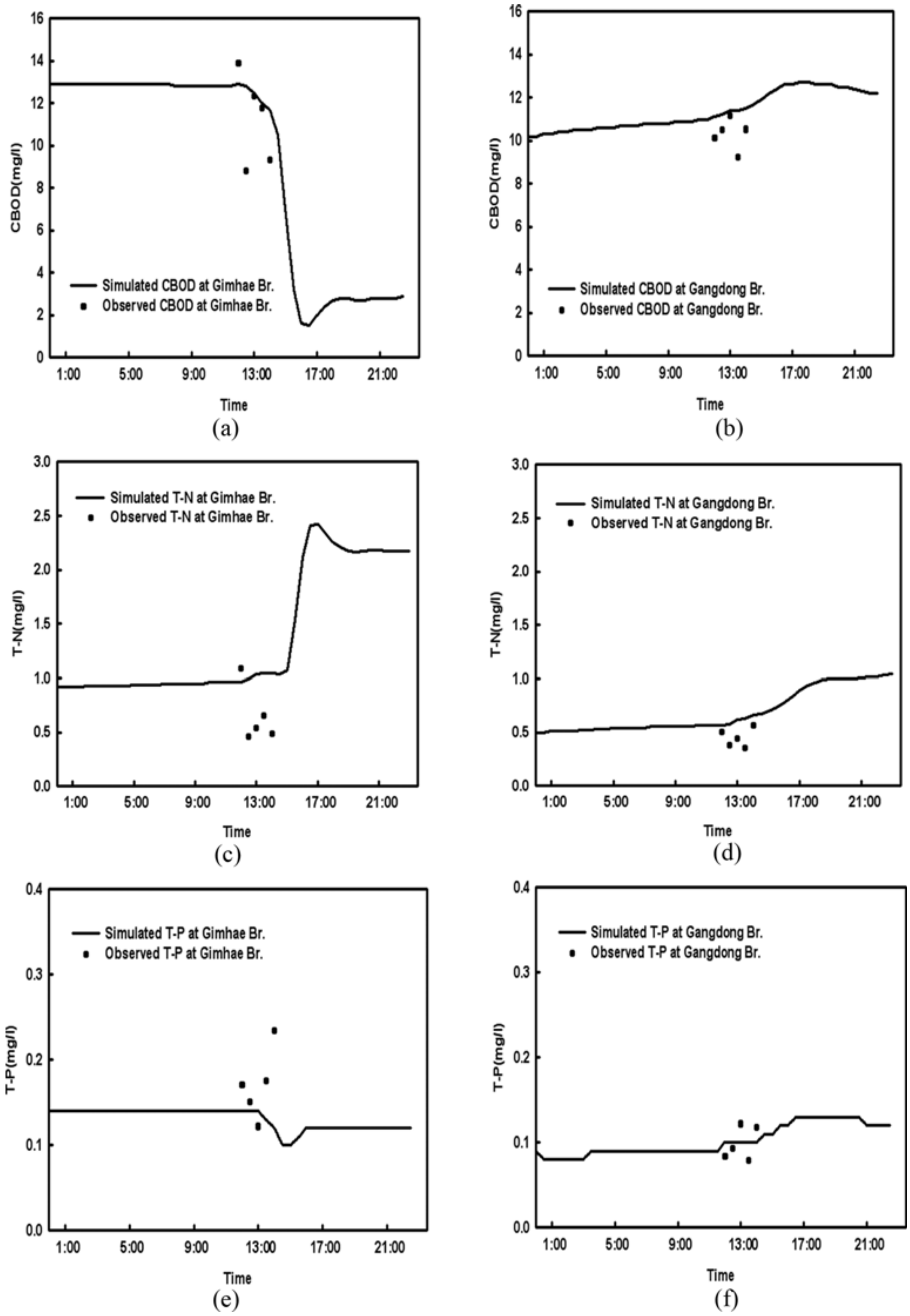

Fig. 5. Verification Results using Field Data on October 19, 2006: (a) CBOD (Gimhae Br.), (b) CBOD (Gangdong Br.), (c) T-N (Gimhae Br.), (d) T-N (Gangdong Br.), (e) T-P (Gimhae Br.), (f) T-P (Gangdong Br.)

models, which were used in this study, after the calibration processes, in the trial-and-error method.

