Algal Boom Characteristics of Yeongsan River Based on Weir and Estuary Dam Operating Conditions Using EFDC-NIER model

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November 22, 2022

Abstract

The Yeongsan River in southwestern Korea is 150 km long and has a basin area of 3,551 km^2. A number of hydraulic structures have been installed along the river, including an estuary dam and two weirs (Seungchon and Juksan). While these structures aid in regional water security and reduced flooding, they stagnate water flow and frequently cause algal blooms during the summer. This study simulated the algal bloom and water quality characteristics in the middle and downstream sections of the Yeongsan River under different weir and estuary dam operating conditions using the Environmental Fluid Dynamics Code-National Institute of Environment Research (EFDC-NIER) model. Results showed that when the management levels of the Juksan Weir and estuary dam were maintained, the simulated water levels were 3.7 and -1.2 m in the Juksan Weir and estuary dam sections, respectively. When both the Juksan Weir and estuary dam were open, the water levels varied with the tide and were maintained at an average of 0.2-0.6 m in contrast, when the Juksan Weir alone was open, the water level was between -1.2 and -0.9 m in line with the management level of the estuary dam. Opening the Juksan Weir alone reduced the algal blooms by 72-84% in the Juksan Weir section, and opening the estuary dam alone reduced the algal blooms by 83% in the estuary dam. This improvement was attributed to the reduced water retention time and dilution due to seawater inflows.

Algal Boom Characteristics of Yeongsan River Based on Weir and Estuary Dam Operating Conditions Using EFDC-NIER model

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Key Points:

- Algal bloom characteristics in the Yeongsan River Basin of Korea were simulated using a three-dimensional water quality model
- The model incorporated the combined influence of multifuctional hydraulic structures and multiplealgal species to enhance simulation accuracy
- Opening the Juksan Weir and estuary dam significantly decreased algal blooms due to reduced retention time and dilution due to seawater inflow.

Abstract

The Yeongsan River in southwestern Korea is 150 km long and has a basin area of 3,551 km^2. A number of hydraulic structures have been installed along the river, including an estuary dam and two weirs (Seungchon and Juksan). While these structures aid in regional water security and reduced flooding, they stagnate water flow and frequently cause algal blooms during the summer. This study simulated the algal bloom and water quality characteristics in the middle and downstream sections of the Yeongsan River under different weir and estuary dam operating conditions using the Environmental Fluid Dynamics Code-National Institute of Environment Research (EFDC-NIER) model. Results showed that when the management levels of the Juksan Weir and estuary dam were maintained, the simulated water levels were 3.7 and –1.2 m in the Juksan Weir and estuary dam sections, respectively. When both the Juksan Weir and estuary dam were open, the water levels varied with the tide and were maintained at an average of 0.2–0.6 m; in contrast, when the Juksan Weir alone was open, the water level was between –1.2 and –0.9 m in line with the management level of the estuary dam. Opening the Juksan Weir alone reduced the algal blooms by 72–84% in the Juksan Weir section, and opening the estuary dam alone reduced the algal blooms by 83% in the estuary dam. This improvement was attributed to the reduced water retention time and dilution due to seawater inflows.

1. Introduction

Estuaries are transition areas between the land and sea, and environmental changes in an estuary can have a significant influence on the adjacent ocean environment. The construction of estuary dams can be highly beneficial in terms of water security and reducing flood damage; however, these dams may also stagnate and pollute the water flow, resulting in water that is unsuitable for agriculture and impacting the organisms that live in it. Furthermore, it has been reported that freshwater eutrophication can degrade coastal water quality and ecosystems as the water is introduced to the coast through an estuary dam (Shin et al., 2015).

The Yeongsan River is located in the southwest of the Korean Peninsula and flows into the Yellow Sea. Two large weirs, (Seungchon and Juksan) and an estuary dam were installed in the middle and downstream sections of the river, causing stagnation of water flow and frequent algal blooms during summer. The Yeongsan River estuary dam was the first in South Korea; construction began on January 20, 1978 and was completed on December 8, 1981 as a part of a five-stage comprehensive development plan for the Yeongsan River Basin. The construction of the dam ensured the viability of vast farmlands and secured freshwater resources via the formation of the large Yeongsan Lake($253.6*10^6$ m3). The normal high water level (NHWL) of the estuary dam is EL. –1.35 m, and it has been managed for the efficient supply of agricultural, industrial, and residential water and lowland flood prevention. However, the estuary dam has damaged the natural ecological environment of the Yeongsan River Basin, evidenced by the ongoing eutrophication and periodic formation of low-oxygen layers in downstream reaches (Shin et al., 2015).

In 2011, 16 weirs were constructed in the main streams of four major rivers in Korea as a part of the Four Major Rivers Restoration Project(MLTM, 2009). The Seungchon and Juksan Weirs were constructed in the middle and downstreamsections of the Yeongsan River Basin. The weirs enabled an average water depth of 5–6 m to be maintained between the weirs based on the management levels of EL. 7.5 and 3.5 m for the Seungchon and Juksan Weirs, respectively.

Although weir construction increased the water storage in the weir section, it also increased the water retention time due to the increased depth and delayed flow (Seo et al., 2018).

While it is apparent that flow stagnation due to the construction of weirs and estuary dams can cause eutrophication and low-oxygen layers, studies regarding the impact of their construction on water quality and aquatic ecosystems are fairly limited. In China, the impact of dams on the river flow system and water quality of the middle and upstream areas of the Huai River Basin were assessed using the Soil and Water Assessment Tool (Zhang et al., 2009). Furthermore, various processing methods were proposed to reproduce the water flow and improve the water quality of the Porsuk Dam Reservoir in the Porsuk River in Turkey using the Enhanced Stream Water Quality model (Muhammetoglu et al., 2005). The water quality prior to and following the construction of the Dadu Weir in the Wu River in Taiwan was reproduced and analyzed using the three-dimensional (3D) Water Quality Analysis Simulation Program (WASP5) model (Chen et al., 2013).

Since 2017, The Korean Ministry of Environment (ME) has monitored the impact of opening weir floodgates on water quality, aquatic ecosystems, and water use to aid in future planning. Studies have also used 3D water quality models to investigate water quality in Korea. For example, Suh et al (2002) investigated the long-term water quality variability of Shihwa Lake following floodgate operation using the 3D CE-QUAL-ICM model (Suh et al., 2002), and the operation of the Seungchon Weir (Yeongsan River) was analyzed using the 3D Estuary, Lake and Coastal Ocean Model and Computational Aquatic Ecosystem Dynamics Model (Chong et al., 2015). Furthermore, the impact of changes in hydraulic characteristics, such as a reduction in management level and an increase in flow velocity, on water quality and algal biomass were assessed for the Chilgok Weir and Gangjeong-Goryeong Weir sections of the Nakdong River using the 3D Environmental Fluid Dynamics Code (EFDC) model (Park et al., 2019). The EFDC-NIER model is an improved version of the EFDC model developed by the National Institute of Environment Research (NIER) to simulate multifunctional weir operation, multiple algal species, and vertical algal movement mechanisms (NIER, 2011; 2014). The impact of opening the estuary dam on water flow and seawater intrusion in the downstream section of the Yeongsan River was assessed using the EFDC-NIER model (Shin et al., 2019); however, this study did not investigate the combined impacts of the weirs and estuary dam on water quality.

