

Factors affecting harmful algal bloom occurrence in a river with regulated hydrology

Jaeyoung Kim ^a, John R. Jones ^b, Dongil Seo ^{a,*}

^a Department of Environmental Engineering, Chungnam National University, 99, Daehak-ro, Yuseong-gu, Daejeon, 34134, Republic of Korea

^b School of Natural Resources, University of Missouri, 103 Anheuser-Busch Natural Resources Building, Columbia, MO, 65211, USA



ARTICLE INFO

Keywords:

Harmful algal blooms
Hydrodynamic and water quality model
Net growth limitation
Hydraulic residence time
Weir gate control
Regulated river

ABSTRACT

Study region: The Geum River Basin, South Korea.

Study focus: In-stream structures potentially amplify harmful algal blooms (HABs) by increasing water residence time and deteriorating water quality. Removal or gate control of in-stream structures is considered a management tool to reduce HAB occurrence. Prior evaluation, however, is necessary to assess the effect of structural modifications to control HABs. This study focused on factors affecting HAB occurrence relative to the operation of 3 in-stream weirs using a 3-dimensional hydrodynamic and water quality model.

New hydrological insights for the study region: Physical changes due to gate opening could not guarantee an improvement in water quality and reduction in cyanobacterial biomass. Cyanobacteria, a major component of HABs, decreased in the upstream reach but conditions deteriorated downstream during summer. Maximum cyanobacteria concentrations in the downstream reach almost doubled during summer with the open-gate scenario. Although the open-gate flow allowed less time for algal growth, (1) increased light availability with decreased water depth and (2) dissolved phosphorus, which was not depleted upstream, promoted cyanobacterial growth. Consequently, the proliferation of cyanobacterial blooms downstream was due to conditions that enhanced algal growth, despite reduced hydraulic residence time under the open-gate scenario. This analysis indicates that hydrologic regulation may not improve water quality and also may affect spatial and temporal distribution of cyanobacteria in the system. Reducing HABs will likely require a reduction in the pollution load.

1. Introduction

Nutrient enrichment by human activity (Huisman et al., 2018; Steffen et al., 2014; Tarczyńska et al., 2001) often results in eutrophication expressed by excessive growth of phytoplankton (Suttle, 2000). Eutrophication in both lentic and lotic environments can increase cyanobacteria (Smith, 2003), resulting in harmful algal blooms (HABs) and associated toxins (Brooks et al., 2016). Cyanotoxins can negatively affect aquatic ecosystems (Anderson, 2007; Codd et al., 1999) and sharply increase the cost and complexity of water treatment (Codd et al., 2005; Srinivasan and Sorial, 2011). HABs often occur in eutrophic water under favorable temperature and solar conditions and will likely increase as water temperature increases from climate change and associated hydrological disruptions (Paerl and Paul, 2012).

* Corresponding author.

E-mail addresses: kimjyo0218@gmail.com (J. Kim), JonesJ@missouri.edu (J.R. Jones), seodi@cnu.ac.kr (D. Seo).

<https://doi.org/10.1016/j.ejrh.2020.100769>

Received 7 July 2020; Received in revised form 4 December 2020; Accepted 6 December 2020

Available online 28 December 2020

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Algal toxins in rivers, specifically regulated rivers, are understudied relative to factors that promote HABs in lakes, estuaries, and coastal regions (Graham et al., 2020). The combination of low-head dams and run-of-the-river impoundments in regulated rivers favors algal growth by slowing velocity, increasing water residence times, and provides improved light in shallow depths (Gore and Petts, 1989; Joo and Jeong, 2005; Kim et al., 2018). Given these favorable conditions, cyanobacteria can affect hundreds of kilometers within a single river system (Otten et al., 2015). Cyanobacteria respond to nutrient enrichment and are found mainly in eutrophic rivers (Graham et al., 2020). Therefore, various advanced management techniques to manage HAB occurrence in regulated rivers with nutrient enrichment should be evaluated and implemented.

Various methods have been applied to control algal blooms in the field. There are chemical agents, such as alum (Cooke et al., 2016) and hydrogen peroxide (Bauzá et al., 2014; Zhou et al., 2018), and physical devices including artificial aerators (Heo and Kim, 2004; Lilndenschmidt, 1999; Schönach et al., 2017) and solar-powered water mixers (Hudnell et al., 2010). However, these methods are mostly lentic applications. Regardless, no control method has effectively overcome the exponential growth of algae (Han et al., 2013; Matthijs et al., 2016; Visser et al., 2016). In riverine systems, flow alteration, using dams or weirs, has been proposed to improve water quality and reduce algal blooms (Qin and Shen, 2019; Watts et al., 2009), which relies on water availability (Paerl and Huisman, 2008).

Korean government constructed 16 in-stream weirs in 4 major rivers from 2009 to 2012 to assist flood and drought control (Jun and Kim, 2011; Seo et al., 2012), despite environmental concerns that this approach might promote algal blooms (Seo et al., 2012). Along with hydrological alterations, in-stream structures often change the natural transportation of suspended materials and increase

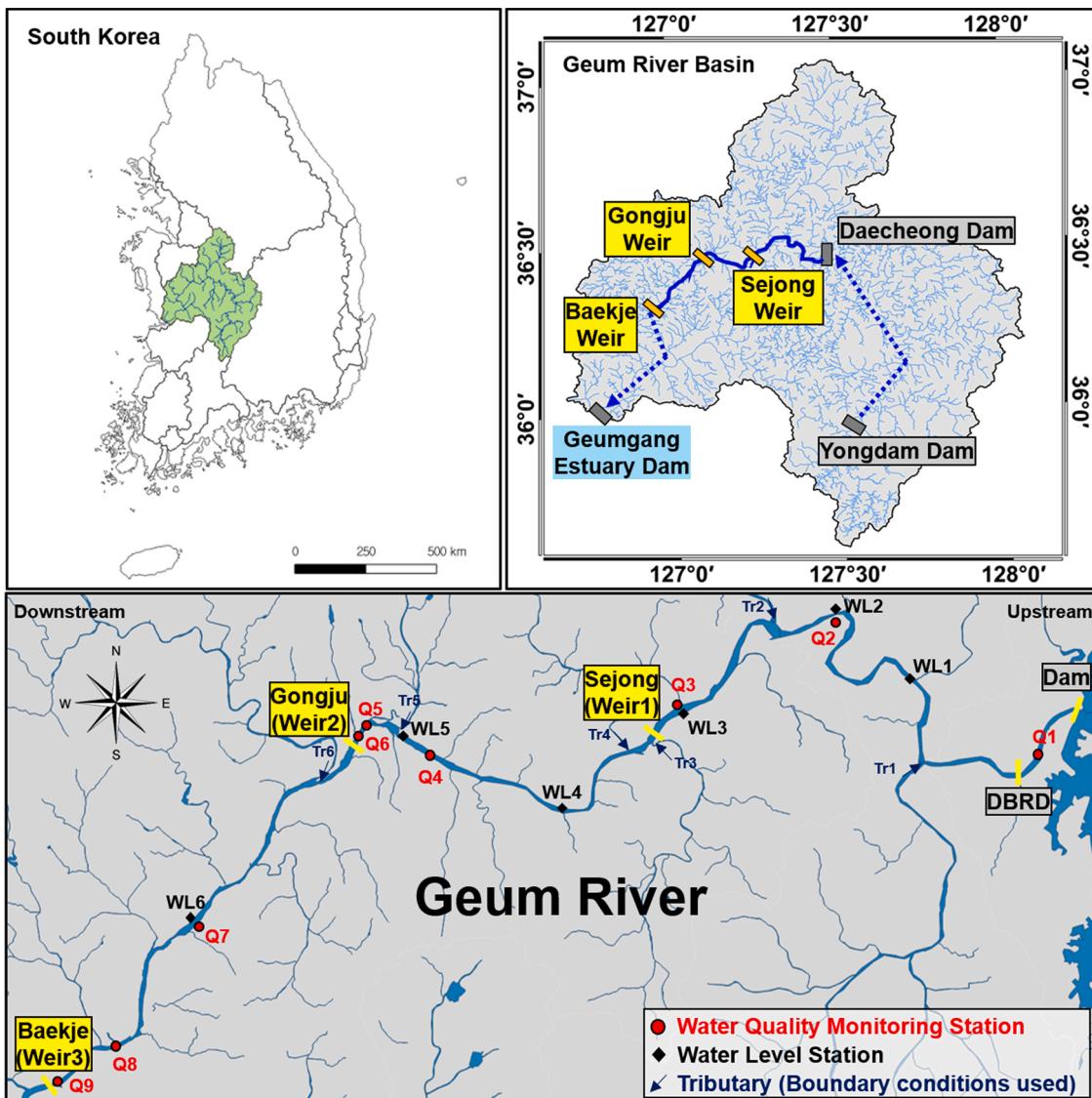


Fig. 1. Locations of monitoring stations and important in-stream structures of the study area.

