2024

Relationship Between Weir Openings and Green Tide Variation in Korean Rivers

Uisuk Jung
University of Kentucky, uisuk.jung@uky.edu

Spring 2024 Capstone Project

Relationship Between Weir Openings and Green Tide Variation in Korean Rivers

Uisuk Jung

Martin School of Public and Administration

University of Kentucky

Faculty Advisor:

Dr. J.S. Butler

Table of Contents

Executive Summary

On the four major rivers in South Korea (Han River, Nakdong River, Geum River, and Yeongsan River), 16 weirs were installed in 2011 to secure water resources. However, there is controversy that the weirs allow the summer Green Tide (hereafter referred to as GT) to thrive, so the South Korean government has been opening them since 2017 to evaluate their effectiveness. The opening of the weirs was mainly done at three weirs on the Geum River, where there are few constraints, and some on the Yeongsan and Nakdong rivers, depending on the degree of constraints, while the Han River was rarely opened.

This study analyzes the correlation between the opening policy and the increase and decrease of GT by dividing the period before the opening (2012-2016) and after the opening (2019-2023) based on 2017-2018, when the weirs were opened, using the difference in difference method. The analysis was divided into two main categories. The first is to compare weirs with high (Gongju weir) and low (Chilgok weir) opening rates in the Geum River and Nakdong River, two rivers with serious GT problems. The second is a comparison between rivers with high and low weir opening rates. I compared a river with a high opening rate (Geum River) with a low opening rate (Nakdong River, Han River). The analysis showed that the weir opening of the Geum River was statistically significant in reducing GT compared to the Han River. The rest of the analysis was not statistically significant.

Considering that the effects on GT are water temperature and nutrients in addition to changes in retention time due to weir opening, there are limitations of this study, so comparative studies between weirs in the same water system are needed if weir opening is expanded in the

future. In addition, since there is a statistical significance between weir opening and GT reduction in the Geum River, and since the summer season in South Korea is characterized by flood risk and low water demand, it would be desirable to improve related facilities so that weir opening can be done flexibly in the future.

1. Introduction

Figure 1 Nakdong River Hapcheon Changnyeong Weir Upstream, August 2016 Algal bloom site (Source: Ministry of Environment)

The South Korean government has built and operated sixteen large weirs in four major rivers (Han River, Nakdong River, Geum River, Yeongsan River) in 2012 to secure water resources and develop the region. The Four Major Rivers Maintenance Project, which was promoted starting with the Nakdong River District groundbreaking ceremony on December 29, 2008, is a major river maintenance project with a budget of 22 trillion KRW[1] until April 22, 2012. The main purpose of this project was to restore the river ecosystem by dredging the four major rivers

[1] At that time, the exchange rate was approximately 1 USD to 1,136 KRW, whereas as of 2024, it is around 1,333 KRW.

of South Korea and installing eco-friendly weirs to significantly increase the water storage capacity of the rivers. However, there were some problems raised that the weir caused a large number of algae to occur in summer, threatening water quality. Since most of South Korea's main sources of drinking water are in the main streams of the four rivers, there were many concerns about the safety of drinking water for residents.

Figure 2 Location of 4 major rivers and sixteen weirs in South Korea (ShinJong-ho, 2012)

Since 2017, the South Korean government has introduced a new policy regarding weirs. Until then, the weir gates were not opened during summer algae blooms. However, since 2017, the government has decided to open the weirs as much as possible. The reason for the different opening ranges for different weirs is that, as I will explain later, it could cause restrictions on water utilization such as pumping stations and water intakes. My main interest in this study is whether the new policy of opening the weirs is effective in reducing algae blooms.