This study aims to ① construct a model that can simulate water flow and water quality in the main stream section and estuary dam of the Yeongsan River using the EFDC-NIER model and ② use the model to assess water flow and water quality characteristics according to the operational conditions of the multifunctional weirs and estuary dam. When the Juksan Weir is fully opened, the middle and downstream sections of the weir are stagnated under the influence of the estuary dam water level. Therefore, the effects of the operational conditions of both the Juksan Weir and estuary dam are comprehensively assessed in this study.

2. Materials and Methods

2.1 Study area

The Yeongsan River is located in southwestern Korea and has a basin area of approximately 3,551 km^2. It originates in Yongchubong (EL. 560 m), Yong-myeon, Damyang-gun, Jeollanam-do and flows into the Yellow Sea through Damyang, Gwangju, Naju, Yeongam, and the estuary dam. The main stream of the Yeongsan River is approximately 150 km long. The

Seungchon and Juksan Weirs are located in the middle and downstream sections of the river, respectively. In the upstream area of the Seungchon weir, Pungyeongjeongcheon, Gwangjucheon, Hwangryonggang, and Pyeongdongcheon are merged in sequence. In the Juksan Weir section, Jisukcheon, Jangseongcheon, Yeongsancheon, Manbongcheon, Moonpyeongcheo, Gomakwoncheon, Hampyeongcheon, Sampocheon, and Yeongamcheon are merged. Figure 1 shows the geographical location of the Yeongsan River Basin, its major tributaries, meteorological stations, and water quality and water level stations located in the main stream of the Yeongsan River.

The estuary dam is a tide embankment constructed by filling in the sea approximately 6 km upstream from the coast of Mokpo City. The dam is 4.35 km long and 20 m high, with eight original drainage sluices (30 m long and 13.6 m high). Five additional drainage sluices (48 m long and 13.6 m high) were added in 2014 to improve water quality due to flood level increases attributed to climate change. The Seungchon (Juksan) Weir has a management level of EL. 7.5 m (3.5 m) and an overflow weir elevation of 2.5 m (–3.63 m). Table 1 summarizes the main specifications of the Seungchon and Juksan Weirs and the estuary dam.

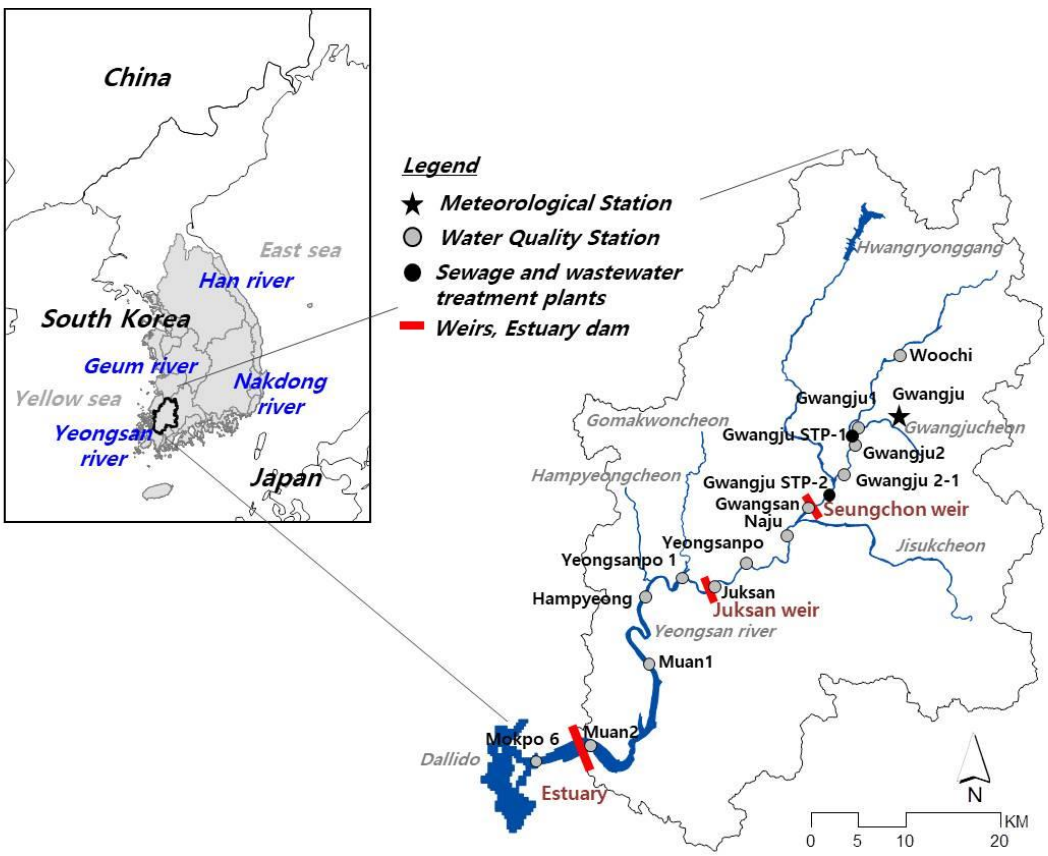

Fig. 1: Site map showing the location of the Yeongsan River in Korea and its major tributaries and monitoring stations

Table 1: Specifications of the Seungchon and Juksan Weirs and the estuary dam

Specification	Seungchon Weir	Juksan Weir	Estuary dam
Management level (EL. m)	7.5	3.5	–1.35
Volume (10^6 m^3) at management level	9.0	25.7	253.6
Total length (m)	512	184	4,350
Gate (m) (length × height × gate)	50 × 5.05 × 2 gates 30 × 5.05 × 2 gates	36.5 × 7.13 × 4 gates	30 × 13.6 × 8 gates 48 × 13.6 × 5 gates

2.2 EFDC-NIER model construction

The EFDC model was developed by the Virginia Institute of Marine Science in the United States (US) in the early 1990s, and has been maintained by Tetra Tech, Inc. with the support of the US Environmental Protection Agency. The EFDC model is a 3D hydraulic, water quality, and sediment movement numerical model applicable to lakes, rivers, coasts, and estuaries. Because the model is comprised of modules (Hydrodynamics, Water Quality, Sediment Transport, and Toxic modules) it can simulate fluid transport and diffusion, suspended solid behavior, salinity and water temperature changes, water quality and eutrophication mechanisms, and toxic pollutant behavior (Shin et al, 2017).

The EFDC-NIER model is an improved version of the original EFDC model to simulate multifunctional weirs, multiple algal species, and vertical algal movement mechanisms. The numerical model has been used to forecast the water quality in large river main streams and to simulate major rivers and lakes in South Korea (NIER, 2011; 2014). The multifunctional weir module used in this study was developed to simulate the operational conditions and operational water levels of major hydraulic structures, such as fixed weirs, movable weirs, fishways, and small hydroelectric power plants, as shown in Fig. 2. Fixed and movable weirs can be classified into weirs and orifices depending on the upstream and downstream water level difference. For fishways, water discharge to the downstream area through the fishway occurs when the water level is higher than the fishway water level. With respect to the estuary dam, the sea tide level can be defined in advance and can be used as the estuary dam discharge condition. The hydraulic structure discharge flow rate can be simulated such that the water level and flow rate conditions designated by the user can be satisfied according to the options.