sediment deposition. Bottom sediment can act as a potential and internal pollution source of nutrients for algal growth ([Seo and Canale, 1999](#)).

In 2018, Korean government formed an evaluation committee to determine operation methods or necessary modification of the installed weirs by evaluating water quality, water use, and socio-economic value. Water quality variables included were algal bloom occurrence (days), Chlorophyll-a concentration (Chl-a), bottom Dissolved Oxygen Concentration (DO), Chemical Oxygen Demand, and sediment pollutant content. In early 2019, the committee suggested measurable improvement of water quality in response to gate opening to accelerate flow ([ME, 2019](#)). In the Geum River, the committee recommended removal of Sejong Weir, partial removal of Gongju Weir, and leaving Baekje Weir fully open, based on field data collected before and after experimental gate operations in 2018.

At issue with this decision is that a simple comparison of field observations for a single year may not warrant sufficient scientific analysis and should not guide decision making because pollutant loading and hydrological conditions may not be fully representative. Furthermore, only after identifying water quality characteristics and HABs occurrence resulting from the operation of hydraulic structures in regulated rivers, can rational river management be determined. In this situation, modeling techniques are effective tools for comparative analysis under fixed conditions over the long-term and across longitudinal reaches in a regulated river ([Ambrose et al., 2009](#)). Previous studies report that flushing, or opening weir gates, benefited water quality and reduced algal blooms in sections of the Nakdong and Yeongsan rivers ([Chong et al., 2015; Park et al., 2019a, b](#)). These studies, however, were conducted in modest sections of these rivers during limited time periods and thus the effects of these methodologies in downstream locations were not fully assessed. The effects of gate operation on HABs should be considered under a range of physical and environmental conditions to develop effective water quality management alternatives.

Therefore, this study evaluates HAB occurrence in the Geum River, using a hydrodynamic and water quality model, under water level management scenarios resulting from altering the operation of the three existing weirs. This process analyzes the effects of hydrodynamic changes on HABs occurrence due to these hydraulic structures making it possible to identify the main factors influencing changes in HAB occurrence. These results can inform operating methods for hydraulic structures to improve river water quality management.

2. Materials and methods

2.1. Study area

The Geum River is the third largest river in South Korea with a length of 395 km and watershed area of 9912 km². The river starts from the bottom center of its basin and flows into Yongdam Lake and Daecheong Lake, the fifth and the third largest reservoirs in the country, respectively ([Fig. 1](#)). Below Daecheong dam, the river turns to the west. Total length of the study area in the river is 69.5 km from Daecheong balancing reservoir dam (DBRD) to Baekje Weir ([Fig. 1](#)). The Gab-cheon River (Tr1) enters at 5 km from DBRD with second greatest pollutant loads in the study area. Then the Miho-cheon River (Tr2) enters at 20.5 km with the greatest loads. The Sejong weir (Weir1) is located at 27.5 km followed by Gongju weir (Weir2) at 46.5 km and Baekje weir (Weir3) at 69.5 km. After the Weir3, the river flows to the West Sea via Geumgang Estuary Dam. The study area has 9 water level monitoring stations (WL1 to 6, Weir1 to 3), 9 water quality monitoring stations on the mainstream (Q1 to 9, Q1 represents the upstream area and Q9 represents the downstream area), and 6 water quality monitoring stations (Tr1 to 6) on tributaries ([Fig. 1](#)). Each weir has a different shape, gate type,

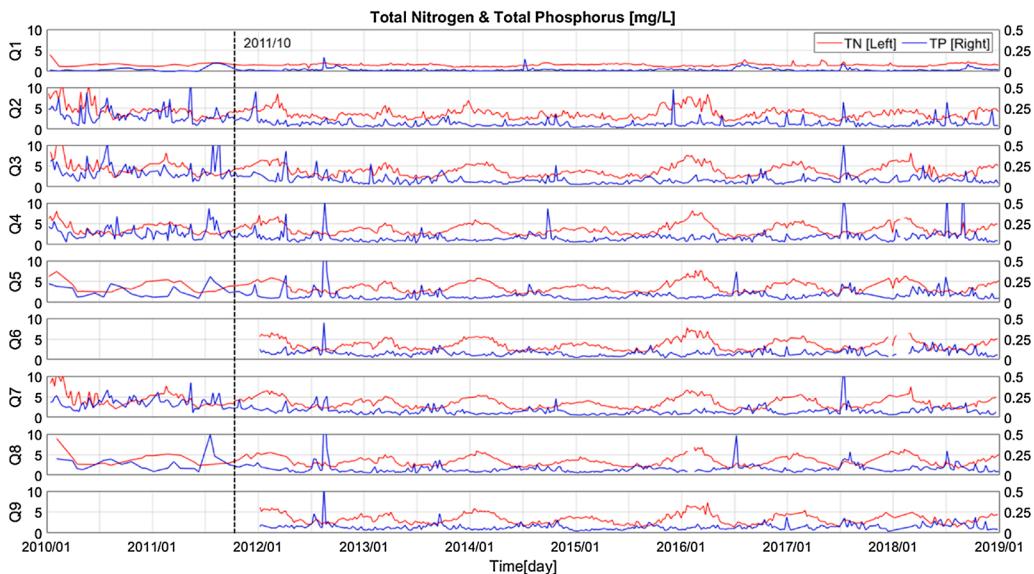


Fig. 2. Observed nutrient concentrations (TN and TP) in the study area.

and specifications (Supplemental Fig. 1). Operation in 2018 was implemented with partial opening of gates on each weir. The gates of Weir1 and Weir2 were operated with the goal of full opening, and for Weir 3, the gates were opened only for a limited period (Supplemental Fig. 2).

2.2. Water quality characteristics of the study sites

Water quality metrics, including total nitrogen (TN), total phosphorus (TP), and Chl-a, showed both temporal and spatial variation in the study reach between 2010 and 2018 (Figs. 2 and 3). The three weirs were completed in October 2011, so the dataset covers the period prior and post-construction.

Water quality at Q1 showed the lowest concentrations for TN, TP, and Chl-a. The first tributary (Tr1) delivers urban pollutant loads from Daejeon City with over a million residents. TN and TP concentrations at Q2 sharply increased by 2.3 and 3.4 times on average, respectively. The second tributary (Tr2) carries pollutants from Cheongju City and its vicinity. As a result, water quality concentrations at Q3 averaged 2.6 and 5.4 times the minimum TN and TP at Q1, showing the worst condition in the study area. Water quality of the Weir1, Weir2, and Weir3 have been monitored at Q3, Q6, and Q9, respectively. Water quality downstream gradually improved due to natural processes such as sedimentation or biochemical reactions though more pollutants were likely introduced from tributaries and other unknown sources.