2. Background

Algae are phytoplankton that photosynthesize in water. Algae are primary producers of the aquatic ecosystem food chain, supplying oxygen and serving as food for zooplankton, playing a significant role like terrestrial plants. Algae are largely classified into diatoms, green algae, and blue-green algae. Green Tide (hereinafter referred to as GT) is a phenomenon in which the color of rivers and lakes turns dark green due to blue-green algae, which are the dominant species during summer and autumn. In particular, some species of blue-green algae[2] threaten the safety of water sources by releasing odorous substances and toxins. (Ministry of Environment, 2019)

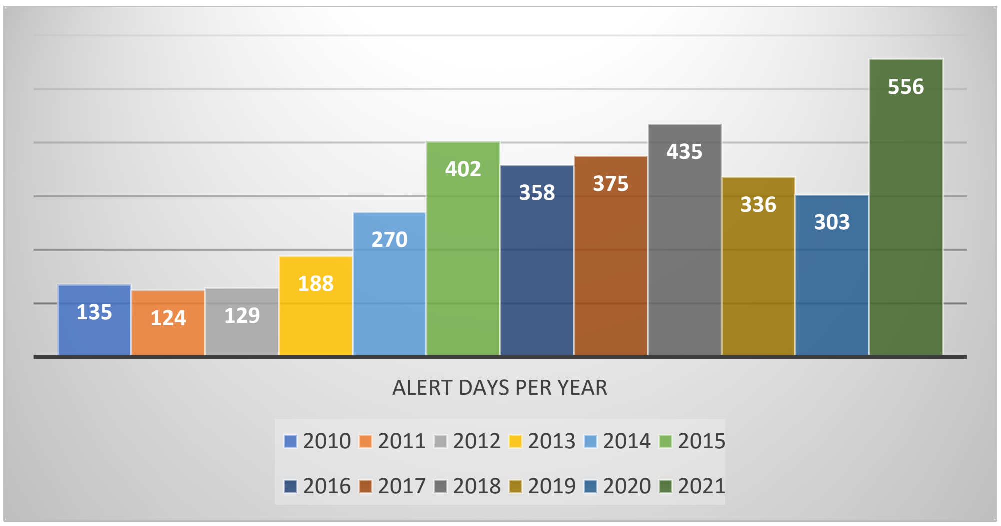


Figure 3 South Korea's Four Major Rivers Algae Warning Issuance Status (Source: Ministry of Environment)

The main river of South Korea, the Nakdong River, is 510 km long and has major water sources in Daegu, North Gyeongsang Province, Busan, Ulsan, and South Gyeongsang Province. According to the current status of issuance of the algae warning system[3] by year by the Ministry of Environment, the number of warnings issued at 10 measurement points in the Nakdong River

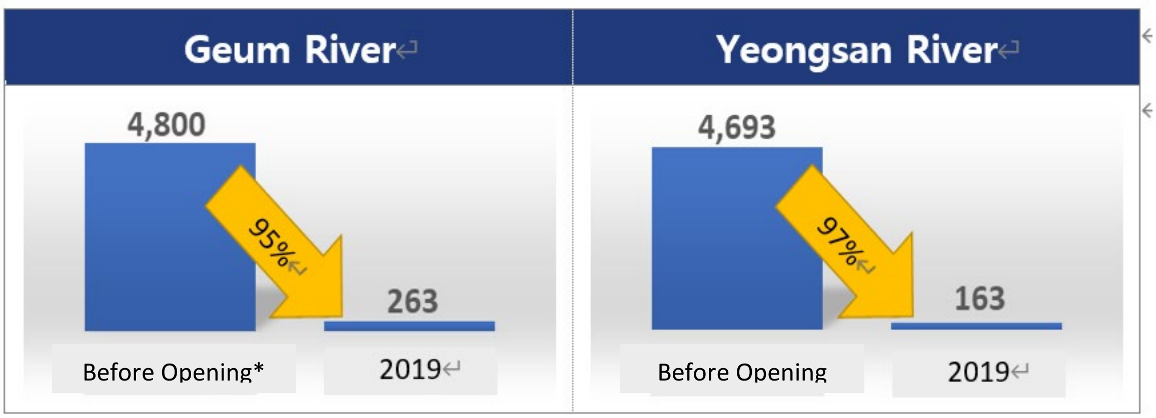
---

[2] Microcystis (excretion of liver toxins), Anabaena (excretion of neurotoxins and odorous substances), Oscilatoria (excretion of liver toxins and odorous substances), Aphanizomenon (discharge of neurotoxins and odorous substances)