Weir opening height and water level monitoring data from the Korea Water Resources Corporation (kwater.or.kr) were used as weir operating data for the multifunctional weir simulation. Dam operating status and water level data from the Yeongsan River Flood Control Office (yeongsanriver.go.kr) were used as data for the estuary dam simulation. The estuary dam drainage sluices were opened only when the water level of the freshwater lake was 0.2 m higher than the outer tide level in accordance with the Yeongsan River estuary dam drainage sluice operation guidelines (KRCC, 1999; Shin et al., 2019).

The spatial range of the EFDC-NIER model was from the Woochi water quality station in the upstream area of the Yeongsan River to Dalido at the river estuary. A horizontal grid network was constructed considering river maps, embankment boundaries, river cross-section data, captured images, and multifunctional weirs. The total number of horizontal grids was 1,731

(1,225 for the main stream and 507 outside the estuary dam), and five water depth layers were constructed. Figure 3 shows the horizontal and vertical grid configuration of the EFDC-NIER model (Shin et al. 2019). Grid size ranged from 62–510 m (mean of 214 m) wide (dx) and 81–560 m (mean of 271 m) in the flow direction (dy). The river bed height ranged from EL. 28.6 m for the uppermost stream to EL. –21.3 m for the estuary dam, and from EL. –30.1 to –0.2 m (mean of EL. –14.1 m) in the sea outside the estuary dam. Mokpo tidal station data were used for the tide level, and average of Mokpo 3, 4, and 8 stations) data were used for water temperature and salinity. Gwangju meteorological station data were used for meteorological conditions, and the ME monitoring network data were used for the water quality and flow rates of the inflowing tributaries. Tele-monitoring system data were used for the water quality and flow rates of sewage and wastewater treatment plants.

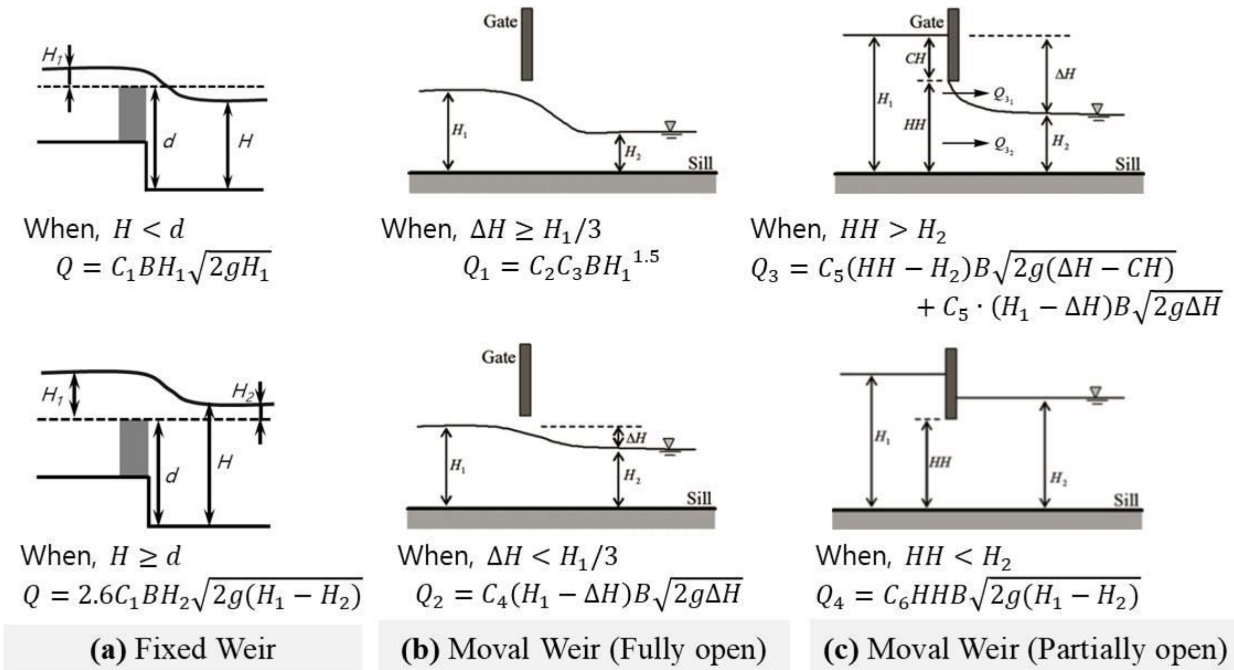

Fig. 2: Schematic and flow equations for (a) fixed weir and (b and c) movable weir operations. C_1– C_6 are the coefficients of discharge and B is the width of the weir.

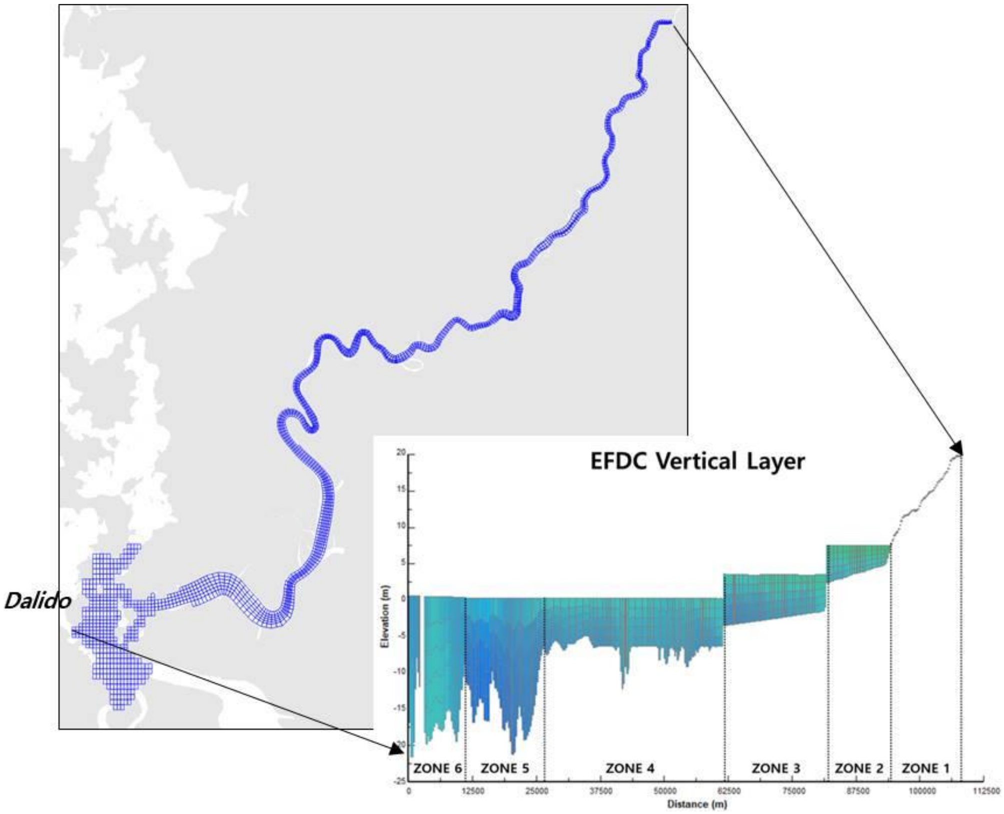

Fig. 3: Grid of the Yeongsan River physical domain. Grid spacing ranges from approximately 62–510 m (Shin et al., 2019).