Summer monsoon weather in Korea increases sediment delivery during storm events (Jones et al., 2009). As TP tends to be strongly adsorbed to sediment, its concentration during summer storms will increase. In contrast, TN is dominated as dissolved forms and is relatively independent of sediment transport (Seo and Kim, 2016).

Nitrogen to phosphorus (N/P) ratios of ten or less indicate nitrogen-limited systems for algal growth while the ratio of twenty or greater indicates a phosphorus-limited system (Thomann and Mueller, 1987). N/P ratios in the Geum River (Supplemental Fig. 3) were calculated using 1) TN-TP and 2) dissolved inorganic nitrogen (Ammonia Nitrogen + Nitrate Nitrogen, hereafter DIN) and dissolved inorganic phosphorus (PO_4^3- , hereafter DIP) which are considered available forms for phytoplankton growth. The ratios were mostly above 20, indicating growth of algae in the Geum River was controlled by phosphorus.

In most seasons, diatoms dominated the suspended phytoplankton at all sampling sites (Supplemental Table 1). A seasonal increase in Chl-a, however, occurs at each site during summer (Fig. 4) when the dominant cyanobacteria taxa were Microcystis (83 %), Aphanizomenon (13 %), Anabaena (2 %), and Oscillatoria (2 %). Maximum Chl-a in 2018 was 209.9 mg/m³ at Q6, although nutrient concentrations were higher at Q3 (Fig. 4). This result suggests hydraulic residence time limited algal growth in Weir1 due to increased water velocity during open-gate conditions in 2018. Summer peak Chl-a was lowest (120.1 mg/m³) at Q9 among the three weirs, which seems related to DIP depletion during active algal growth at Q6 (discussed in detail later).

2.3. Model construction and application

2.3.1. Hydrodynamic and water quality model

The major purpose of model application is to analyze possible outcomes by computer methods, given actual operation can be costly or impossible to implement. Mathematical model application is best suited for scenario analysis or sensitivity analysis. In this study, Environment Fluid Dynamics Code (EFDC), a three dimensional hydrodynamic and water quality model (Hamrick, 1992), was used.

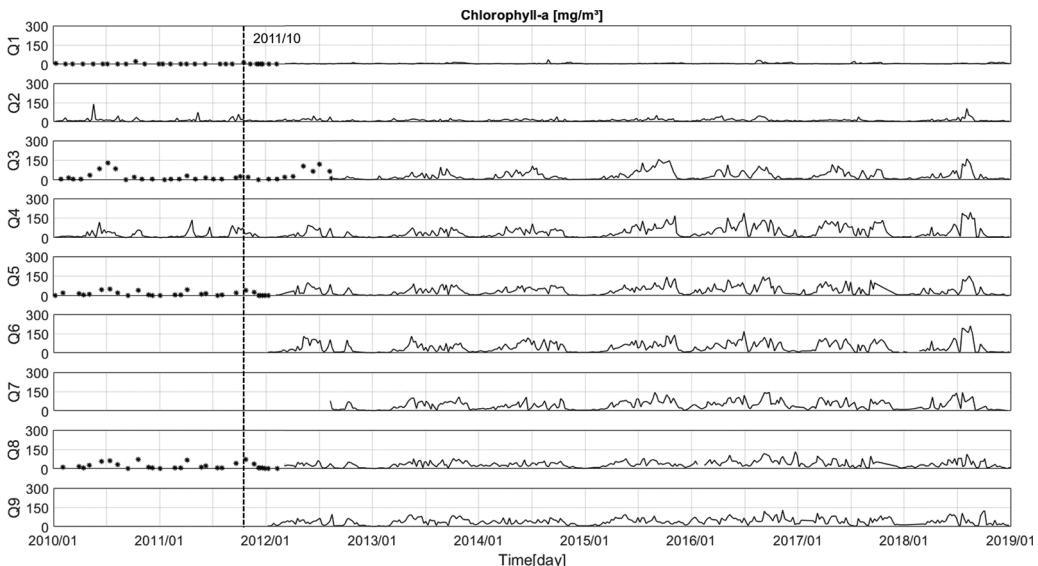


Fig. 3. Observed Chl-a concentrations in the study area.

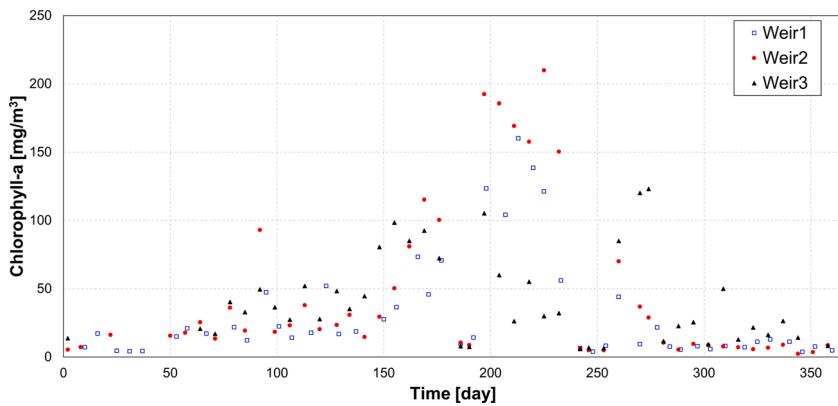


Fig. 4. Chl-a concentrations in three Weirs in the study site (2018). X axis is day of the year.

This model has been applied to rivers, lakes, estuaries, and coastal areas in various locations (Li et al., 2011; Park et al., 2005; Tang et al., 2016). The EFDC can efficiently reflect complicated morphology of the study site using orthogonal curvilinear coordinate methods (Chikhliwala and Yortsos, 1985) and can consider weir operation. The water quality module of EFDC is focused on the growth of multiple algal groups (Park et al., 1995). A detailed description of EFDC can be found in previous studies (Bae and Seo, 2018; Kim et al., 2017). In addition, the equation for algal growth of EFDC is in the supplemental file (Equations (1) ~ (3)).

2.3.2. Grid development

For this study, a grid system was developed with 6698 horizontal cells and 5 vertical cells by the curvilinear orthogonal coordinate method (Fig. 5). The number and size of horizontal cells were adjusted to accurately reflect locations of water gates in each weir. The Courant–Friedrichs–Lewy (CFL) Condition (Courant et al., 1928) was less than 0.4, and the average of Orthogonal Deviation (OD) was 1.37. The suggested limit of CFL number for an appropriate grid system is 1.0, and the closer the OD is to 0, the smaller the error for developed curvilinear grid.

2.3.3. Boundary condition

Water quality, temperature, flow rates, and meteorological data were obtained from the national database system of the Republic of Korea (water.nier.go.kr; wamis.go.kr; data.kma.go.kr). Data were interpolated as daily rates for variables with longer monitoring intervals. Algae were divided into three groups as cyanobacteria, diatoms, and other algae, including green algae and flagellates (Supplemental Table 1).