This study used measurements on August 10 and October 19, 2006 in the water quality simulation. The standard flow of the Seonakdong River was set at an average of 5.0 CMS as the flow passes through the Daejeo water gate, which is computed for the Total Water Pollution Load Management Plan for the Nakdong River (Gimhae City, 2006). The hydraulic model HEC-RAS was constructed with 92 cross sections separated by a total length of 18.5 km from the Daejeo gate to the Noksan gate. In the QUAL2E simulation, the total length of the Seonakdong River was divided into four reaches with the same hydraulic parameters and the same water quality parameters by dividing the length into equal intervals of 1 km. In the CE-QUAL-RIV1 simulation, 18 nodes were constructed, without considering additional tributary nodes. The cross-sectional data can be entered after converting a natural river section into a quadrangle, trapezoid, triangle, or circle using the field survey data (USACE, 1990).

4. Results and Discussion

Field data were obtained during the period from July to December 2006 for use in calibration and verification of both the steady-state and unsteady-state models. To obtain stable simulation results from the unsteady-state model, a simulation of a period of 10 days was performed before water gate flushing discharge. Fig. 4 shows the results of the model calibration of CE-QUAL-RIV1 compared with the field data measured on August 10, 2006. As shown in Fig. 4, the field-measured CBOD increased rapidly during the early stages of water gate discharge. However, the numerical model was limited in simulating this instantaneous change. The rapid increase in CBOD seems to have been due to the resuspension of the sediment from the river bed (Chung, 2004). The T-P and T-N concentrations exhibited trends similar to that of CBOD. The model was also verified using the data measured on October 19, 2006. Fig. 5 shows the results of the model verification. The model simulated relatively well the variation in the water quality due to the gate operation in the Seonakdong River.

To compare the two models, QUAL2E and CE-QUAL-RIV1, for the same boundary conditions, the same parameters were used for the steady-state simulations. Fig. 6 shows the calibration and verification results for QUAL2E. For steady-state simulations, the calibration of the water quality parameters was performed

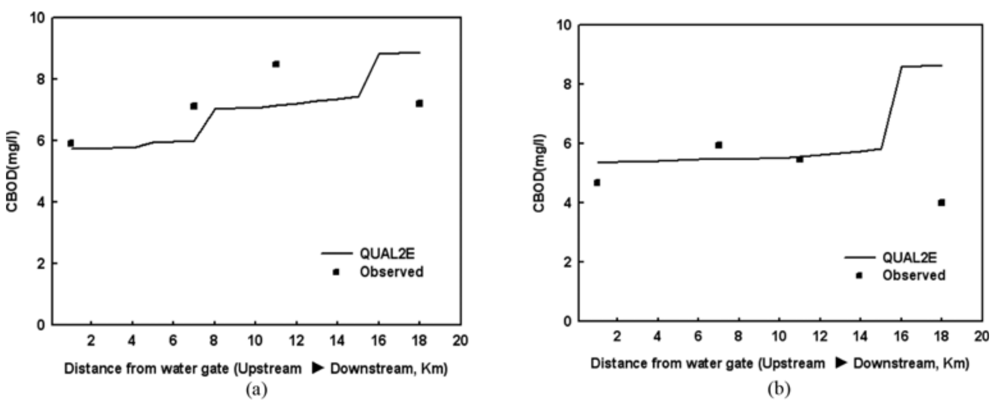

Fig. 6. (a) Calibration Results for QUAL2E using Field Data on August 10, 2006 and (b) Verification Results for QUAL2E using Field Data on October 19, 2006