2.3 Algae simulation method

Population at the class level or the total amount of carbon is generally used to quantitatively analyze temporal changes in phytoplankton (i.e. its transition process) from a macroscopic perspective. This is because there are too many types of phytoplankton for species or genus classification to be considered. The EFDC model can simulate algae by classifying it into three classes (cyanophyceae, bacillariophyceae, and chlorophyceae); however, it cannot easily reproduce the rapid algal blooms of specific species and complex species transitions based on these broad classifications. To address this limitation, NIER developed a simulation function for multiple algal species through the water quality prediction system construction project for protecting the water source of the Han River water system (II) (NIER, 2015). In this study, phytoplankton was simulated using the multiple algal species simulation function, and plankton was grouped according to phytoplankton functional group (PFG) as proposed by Reynolds et al. (2002). PFGs can be defined as “a community of algal species with similar characteristics from morphological, physiological, and ecological perspectives,” and having similar main habitats or appearance environments(Reynolds et al., 2002). A PFG also exhibits similar tolerance and sensitivity characteristics to changes in the external environment. In this study, groups that represented over 95% of the total phytoplankton carbon mass were selected by arranging each group in the order of the relative carbon-based occupancy. Nine groups were classified, as presented in Table 2.

To simulate phytoplankton, it is necessary to convert the number of observed algal cells into the mass of carbon (a model parameter). The carbon mass of each group was calculated by multiplying the number of cells for each phytoplankton species by the average carbon mass per cell as follows (Eq. 1):

$$\text{Group A carbon mass(mg C/L)} = \sum_{i=1}^{n}(\text{ Algae cell no. (cells/L)} \times \text{ Algae carbon mass(mg C/cell)})_i \quad (1)$$

where algae are the phytoplankton species included in Group A.

Table 2. Trait-separated phytoplankton functional groups in the Yeongsan River (Reynolds et al., 2002)

Codon	Habitat	Typical representatives	Tolerances	Sensitivities
M	Diurnally mixed layers of small eutrophic, low latitude lakes	Microcystis	High insolation	Flushing, low total light
H1	Dinitrogen-fixing Nostocaleans	Anabaena flos-aquae Aphanizomenon	Low nitrogen, low carbon	Mixing, poor light, low phosphorus
P	Eutrophic epilimnia	Fragilaria crotonensis Aulacoseira granulata Staurastrum pingue Melosira Closterium	Mild light, C deficiency	Stratification, Si depletion
D	Shallow, enriched turbid waters, including rivers	Synedra acus Nitzschia spp Stephanodiscus Skeletonema	Flushing	Nutrient depletion
G	Short, nutrient-rich water columns	Eudorina Pandorina	High light	Nutrient deficiency
X2	Shallow, clear mixed layers in meso-eutrophic lakes	Chlamydomonas Cryptomonas	Stratification	Mixing, filter feeding
J	Shallow, enriched lakes, ponds, and rivers	Actinastrum Coelastrum Crucigenia Golenkinia Pediastrum Tetrastrum Scenedesmus		Settling into low light
LO	Summer epilimnia in mesotrophic lakes	Peridinium Merismopedia	Segregated nutrients	Prolonged or deep

		Chroococcus Ceratium		mixing
C	Mixed, eutrophic small–medium lakes	Asterionella formosa Aulacoseira ambigua Cyclotella	Light, C deficiencies	Si exhaustion, stratification

2.4 Model assessment

In a previous study, Shin et al. (2019) examined the reproducibility of water flow in the Yeongsan River main stream and the inner and outer sections of the estuary dam using the EFDC-NIER model. They found that water level, water temperature, flow velocity, flow rate, and salinity were well simulated at the Seungchon and Juksan Weirs, estuary dam, and the Mokpo tidal station (Shin et al., 2019). The water quality of the Seungchon and Juksan Weirs was calibrated using data from Gwangsan and Juksan, which are 500 m upstream of each weir and are assumed to be representative of the weirs by the National Water Environment Monitoring Network (water.nier.go.kr/Ministry of Environment). Estuary dam water quality was calibrated using data from the Muan 2 point in the general water quality monitoring network. Bias (mean error) and normalized root mean square error (NRMSE) were used as statistical indices for assessing model accuracy. The bias represents the average direction of prediction errors, and NRMSE is used to assess the precision of predicted values (Table 3).

Table 1. Statistical indices used to evaluate model accuracy

Statistical index	Equation	Desired value
Bias	$\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)$	0
NRMSE (%)	$\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2}}{\overline{O_i}}$	0

P_i is the simulated value at time i, O_i is the observed value at time i, and $\overline{O_i}$ is the mean of observed values for the entire period

2.5 Operational conditions of the Juksan Weir and estuary dam

Changes in water quality were assessed according to the operating conditions of the Juksan Weir and estuary dam. Four scenarios were evaluated, as presented in Table 4. The Juksan Weir was either maintaining the management level (EL. 3.5 m; closed) or the four floodgates were open. The estuary dam was either maintaining NHWL (EL. –1.35 m; closed) or seawater was being introduced and discharged (open).

Table 2. Scenarios for the operation of the Juksan Weir and estuary dam

Scenario		Juksan Weir	
		Closed (Management level, EL. 3.5 m)	Open
Estuary dam	Closed (NHWL, EL. – 1.35 m)	ⓐ	ⓑ
	Open (Free tidal)	ⓒ	ⓓ

3. Results and Discussion

3.1 Algal bloom characteristics

The middle and downstream sections of the Yeongsan River show high phytoplankton concentrations attributed to increased retention time caused by the Seungchon and Juksan Weirs and the estuary dam, and the influence of point and non-point pollution sources scattered throughout the basin. Figures 4 (a and c) show transition characteristics by class, and Figs. 4 (b and d) show the transition characteristics by PFG for 2018. Large quantities of diatoms are produced in early spring due to temperature increases and abundant solar radiation and a transition to green algae and cyanobacteria occurs as summer begins.