[3] The algae warning system is a system to issue an alarm when algae at a certain level occur and take necessary measures to ensure a stable supply of tap water and promote public safety from algae toxins during water-friendly activities. The criteria for issuance are 'interest' if the number of blue-green algae cells per 1mL of water exceeds 100, and 'warning' if the number exceeds 10,000, and is issued if the number exceeds the criteria for two consecutive times. (Ministry of Environment, 2019)

from January to September 2021 totaled 491, almost doubling from the same period in 2020 (247). Looking at the overall four major rivers, there is a trend of increasing from 135 times in 2010 to 556 times in 2021. (선정민, 2021)

The Ministry of Environment also announced results showing that the population of harmful blue-green algae has been decreasing on average since the water gates were opened. In other words, in 2019, when the weir was completely opened, the population of harmful blue-green algae decreased by 95% in the Geum River and 97% in the Yeongsan River compared to before the weir was opened (2013 to 2017). (Ministry of Environment, 2021)



* Before Opening refers in this figure to the annual average between 2013 and 2017.

Figure 4 Comparison of average occurrence of green algae (number of harmful blue-green algae cells, cells/mL) in summer (June to September) before and after weir opening. (Ministry of Environment, 2021)[4]

[4] The Ministry of Environment said that the reason it compared 2019 with the annual average before opening (2013-2017) was because weather conditions were similar.

3. Literature Review

GT is very harmful to ecosystems, including humans. (Kim, 2017) First of all, the flourishing of algae leads to oxygen depletion in the deep layers of rivers and lakes. Algae prospering in the surface layer settle down, but in the deep layer, the algae decompose and consume too much oxygen. At this time, the ecosystem of the deep layer where oxygen is depleted is destroyed. Many aquatic ecosystems, including fish, die.

Blue-green algae are more dangerous because they produce toxins that damage the liver or nervous system of animals. In foreign countries, there are cases of mass deaths of livestock or deaths of people, and reports of an increase in the incidence of liver cancer. Since most of the toxins in blue-green algae are removed in the advanced water purification process, the possibility of human consumption through tap water is low. However, care must be taken because there is a possibility that the toxin can be ingested through accumulated fish and shellfish or agricultural products.

Table 1 Current Status of TP Concentrations in Major Rivers in South Korea (Unit: mg/L)

Classification	Han river	Nakdong river	Geum river	Yeongsan river
Upstream	0.013	0.014	0.019	0.141
Midstream	0.045	0.038	0.115	0.149
Lower	0.104	0.039	0.099	0.067

For GT to occur, high concentrations of nutrients such as phosphorus and nitrogen are required. In particular, the condition in which these nutrients are abundant in rivers and lakes is called eutrophication. The trend of Total Phosphorus (hereinafter referred to as TP) among nutrients that play a role as fertilizer in the growth of algae is as follows (김동욱, 2021). The concentration of TP in major rivers in South Korea is generally low in the upper reaches and higher in the middle and lower reaches, ranging from 0.013 to 0.149 mg/L. In the middle and lower reaches of the river, the TP exceeds 0.015 mg/L and is regarded as eutrophication. This is the basis for abnormal algae growth and destruction of river ecosystems.