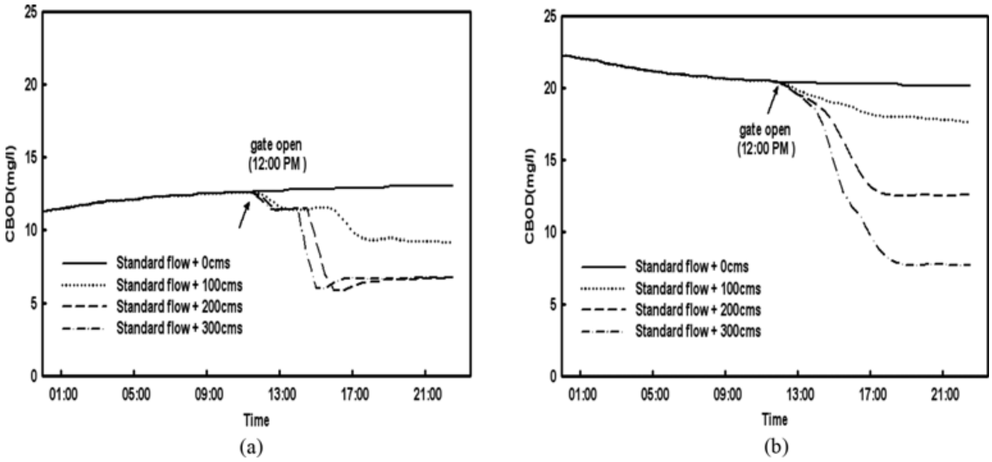

Fig. 7. Water Quality Change with Respect to Flowrate Increase at: (a) Gimhae Br. and (b) Gangdong Br.

using the time-averaged results of monitoring on August 10, 2006. The verification of the simulation results was performed using the average of the time series data from October 19. The results from the upstream head to Gangdong Bridge, which is 11 km away from the Daejeo gate, were relatively well simulated. At the end of the Seonakdong River, where the Joman River enters and the Noksan water gate is located, the calculated values were found to be larger than the measured values. These results indicate that there is a limitation in the steady-state simulation in terms of the flushing and dilution effects due to the increased flowrate after opening of the Daejeo and Noksan water gates.

A simulation was conducted to investigate the arrival time at major points downstream and the water quality improvement effects after opening of the Daejeo gate. The simulation was performed with boundary conditions representing the drought season, when the Nakdong River and Seonakdong River are quite different in water quality. The inflow from the Daejeo gate was increased for five hours. The comparison of river water quality changes following the increased inflow to the Daejeo water gate and the simulation results is shown in Fig. 7. The average standard flow of the Seonakdong River was 5.0 CMS, and the peak inflow rate was increased to 100, 200, and 300 CMS. Fig. 7 shows the results for the Gimhae bridge (Site 2) and Gangdong Bridge (Site 3), which indicate the clear effect of water quality improvement, because the CBOD value decreased as the inflow increased. While the concentrations at 200 CMS and 300 CMS were not much different at the Gimhae bridge, a greater water quality improvement was obtained with an inflow of 300 CMS at the Gangdong Bridge. These results show that the water quality improvement achieved by increased inflow was higher at the Gimhae Bridge, which is the closest to the Daejeo water gate, and some water quality improvement can be achieved at an inflow of 200 CMS or more. However, at the location farthest downstream, more inflow is required for water quality improvement. The gate operators need to determine how to supply water during a drought season to achieve effective water quality improvement. This study shows that water gate operators can determine the appropriate supply volume and duration from these simulations for various scenarios, depending on the flushing purpose.

5. Conclusions

The purpose of this study was to build a river water quality model to identify the optimum water gate operation method for improvement of water quality, based on past analysis data and monitoring results. Based on an analysis of actual measurement data and numerical simulation of unsteady-state river flow and water quality changes, we found that the increase of flow to the Daejeo water gate can contribute to the improvement of the water quality of the Seonakdong River. CBOD are sharply increased during the early stages of the water gate discharge. The unsteady model, CE-QUAL-RIV1, has a limitation in simulating such instantaneous changes. In this study, the simulation results from the typical steady-state model, QUAL2E, and the unsteady-state model, CE-QUAL-RIV1, were compared using data for the Seonakdong River. By comparing the calculation results from the two models, simulations could be performed for the same response coefficients and boundary conditions. The results of the river water quality changes were verified with respect to the long-term predictions of water quality and the increasing water flow to and discharge from the water gate. We found that the steady-state model is somewhat inappropriate for simulation of the water gate operation on the Seonakdong River. It seems that the CE-QUAL-RIV1 model better simulates the water flow and water quality changes for unsteady-state conditions during the operation of the water gate. The numerical simulation showed that a discharge of 300 CMS, which is an instantaneous peak inflow from the Daejeo water gate, can make it possible to achieve the target water quality of the Seonakdong River if the Daejeo water gate can remain open in connection with the Noksan water gate operation.

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