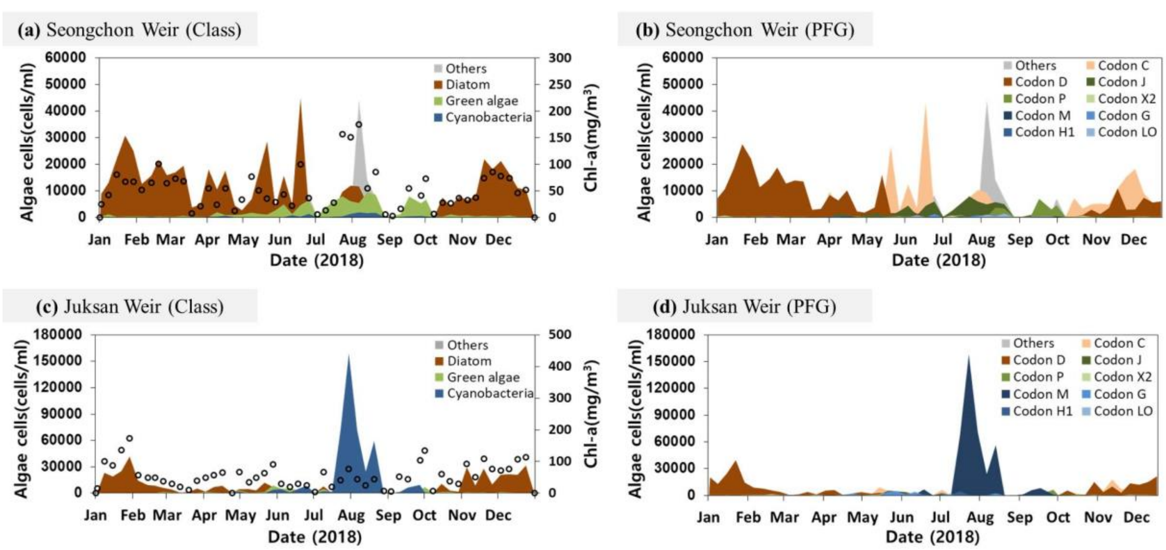

Fig. 4 Chlorophyll-a concentration and algal cells at the Seungchon Weir by (a) class and (b) phytoplankton functional group (PFG) and Juksan Weir (c) class and (d) PFG for 2018.

3.2 Model Validation

Figure 5 and Table 5 show the results of the EFDC-NIER model in comparison with observations for 2018. Variability in BOD, COD, DO, T-N, chlorophyll-a, and algae (number of harmful cyanobacteria cells) was reproduced well by the model at the Seungchon and Juksan Weirs and the estuary dam. The average water level deviation ranged from 0.0–0.2 m and deviations were less than 1 ºC for water temperature, 1 mg/L for BOD concentration, 1.4 mg/L for DO concentration, and 1.0 mg/L for T-N concentration. Chlorophyll-a concentration ranged from –27 to 28 mg/m^3, and the prediction accuracy was lower than other physicochemical water quality metrics. We attribute this to the high spatiotemporal distribution of algae based on weather and environmental conditions. Cyanobacteria were not measured at the Muan 2 point (estuary dam).

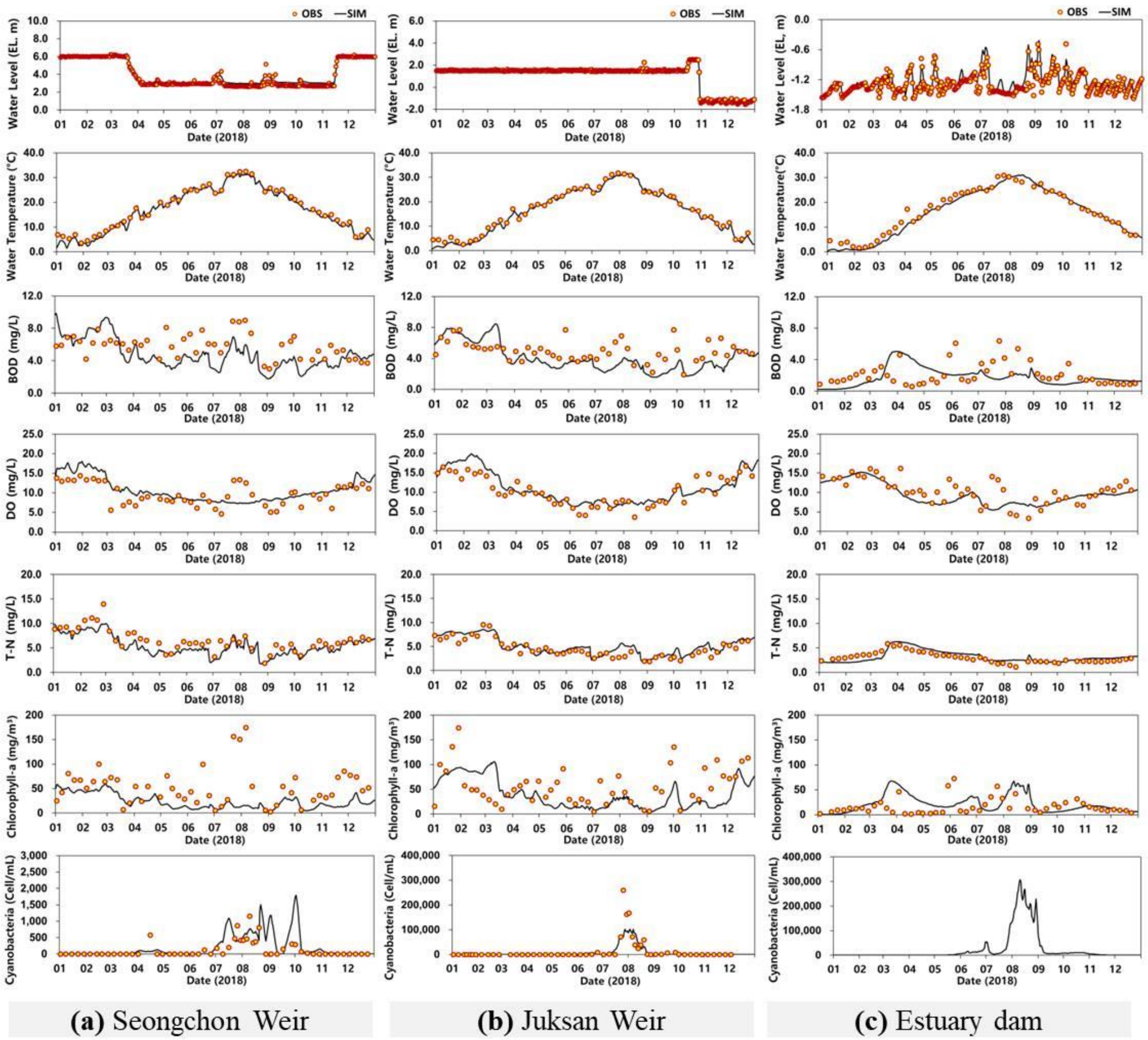

Fig. 5: Comparison of observed and simulated values of water quality for the (a) Seungchon Weir, (b) Juksan Weir, and (c) estuary dam for 2018. The number of observed cyanobacteria cells is the sum of cell numbers for the genera Anabena, Aphanizomenon, Microcystis, and Oscillatoria.