2.4. Calibration of water levels and water quality concentrations

Model calibrations were performed against field observations in 2018. Water level calibrations were performed at 9 water level

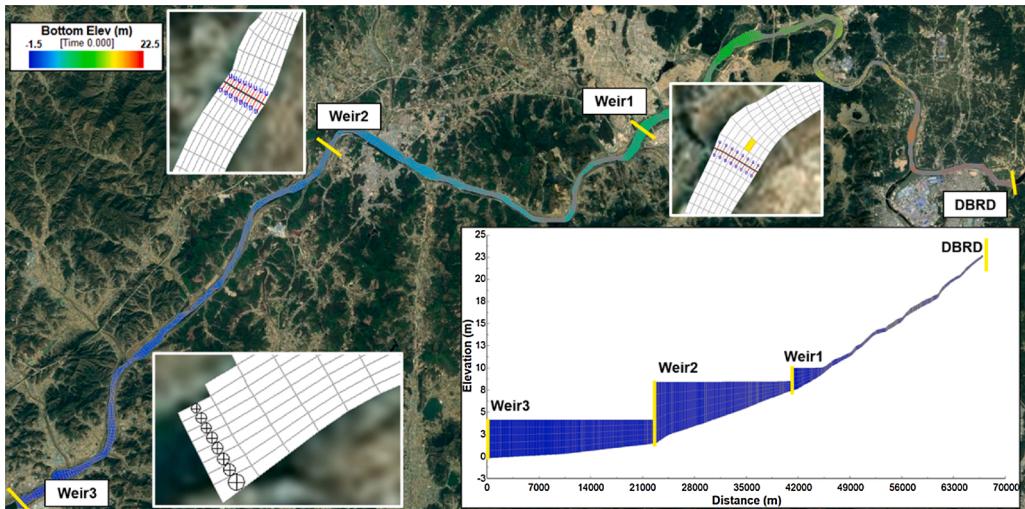


Fig. 5. Horizontal and vertical grid development for this study.

monitoring stations, including 6 water level monitoring stations and 3 weir locations. Water quality calibrations were performed at 8 water quality monitoring stations ($Q_2 \sim 9$) for Total organic carbon (TOC), TN, TP, Chl-a, DO, Ammonia nitrogen ($\text{NH}_3\text{-N}$), Nitrate nitrogen ($\text{NO}_3\text{-N}$), and DIP. Fig. 6 shows the calibration results for three weir locations. Calibration accuracy was calculated (Table 1) using Root Mean Square Error (RMSE) and the coefficient of determination (R^2). The parameters were initially chosen from previous research reports (Bowie et al., 1985; Shin et al., 2008) and adjusted further to improve calibration accuracy (Table 2).

2.5. Scenario development

In this study, three water level operation scenarios were considered. “CLOSED” means weir gates remain closed all year, and water flows over fixed structures. In contrast, “OPEN” indicates all the weir gates remain open, and water flows freely through the gates. Water levels differ between the CLOSED and OPEN scenarios (Table 3). During the 2018 evaluation, weir gates were operated between closed and open levels for various test purposes, and this flow condition is characterized as “FIELD” (Supplemental Fig. 2).

3. Results and discussion

3.1. Changes in water levels and water quality due to gate control

Water level, water temperature, and velocity fluctuated in three weirs in response to gate control scenarios (Fig. 7): fully closed condition (CLOSED), fully open condition (OPEN), and field operation condition (FIELD, after 2018). To evaluate the effects of different gate operations, volume-averaged values of 40 horizontal and vertical cells were used in the vicinity of weirs. For the weighted averaged values, calculated values for OPEN and FIELD scenarios were compared with the CLOSED scenario at each Weir (Table 4).

Water temperature in all regions does not show appreciable differences among these scenarios. However, in CLOSED, water temperature averaged 0.5 °C higher than in other scenarios. Water velocity was the fastest for OPEN and the slowest for CLOSED. The hydraulic residence time in a finite segment is inversely proportional to water velocity for the same cross-sectional area. Therefore, annual average hydraulic residence times were 0.26~0.40 times lower for OPEN than CLOSED conditions.

Water quality and algal biomass varied in response to gate operation scenarios (Fig. 8). While TN and DIN do not show large changes, greater changes were observed in DIP, Chl-a, Cyanobacteria (Cyano), and TOC. For OPEN, TP increased in Weir3 by 79 % relative to the CLOSED operation, concurrent with seasonal algal growth (days 200–240). TOC was affected by increases in Chl-a, reflecting production of organic material through photosynthetic activity. Two different peaks were observed for Cyano during the summer and fall. During the non-summer periods, Chl-a was considerably higher in Weir2 than elsewhere in the study reach.

In Weir1, DIP was depleted under the CLOSED scenario when the algal biomass measured as Chl-a and Cyano peaked at 131 and 94 mg/m³, respectively (days 200–240), which coincided with increased hydraulic residence time. DIP depletion, however, was also

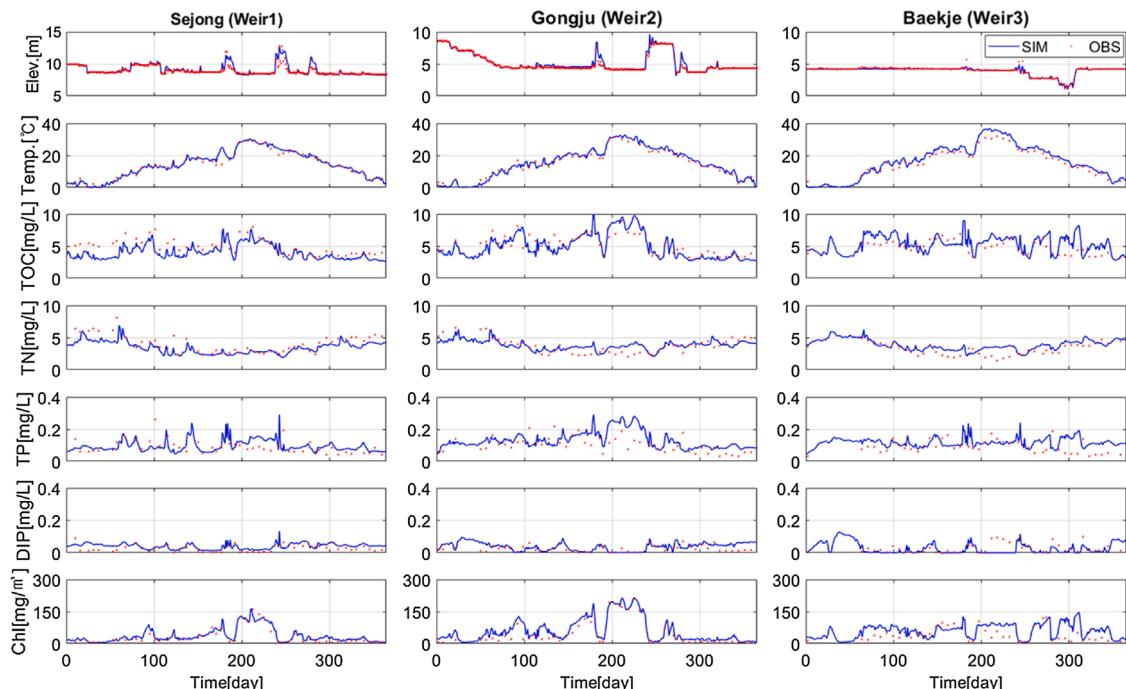


Fig. 6. Water level, temperature, and water quality calibration results in the Geum river.

Table 1

Performance statistics of calibration results in the Geum river.

Variable	Weir1		Weir2		Weir3	
	RMSE	R ²	RMSE	R ²	RMSE	R ²
Elevation [m]	0.37	0.83	0.29	0.97	0.12	0.97
Temp [°C]	1.95	0.95	1.72	0.97	2.64	0.97
Chl-a [mg/m ³]	13.50	0.86	26.41	0.90	37.80	0.25
TOC [mg/L]	1.24	0.41	1.12	0.65	1.35	0.16
TN [mg/L]	1.16	0.67	0.89	0.45	0.88	0.40
NH ₃ -N [mg/L]	0.25	0.85	0.23	0.86	0.25	0.66
NO ₃ -N [mg/L]	0.85	0.69	0.59	0.50	0.57	0.51
TP [mg/L]	0.04	0.05	0.06	0.16	0.05	0.02
DIP [mg/L]	0.02	0.33	0.02	0.11	0.03	0.08
DO [mg/L]	1.72	0.34	2.06	0.21	2.55	0.19

Table 2

Summary of the kinetic coefficients in the current model application.