Table 3. Statistical summary of simulated and observed water quality at the Seungchon Weir,

Juksan Weir, and estuary dam for 2018

	Water level (EL, m)	Water temperature (℃)	BOD (mg/L)	DO (mg/L)	T-N (mg/L)	Chlorophyll-a (mg/m^3)	Cyano-bacteria (cells/mL)
Seungchon Weir							
Observation	4.0	17.3	5.8	9.6	6.509	53.2	131
Simulation	4.2	16.7	4.8	10.8	5.358	25.2	196
Bias	0.2	–0.9	–0.9	1.4	–0.9	–27.6	82.0
NRMSE (%)	7.3	6.9	35.3	30.2	21.0	87.2	287.0
Juksan Weir							
Observation	1.6	16.5	5.0	10.3	4.577	56.4	16,781
Simulation	1.6	16.0	4.2	11.5	5.045	47.1	10,014
Bias	0.0	–0.7	–0.8	1.3	0.5	–10.8	–6,285
NRMSE (%)	5.2	6.5	36.4	23.0	21.6	68.4	220.1
Estuary dam							
Observation	–1.3	16.6	2.2	10.4	2.980	16.2	-
Simulation	–1.2	15.7	1.8	9.4	3.160	21.1	23,857
Bias	0.1	–0.8	0.5	–0.8	0.3	27.7	-
NRMSE (%)	–9.3	11.0	83.7	25.9	26.5	143.0	-

3.3 Algal bloom characteristics according to the operating conditions of Juksan Weir and the estuary dam

Tables 6 and 7 and Figs. 6–8 show the simulation results of the water level and algal bloom characteristics according to the operating conditions of the Juksan Weir and estuary dam. When the Juksan Weir and estuary dam are both closed, the Juksan Weir and estuary dam sections maintain water levels of 3.7 and –1.2 m, respectively. When the weir is open and the dam closed, the region is connected as a single water body and the entire section exhibits similar water levels. Simulations suggest that a water level between –1.2 and –0.9 m is maintained due to the influence of the management level of the estuary dam. When both the weir and dam are open, the water level varies depending on the outer tide and maintains an average of 0.2–0.6 m.

Opening the Juksan Weir and estuary dam significantly decreased algal blooms due to reduced retention time and dilution due to seawater inflow. The number of algal cells in the Juksan Weir section was between 3,201 and 38,185 cells/mL when the Juksan Weir and estuary dam were closed; however, this number decreased by 72–84% to (889–6,099 cells/mL) when the

Juksan Weir alone was opened. This is because the average retention time decreases from 11.2 to 1.8 days due to a reduction in water level, as shown in Table 7. Conversely, when both the Juksan Weir and estuary dam were opened, algal blooms in the Juksan Weir section decreased by 0–32%, a smaller reduction than that when the Juksan Weir alone was opened. This is because the increased water level further stagnates the water flow and increases the retention time under the direct influence of the outer tide level.

The simulated number of algal cells in the estuary dam section was 67,041 cells/mL when the estuary dam was closed; however, this decreased to 11,313 cells/mL (83 %) when the estuary dam was opened due to dilution by seawater inflows. Conversely, the impact of opening the Juksan Weir was insignificant.

Similar to algal blooms, the model showed that opening the Juksan Weir and estuary dam decreased the chlorophyll-a concentration due to a reduced retention time caused by water level changes and seawater dilution impacts; however, the decrease was smaller than that of algal blooms. This is because diatoms, which are dominant during the winter, are not markedly impacted by the weir opening because they can grow in a relatively stable manner with low water levels or fast water flow (Codon D in Table 2).

Table 4. Simulation results according to the operating conditions of the Juksan Weir and estuary dam

Variables	Section	Location (From weir and dam)	Estuary dam: Closed		Estuary dam: Open	
			ⓐ Weir closed	ⓑ Weir open (ⓑ - ⓐ, %)*	ⓒ Weir closed (ⓒ - ⓐ, %)*	ⓓ Weir open (ⓓ - ⓒ, %)*
Water level (EL. m)	Juksan Weir	Naju (15.5 km)	3.7	–0.9	3.7	0.6
		Yeongsanpo (6.6 km)	3.7	−1.1	3.7	0.5
		Juksan (0.8 km)	3.7	−1.2	3.7	0.4
	Estuary dam	Muan 2 (0.2 km)	−1.2	−1.2	0.2	0.2
Cyanobacteria (Jun–Sep average; (cells/mL)	Juksan Weir	Naju (15.5 km)	3,201	889 (72 % ↓)	3,195 (-)	2,169 (32 % ↓)
		Yeongsanpo (6.6 km)	8,385	1,578 (81 % ↓)	8,405 (-)	8,265 (-)
		Juksan (0.8 km)	38,185	6,099 (84 % ↓)	38,185 (-)	37,601 (-)
	Estuary dam	Muan 2 (0.2 km)	67,041	65,978 (-)	11,313 (83 % ↓)	12,706 (-)
Chlorophyll-a (mg/m^3)	Juksan Weir	Naju (15.5 km)	31.0	28.2 (9 % ↓)	31.0 (-)	31.7 (-)
		Yeongsanpo (6.6 km)	36.4	30.4 (16 %↓)	36.5 (-)	38.7 (-)
		Juksan (0.8 km)	48.3	42.8 (11 % ↓)	48.3 (-)	51.5 (-)
	Estuary dam	Muan 2 (0.2 km)	25.3	25.8 (-)	7.4 (71 % ↓)	7.9 (-)

* A T-test was applied to evaluate the differences between weir and dam operational conditions. When the change

was significant (95% confidence level), a reduction was marked with "↓" and an increase was marked with "↑". Changes with no significance are marked with "-".

Table 5. Simulations of water level and retention time in the Juksan Weir section according to the operating conditions of the Juksan Weir and estuary dam (averaged from June to September 2018)

Scenario		Water level (EL. m)	Water volume (m^3)	Flow (m^3/s)	Retention time (day)
Estuary dam	Juksan Weir	(min–max)	(min–max)	(min–max)	(min–max)
Closed	Closed	3.8 (3.6–4.6)	27.8 (26.4–34.1)	102.8 (9.0–1318.1)	11.2 (0.3–34.1)
	Open	−1.1 (−1.5 – −0.2)	4.9 (3.5–8.4)	102.8 (9.0–1318.1)	1.8 (0.1–5.5)
Open	Closed	3.8 (3.6–4.6)	27.8 (26.4–34.1)	102.8 (9.0–1318.1)	11.2 (0.3–34.1)
	Open	0.6 (0.2–1.3)	12.3 (10.3–12.3)	102.8 (9.0–1318.1)	4.9 (0.1–14.3)

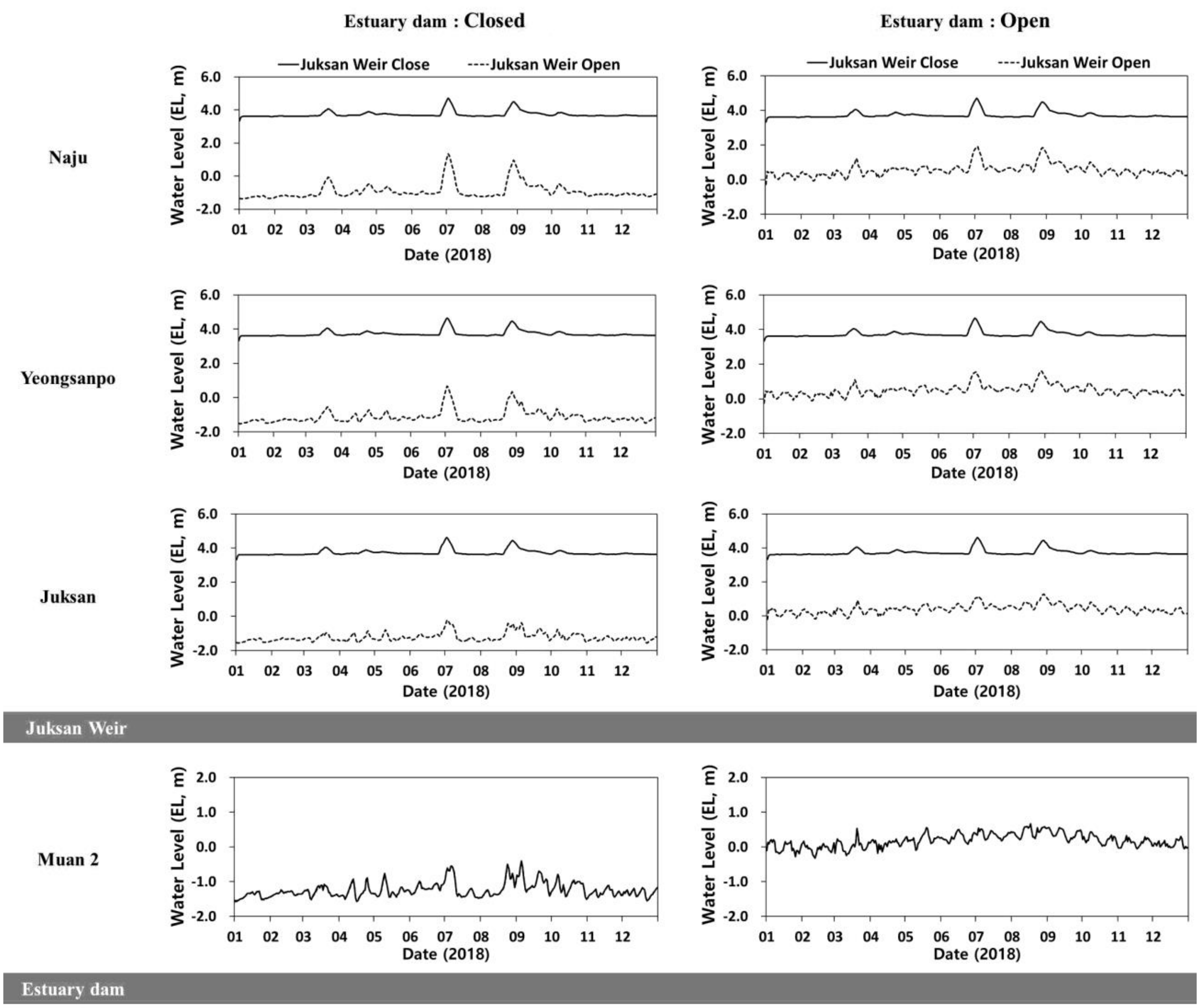

Fig. 6: Simulated water levels according to the operating conditions of the Juksan Weir and estuary dam

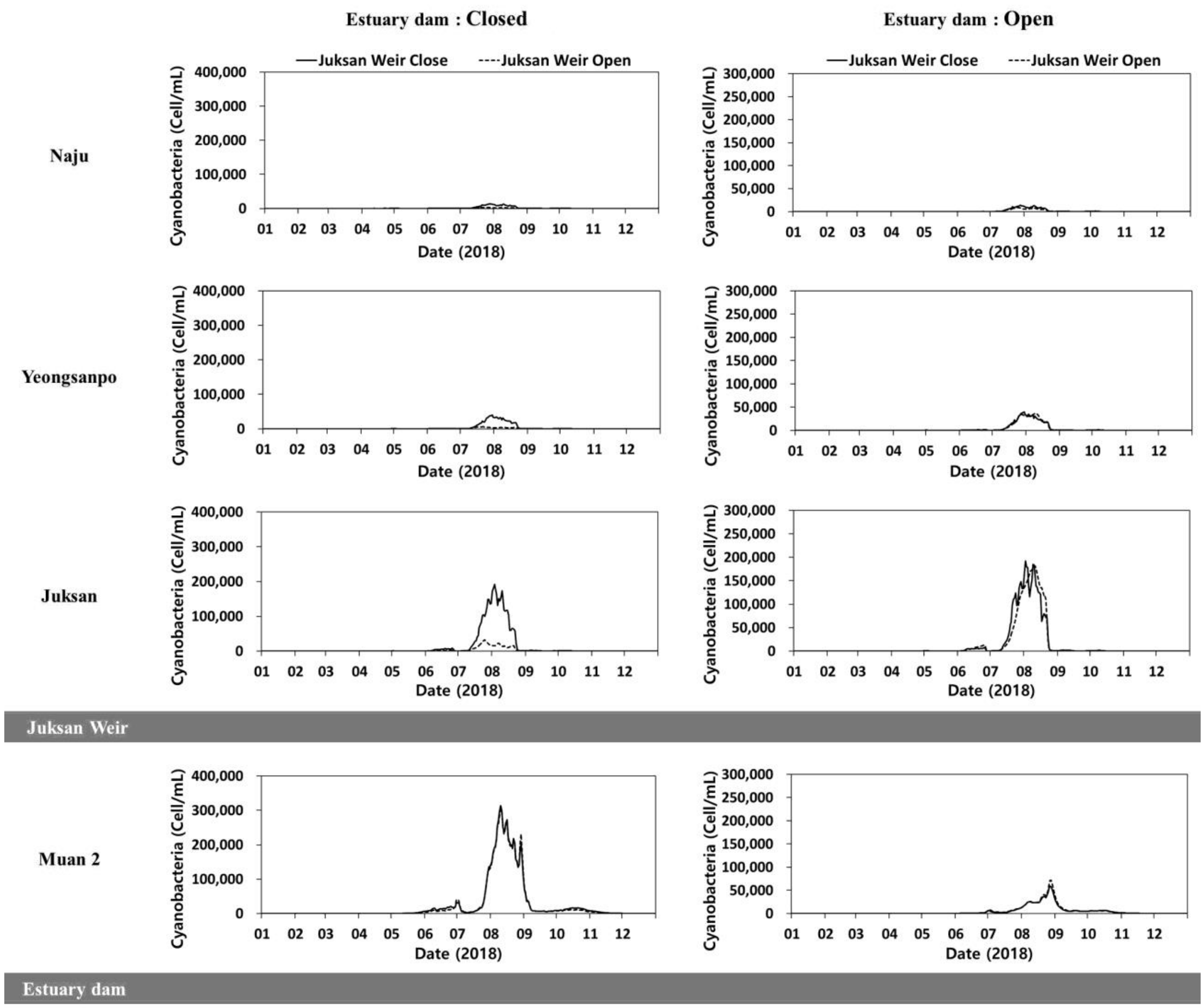

Fig. 7: Simulated cyanobacteria concentrations according to the operating conditions of the Juksan Weir and estuary dam