Parameter	Value
C : N : P : Chl-a ratio	50.1 : 11.5 : 1.3 : 1
Optimal temperature for algal growth (°C)	18–31, 12, 20–25 ^a
Maximum growth rate for algal growth [day ⁻¹]	3.5, 2.5, 3 ^a
Basal metabolism rate for algae [day ⁻¹]	0.06
Predation rate for algae [day ⁻¹]	0.0, 0.05, 0.02 ^a
Half-saturation constant for nitrogen uptake of algae [mg L ⁻¹]	0.01
Half-saturation constant for phosphorus uptake of algae [mg L ⁻¹]	0.001
Algae settling rate [m day ⁻¹]	0.0, 0.2, 0.05 ^a
Decay rate of organic carbon [day ⁻¹]	0.005, 0.075, 0.01 ^b
Decay rate of organic phosphorus [day ⁻¹]	0.005, 0.075, 0.2 ^b
Decay rate of organic nitrogen [day ⁻¹]	0.005, 0.075, 0.015 ^b
Settling velocity of particulate organic matter [m day ⁻¹]	2
Benthic flux rate of phosphate [g m ⁻² day ⁻¹]	0.02

^a For cyanobacteria, diatoms, and other algae, respectively.^b For refractory particulate, labile particulate, and dissolved organic matter, respectively.**Table 3**

Water level changes of weir for gate scenarios.

Weir No. (Name)	CLOSED [meter]	OPEN [meter]	Change Percent [% Min/Max]
Weir1 (Sejong)	11.80	8.20	69
Weir2 (Gongju)	8.75	2.60	30
Weir3 (Baekje)	4.20	1.00	24

occurred in Weir2 and Weir3 during the same period for all gate scenarios. While DIP depletion did not occur in Weir1 during days 290–310, it occurred in Weir2 and Weir3 only for CLOSED.

Annual average Chl-a and Cyano were lower in all locations in the study site in an OPEN scenario relative to CLOSED condition (Table 4 and Fig. 8). The maximum change rates of annual average Chl-a and Cyano were -52 % and -55 % in Weir2 and Weir1, respectively, whereas the minimum change rates of them were -28 % and -2% in Weir1 and Weir3, respectively. Algal bloom occurrence, however, shows a seasonal pattern, and annual averages may not fully represent field conditions. In OPEN, summer averages of Cyano were 55 % and 36 % lower for Weir1 and Weir2, but this was 17 % higher in Weir3 than CLOSED. The maximum value of Cyano in the first peak was 71 % and 14 % lower in Weir1 and Weir2 but it was 90 % higher in Weir3 in OPEN than CLOSED.

Noteworthy, average bottom slopes from DBRD to Weir1 and from Weir2 to Weir3 are 0.054 % and 0.012 %, respectively. Steeper bottom slopes increase the kinematic water velocity due to increased gravity. Higher water velocity reduces hydraulic residence time, allowing less time for algal growth. This effect was especially pronounced in Weir1, in the upper stream area of this study site, where the bottom slope was the steepest. For OPEN, less algal growth would result in reduced uptake of DIP, which would increase DIP transport downstream. Therefore, lower uptake of DIP in Weir1 provides nutrients for algal growth in Weir2 and Weir3 during OPEN conditions despite shorter residence time than CLOSED. This situation may lead to a chain reaction downstream during the period between days 200–240.

During this same period (days 200–240), in Weir1, CLOSED showed higher Chl-a and Cyano than OPEN and coincided with extremely low DIP (Fig. 8 and Supplemental Table 2). In Weir2, Chl-a and Cyano peaks relative to Weir1 were lower by 31 % and 19 % during CLOSED operation, whereas they were 29 % and 143 % larger during OPEN. This difference was due to DIP uptake occurring in

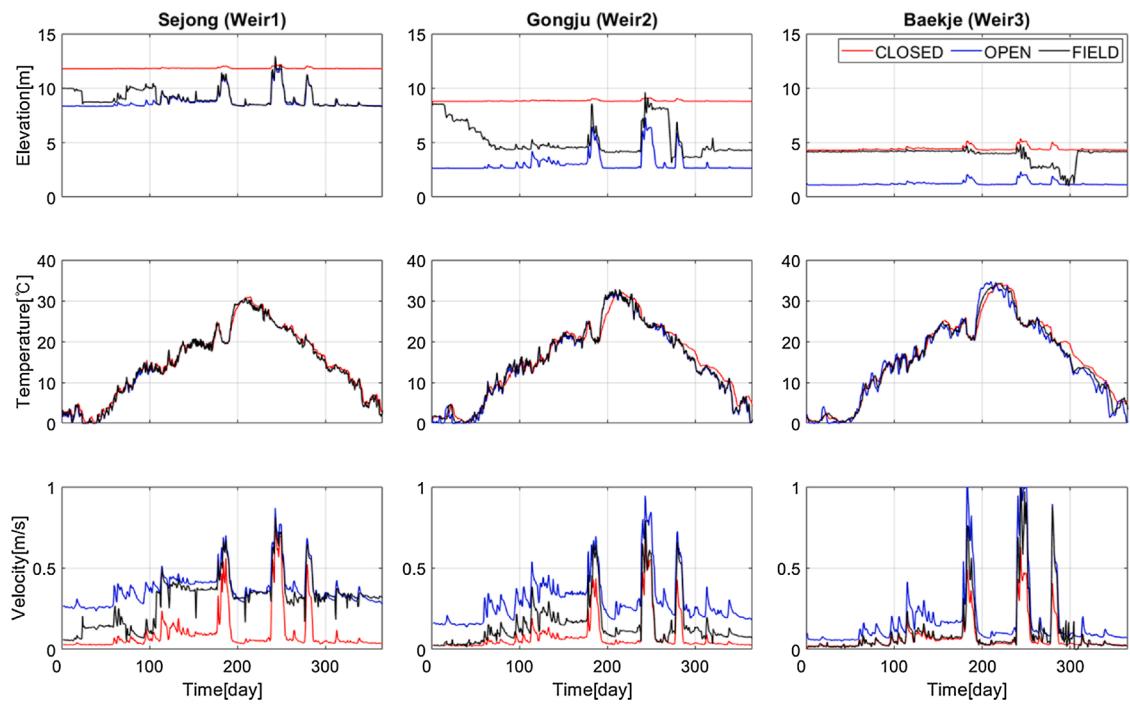


Fig. 7. Water level, temperature, and water velocity changes of different gate operations.

Weir1 during the CLOSED scenario, which did not occur during the OPEN operation. In Weir3, DIP was depleted during the CLOSED operation, which may limit algal growth. DIP in OPEN condition, however, it was supplied from upstream at concentrations to support algal growth.

Therefore, gate operation in the OPEN condition may reduce algal blooms upstream but may increase them downstream. In conclusion, algal blooms in the study site seem to be determined by not only residence time, but also the delivery of limiting nutrients, especially DIP, from the upstream reach.

3.2. Changes in algal growth limiting conditions due to gate operations

DIN and DIP are limiting nutrients for algal growth (Supplemental Eq. 2, [Odum and Barrett, 1971](#)). As confirmed by N/P Ratios (Supplemental Fig. 3), DIP is the nutrient controlling algal growth in the Geum River. In this study, DIP was especially low in all cases during days 200–240, when HABs were $>20 \text{ mg/m}^3$ Chl-a for all scenarios and all locations. This phenomenon in Weir1 was more pronounced for CLOSED than other gate operations, but DIP depletion occurred for all gate conditions in Weir2 and Weir3 concurrent with summer algal blooms. When the second algae peak occurred in fall, however, DIP was higher in Weir2 and Weir3 for OPEN than CLOSED, reflecting less consumption in upstream and greater supply to downstream areas. It is probable that extreme HAB occurrences can occur downstream of Weir3, though this area is beyond the scope of this study.

Light availability for algal photosynthesis (Supplemental Eq. 3, [\(Steele, 1965\)](#)) is a function of water depth (H) and light extinction coefficient (Ke). Also, Ke is a function of total suspended solids and Chl-a concentration (Supplemental Eq. 6), reflecting scattering and adsorption by particulates. Consequently, algal growth benefits when the water depth is shallow, as is the case in the OPEN scenario. However, during days 200–240, light limiting factors were lowest for all gate conditions concurrent with peak Chl-a and Cyano as a result of self-shading by phytoplankton, which made Ke larger. During this period, depth control may not be the major factor for algal blooms ([Fig. 9](#)).

In this paper, total multiplication of limiting factors (Supplemental Eq. 1, [\(Di Toro et al., 1971\)](#)) will be referred to as the net growth limiting (NGL) value for algal growth. Algal growth becomes closer to the maximum when this value is closer to unity. NGL ([Table 5](#)) was calculated during summer (days 180–320) when Cyano peaks occurred in the study site. OPEN showed $0.38 \sim 0.64$ NGL values while CLOSED showed $0.13 \sim 0.38$, which means cyanobacteria can grow up to 4 times greater in OPEN. This contrast seems in response to reduction of water depth, allowing greater light penetration. Also, more DIP would be available for Weir2 and Weir3 when OPEN.

Although annual average NGLs increased in OPEN, water velocity also increased. To evaluate the effect of the residence time change, Lagrangian Particle Tracking (LPT) ([Dunsbergen and Stelling, 1993](#); [Hamrick, 1992](#)) was used for Cyano particles. The LPT method uses total derivative, rather than partial derivative, to accurately track the path of a particle in the water. In this study, LPT module in EFDC was applied and a hundred particles were introduced every 10 days for 7 times during the summer between days 180 and 240, when Cyano growth was greatest in all conditions. LPT residence time can be 1.2~6.7 times longer with an average of 3.7

Table 4

Changes of major variables at three weirs for different gate operation scenarios.

Variables	Unit	Sejong (Weir1)			Gongju (Weir2)			Baekje (Weir3)		
		CLOSED	OPEN	FIELD	CLOSED	OPEN	FIELD	CLOSED	OPEN	FIELD
WL	m	11.83	8.75	9.10	8.83	3.06	5.25	4.43	1.24	3.91
	%	100.00	73.99	76.98	100.00	34.63	59.44	100.00	27.95	88.35
Temp	°C	14.94	14.53	14.59	15.37	14.69	15.01	16.24	15.46	15.80
	%	100.00	97.30	97.70	100.00	95.57	97.62	100.00	95.19	97.29
Velocity	m/s	0.098	0.372	0.300	0.078	0.297	0.149	0.071	0.176	0.102
	%	100.00	377.87	304.96	100.00	380.50	191.28	100.00	248.21	143.90
TOC	mg/L	4.66	4.16	4.17	5.98	4.19	4.54	5.83	4.43	5.28
	%	100.00	89.23	89.52	100.00	70.06	75.82	100.00	76.05	90.57
TN	mg/L	3.99	3.99	3.98	4.07	3.97	3.99	3.96	4.10	4.06
	%	100.00	100.09	99.80	100.00	97.58	97.90	100.00	103.40	102.48
DIN	mg/L	3.20	3.33	3.31	2.91	3.26	3.18	2.76	3.29	3.03
	%	100.00	103.99	103.51	100.00	112.05	109.53	100.00	119.14	109.64
TP	mg/L	0.102	0.101	0.101	0.106	0.106	0.105	0.092	0.114	0.101
	%	100.00	98.99	98.69	100.00	100.23	99.07	100.00	124.66	109.77
DIP	mg/L	0.035	0.044	0.043	0.014	0.048	0.040	0.014	0.055	0.027
	%	100.00	125.55	123.68	100.00	356.21	293.77	100.00	404.01	202.43
S* DIP	mg/L	0.032	0.044	0.043	0.016	0.039	0.032	0.014	0.033	0.017
	%	100.00	136.48	136.28	100.00	241.59	194.76	100.00	241.91	124.39
Chl-a	mg/m³	31.78	22.90	23.25	58.39	28.23	34.47	47.72	31.09	41.83
	%	100.00	72.07	73.17	100.00	48.34	59.04	100.00	65.14	87.65
S* Chl-a (Peak**)	mg/m³	49.79 (128.14)	37.47 (74.78)	37.41 (74.57)	60.11 (88.24)	45.85 (96.20)	51.90 (105.61)	47.90 (52.90)	52.68 (103.75)	51.48 (59.25)
	%	100.00	75.26	75.13	100.00	76.27	86.33	100.00	110.00	107.49
Cyano	mg/m³	8.30	3.72	3.72	12.92	7.54	8.45	11.32	11.06	10.15
	%	100.00	44.85	44.80	100.00	58.31	65.42	100.00	97.77	89.70
S* Cyano (Peak**)	mg/m³	24.29 (94.49)	10.97 (27.12)	10.96 (26.87)	34.54 (76.92)	22.15 (65.86)	24.62 (75.89)	27.65 (51.10)	32.26 (96.99)	26.20 (56.09)
	%	100.00	45.15	45.10	100.00	64.13	71.28	100.00	116.70	94.77

S* = Summer (June to September), Non-summer (October to May).

Peak**: July 25th (206 day).

times longer for CLOSED than OPEN (Table 6).

To assess the dominant factor affecting algal growth, which would be either a decrease in hydraulic residence time (DHRT) or an increase in net growth limitation (INGL), factors for OPEN and FIELD scenarios were compared with the based case, CLOSED (data from Table 6). Individual scenarios were plotted in DHRT vs. INGL space and assessed relative to the isocline of no net change (Fig. 10). Positive direction on the y-axis suggests favorable conditions for algal growth, whereas positive on the x-axis does not. At the x-y intercept (0, 0), algal growth conditions for OPEN and FIELD options are the same as CLOSED. In the case of O5 (Fig. 10), its coordinates are (85, 1495), which means residence time decreased by 85% ($(17.33 - 2.58)/17.33 = 0.85$), while NGL increased by 1,495% ($((0.299 - 0.022)/0.022 = 14.95$). This calculation indicates INGL in O5 is far greater than DHRT, suggesting the algal growth rate would be higher for OPEN than CLOSED despite the shorter residence time. Alternatively, coordinates of F7 (Fig. 10) are (21, 6.7) where DHRT is greater than INGL.

Fig. 11 shows horizontal Cyano distributions in the study site on the 206th day (July 25th) in the surface layer during the hydrodynamic simulation. For CLOSED, Cyano, or harmful algal bloom occurred at the highest level at a location between Weir1 and Weir2. For FIELD and OPEN, the maximum HAB occurrence locations tend to move further downstream due to increased hydrodynamic transportation.

Under the OPEN scenario, the lateral difference of Cyano became more pronounced as longitudinal advection was stronger, which would limit lateral transportation of matter compared to other scenarios. For OPEN, lateral Cyano distribution in Weir1 became more apparent when Tr2, the largest tributary in the study area, was introduced, which increased velocity in the left side of the river (from upper to downstream direction, (Kim et al., 2018)). This pattern was more pronounced near Weir2 and downstream (shown in the magnified section of Fig. 12). In contrast, CLOSED shows an almost completely mixed pattern in the lateral direction near Weir3, Cyano growth was apparently greater along the river margins than the middle in OPEN. Therefore, when the gate operation method changed from CLOSED to OPEN, HABs occurrence pattern changed both in a longitudinal direction as well as lateral.

The lateral pattern for TOC, TN, TP, Chl-a, and Cyano in the right, center, and left cells in three weirs shows distinct differences (Fig. 12). In CLOSED, Weir2 and Weir3 did not show significant concentration differences in the lateral direction relative to other scenarios. The most obvious concentration distinction was found in OPEN. Overall, nutrient concentrations tended to become greater at the right side of the river and this pattern was clearer in OPEN case.