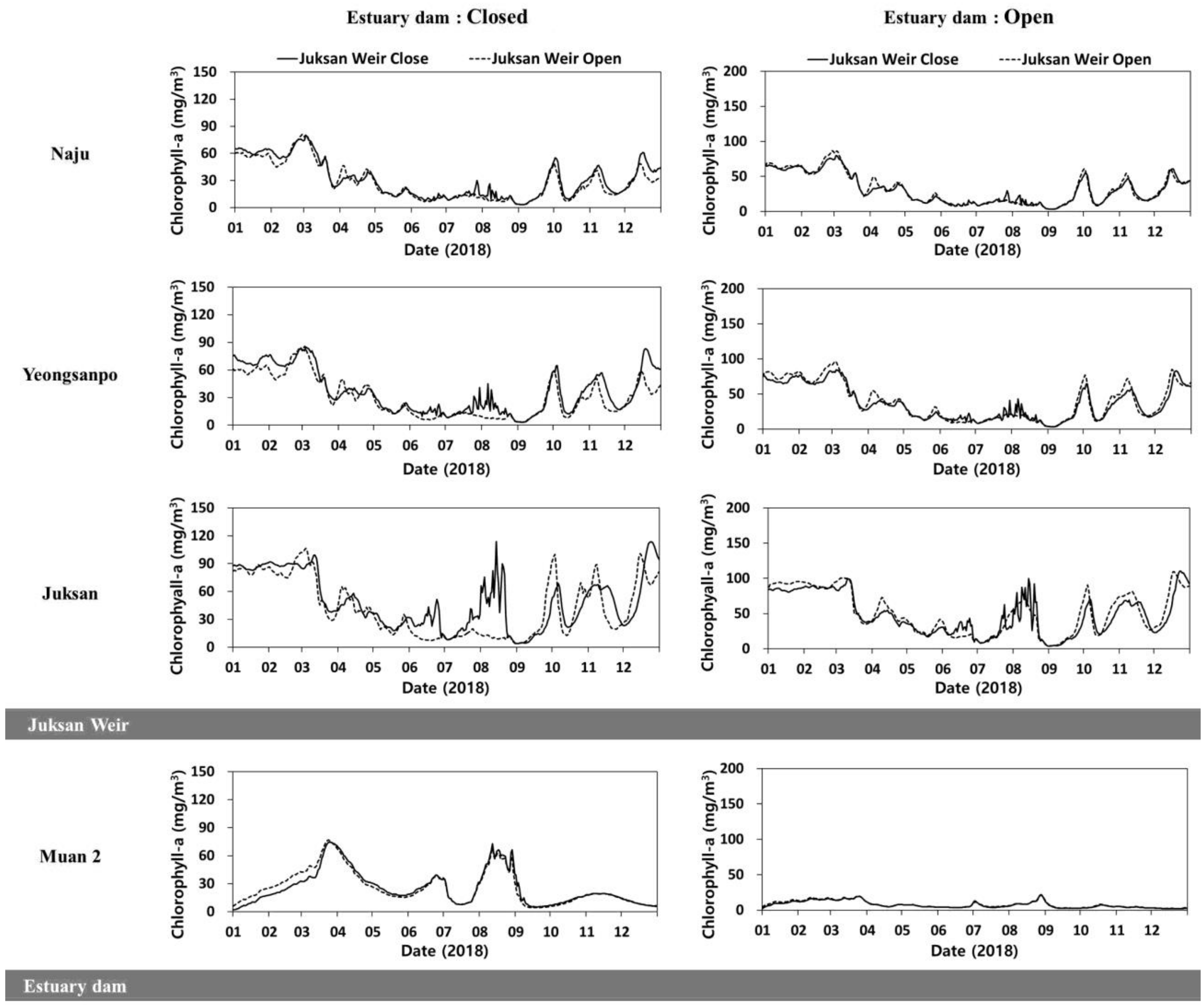

Fig. 8 Simulated chlorophyll-a concentrations according to the operating conditions of the Juksan Weir and estuary dam

4. Conclusion

In the middle and downstream sections of the Yeongsan River, waters are stagnated by the Seungchon and Juksan Weirs and an estuary dam, causing frequent algal blooms and hypoxic layers during the summer. This study investigated the impacts of operating the Juksan Weir and estuary dam, in terms of water quality and algal bloom characteristics, in the middle and downstream sections of the Yeongsan River. A water quality prediction model was constructed and validated for the main stream and estuary dam sections using the 3D EFDC-NIER model. A multifunctional weir module was applied to reproduce water flow characteristics in the river, and a simulation function for multiple algal species was applied to reflect the occurrence, transition, and extinction characteristics of various algal species. The model was then used to compare and assess water flow and algal bloom characteristics according to the operating conditions of the Juksan Weir and estuary dam. The model validation results indicated that the model could reproduce the water levels under different operating conditions well. Furthermore, the temporal distributions of water quality indicators were generally simulated with a high degree of accuracy..

When the Juksan Weir and estuary dam were closed (the water level was maintained), the Juksan Weir and estuary dam sections maintained the average water levels of EL 3.7 and –1.2 m, respectively. Furthermore, mean algae abundance was 3,201–38,185 cells/mL for the Juksan Weir section and 67,041 cells/mL for the estuary dam during summer, indicating relatively high levels of algae. Senario simulations showed that opening the Juksan Weir while keeping the estuary dam closed would reduce algal blooms by an average of 72–84% in the Juksan Weir section. This was attributed to reduced retention time caused by decreased water levels. Furthermore opening the estuary dam while keeping the Juksan Weir closed would reduce algal blooms by an average of 83% due to dilution by seawater inflow. However, when both the Juksan Weir and estuary dam were open, simulations showed that the algal bloom reduction in the middle and downstream sections of the Juksan Weir was smaller than the reductions from opening the Juksan Weir alone. This was attributed to the increased water level caused by the outer tide level.

The EFDC-NIER model for the Yeongsan River main stream and estuary can be used to analyze water flow and water quality characteristics according to the operational conditions of the multifunctional weirs and estuary dam in the river system, and to establish and evaluate plans for improving the water quality and aquatic ecosystems of the Yeongsan River.The occurrence of algae in rivers and estuaries is complexly affected by various factors such as changes in point/nonpoint pollutant sources in the watershed, weather, as well as opening condition of wears and estuary dams, so the scenario simulation results of this study are appropriate to be referenced as relative comparison values according to the opening conditions.

For a more accurate simulation of water quality and algal bloom in in the aquatic environment, basic research on the physiological characteristics of aquatic environment and algae, development of a numerical model(or data based model) that reflects the research results, and application of the model based on a deep understanding of the model mechanism and the target watershed and waterbody are all necessary, for which active cooperation among multidisciplinary schools is required.

Acknowledgements

This work was supported by a grant from the National Institute of Environmental Research (NIER), funded by the Ministry of Environment of the Republic of Korea (NIER-RP2019-130)

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