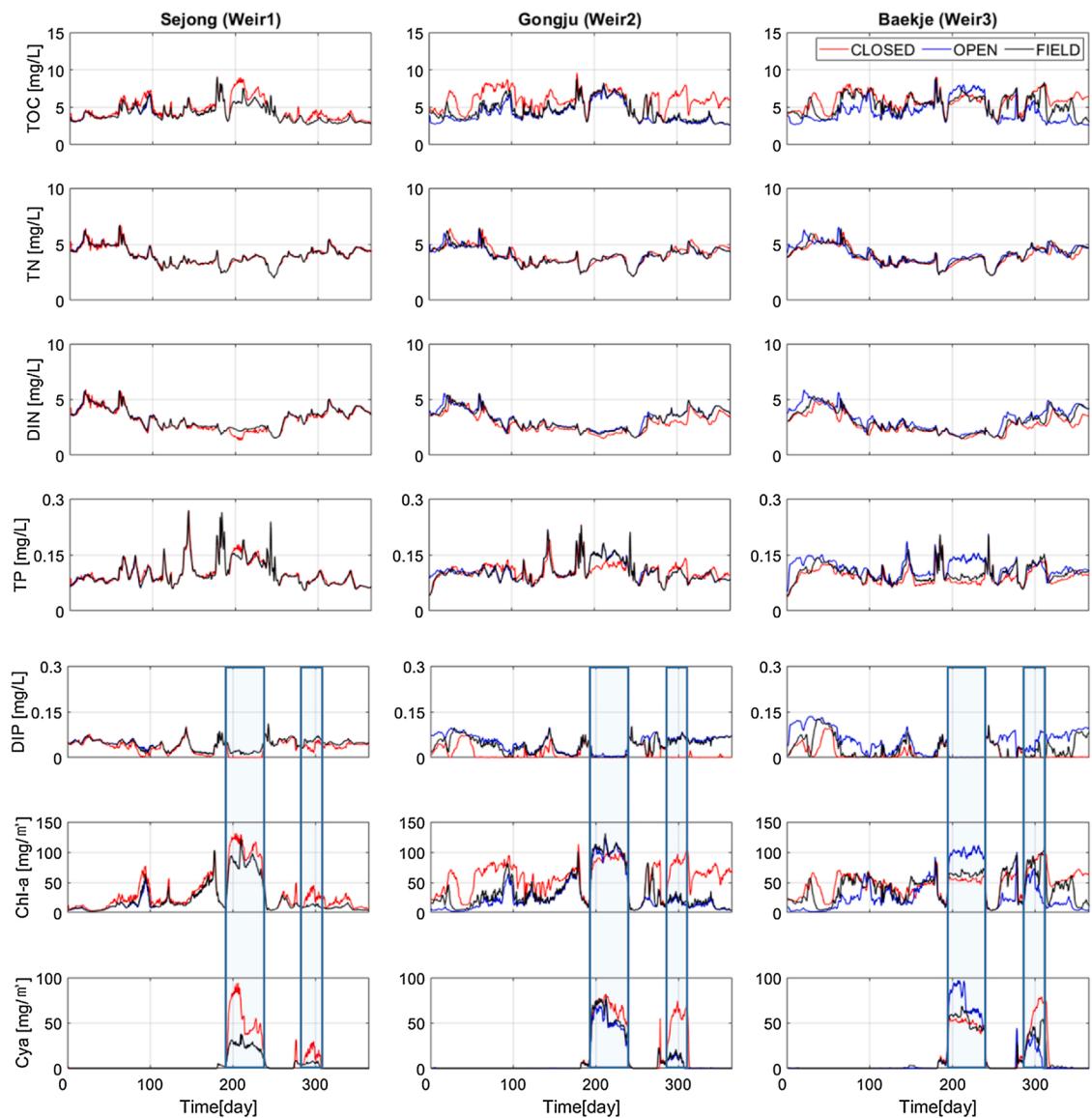


Fig. 8. Water quality predictions at weirs for different water gate operation scenarios. The blue boxes emphasize the two peak seasons of Cyanobacteria.

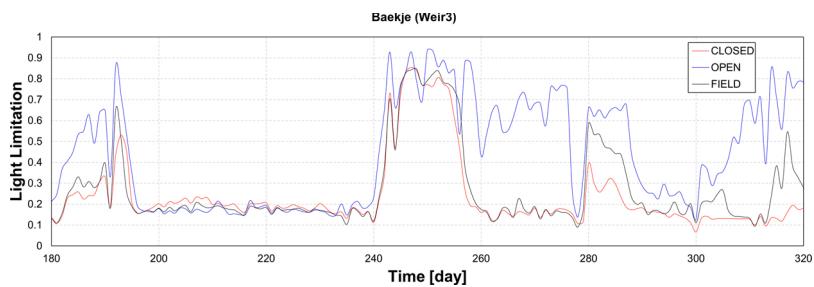


Fig. 9. Estimated light limiting factor values for different gate operations.

Table 5

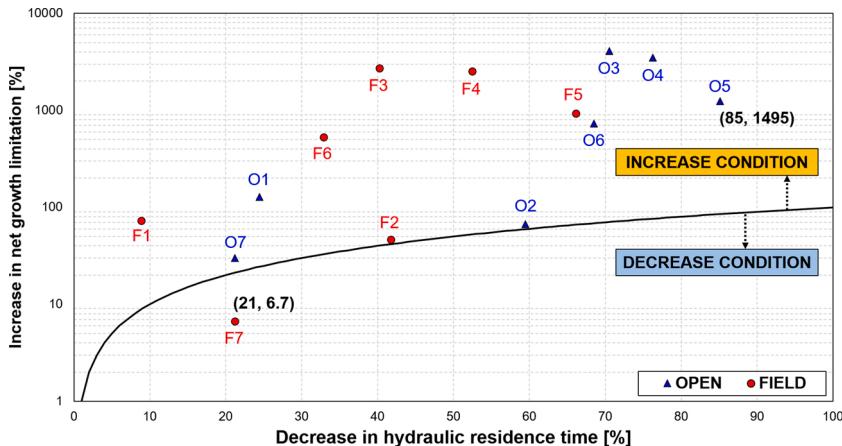
Estimated net growth limitation (NGL) of cyanobacteria.

Average	Weir1			Weir2			Weir3		
	CLOSED	OPEN	FIELD	CLOSED	OPEN	FIELD	CLOSED	OPEN	FIELD
-	0.38	0.64	0.64	0.14	0.56	0.36	0.13	0.38	0.18
%	100.0	168.1	167.3	100.0	403.6	264.8	100.0	289.4	140.2

Table 6

Total residence time of a particle calculated by Lagrangian Particle Tracking (LPT) method.

No.	Input Day	Residence Time [day]			Net Growth Limitation		
		CLOSED	OPEN(O)	FIELD(F)	CLOSED	OPEN(O)	FIELD(F)
1	180	1.88	1.42	1.71	0.18	0.41	0.31
2	190	3.29	1.33	1.92	0.37	0.62	0.54
3	200	10.46	3.08	6.25	0.01	0.31	0.21
4	210	14.38	3.42	6.83	0.01	0.26	0.19
5	220	17.33	2.58	5.88	0.02	0.30	0.23
6	230	9.00	2.83	6.04	0.04	0.34	0.26
7	240	1.38	1.08	1.08	0.33	0.43	0.35
	Mean	8.25	2.25	4.24	0.137	0.38	0.30

**Fig. 10.** Decrease in hydraulic residence time (DHRT) versus increase in net growth limitation (INGL) for 7 LPT analysis events for OPEN and FIELD conditions compared to CLOSED.

4. Conclusion

The purpose of this research was to analyze the effect of hydrodynamic conditions on the water quality and HAB occurrence dynamics in the 69.5 km section of the Geum River in response to gate operation controls (CLOSED, OPEN, and FIELD) of 3 in-stream weirs. The major findings are as follows.

When gates were fully open, annual averages of HABs decreased by 55 % upstream (Weir1) and 2 % downstream (Weir3). Summer averages and peak values, however, were lower in upstream areas and higher downstream. The summer peak value of cyanobacteria in Weir3 was nearly two times greater (97 %) for OPEN than CLOSED. Therefore, OPEN can reduce HAB occurrences in upstream area but can cause HABs proliferation downstream.

When HABs occurred during summer, DIP depletion was observed in all locations indicating P was the limiting factor for algal growth. For OPEN, decreased hydraulic residence time allowed less time for algal growth and this would result in less consumption of DIP upstream allowing greater DIP delivery downstream. As a result, less consumed DIP in Weir1 promotes algal bloom occurrences in Weir2 and Weir3 in OPEN. In addition, water depth reduction in all regions provides more light for photosynthesis. Therefore, algal blooms in the study site seem regulated by not only physical changes including hydraulic residence time (HRT) time and vertical average light but also the availability of limiting nutrients, especially DIP, in the study site.

HRTs were estimated by Lagrangian Particle Tracking (LPT) method in EFDC model. Summer average HRT was 3.7 times longer for CLOSED than OPEN. The plot of DHRT (decrease in hydraulic residence time) versus INGL (increase in nutrient growth limitation) was developed to evaluate factors controlling algal growth control under alternative gate operations, relative to a base case, CLOSED. Most of the time, INGL were significantly higher than DHRT, which indicates nutrient effect on algal growth would be greater than the effect

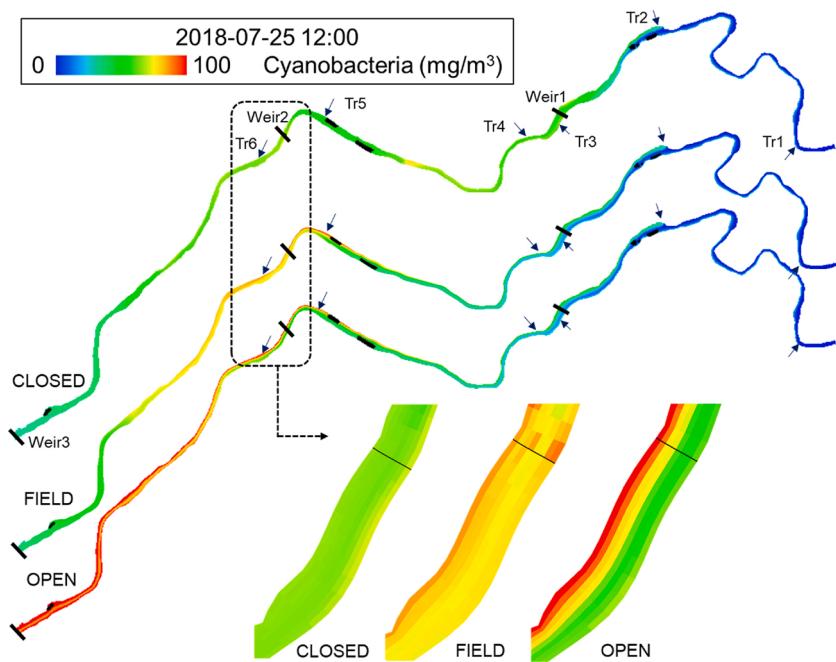


Fig. 11. Predicted horizontal cyanobacteria distributions for different gate operations in the summer.

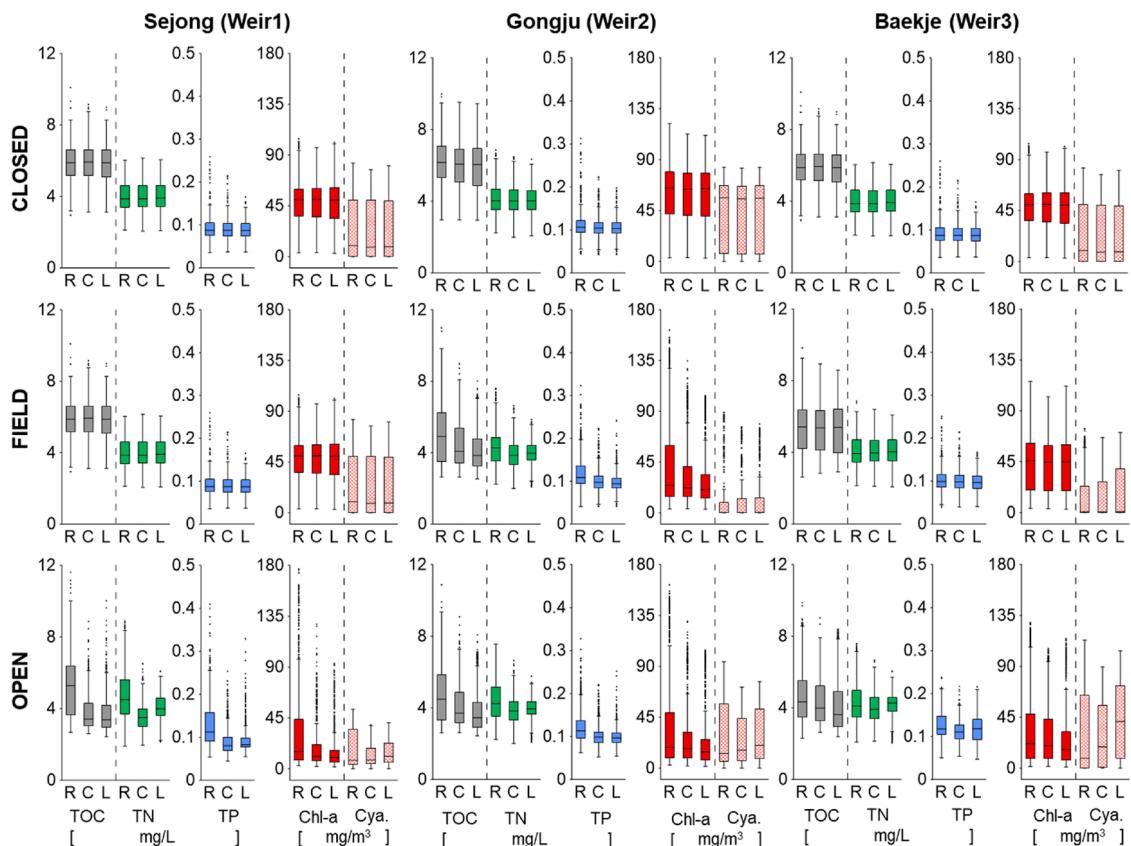


Fig. 12. Predicted lateral distribution of water quality variables for different gate operations at each weir (R: Right, C: Center, and L: Left).

of water velocity, despite the interconnection between these factors.

This research focused on the changes in HABs for the full opening and closing of gates in the three weirs. Actual operation methods of the weir gates, however, can be determined using various combinations of gate control. This study considered limited scenarios for specific time conditions, there may be limits to generalize the weir gate operation method for all circumstances. Therefore, further study would be necessary considering external and internal conditions of the receiving water body on water quality and HABs occurrences.

This study suggests the effect of physical changes on the improvement of water quality and HABs would be limited when other factors such as pollution load do not change. Although this conclusion was derived for a specific river, similar results and conclusions can be drawn in other water systems using the same analysis methodology.

The weir gate control in the Geum River will affect hydrodynamic conditions and algal growth kinetics along the river significantly. Downstream areas are directly affected by operations upstream, which determines conditions that promote HAB occurrence. Careful consideration must be made before making any decision on whether gate operations should be changed or gates removed.

CRediT authorship contribution statement

Jaeyoung Kim: Conceptualization, Methodology, Software, Formal analysis, Validation, Visualization, Writing - original draft.
John R. Jones: Formal analysis, Validation, Writing - review & editing. **Dongil Seo:** Supervision, Resources, Formal analysis, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by research fund of Chungnam National University.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejrh.2020.100769>.

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