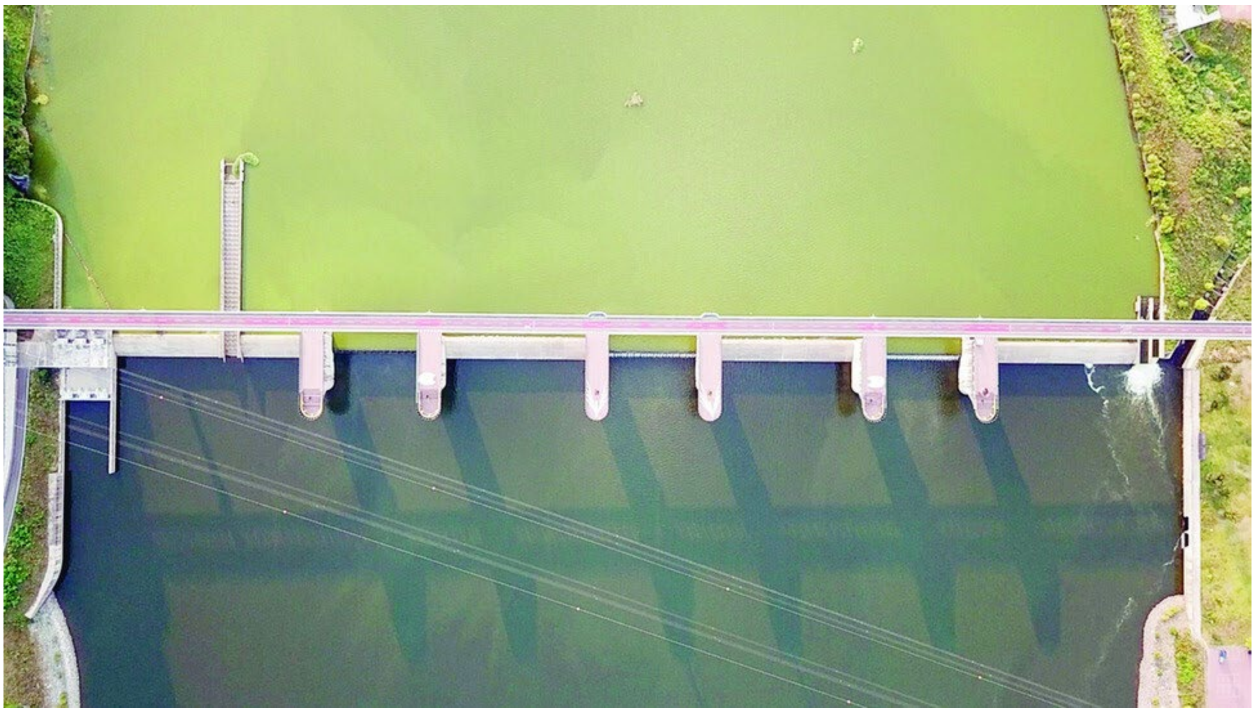


Figure 5 Nakdong River Dalseong Weir, August 1st, 2019, Blue-Green algae is blooming upstream of the weir. (Source: The Hankyoreh)

Since the start of the project in 2009, the Weir of the Four Rivers has caused a lot of controversy in various aspects, and GT was one of them. According to the audit results of the Board of Audit and Inspection conducted in 2018 (김평화, 2018) after the completion of the weir construction, there was a high correlation between the weirs and GT after the Four Major Rivers Project. However, the conclusion was not clear because there were limitations in analyzing the specific cause due to the lack of necessary data. In politics, conservatives and progressives have different positions. Conservatives do not acknowledge the correlation between the weirs of the four major rivers and GT, but progressives claim that there is a correlation. In the 2017 presidential election, Democratic Party candidate Moon Jae-in attributed the algal bloom problem to the Four River project, and Liberty Korea Party candidate Hong Joon-pyo attributed the cause to pollutants and high temperatures. (고성표, 2017)

There have been several audits and government committee investigations related to the weirs and GTs installed on the four major rivers. (구정모, 2023) In January 2013, the National Audit Office pointed out that water quality management standards were improperly established, and water quality forecasts were unreasonable, even though it was expected that eutrophication would occur due to the increased retention time of water after weirs were installed on the four major rivers. Instead of biochemical oxygen demand (BOD), which is the standard applied to rivers, water quality should have been measured based on chemical oxygen demand (COD) or algae concentration, which is the standard applied to lakes and swamps.

In September 2013, a civilian committee under the Prime Minister's Office, the Four Major Rivers Survey and Evaluation Committee (hereinafter referred to as the Committee), was formed to conduct the verification. In December 2014, the Committee released the results of the verification, citing the installation of weirs and dredging as factors that contributed to the deterioration of water quality in the four major rivers. According to the Committee, BOD and phytoplankton generally decreased in the Han River, Nakdong River, and Geum River as a result of the Four Rivers Project, but BOD increased in the upstream section of the Nakdong River at four weirs, and phytoplankton increased in the Yeongsan River. After evaluating the impact of each project on water quality separately, it was determined that the project that removed phosphorus from sewage was the main factor that improved water quality, but the longer retention time of water due to weirs and dredging was a factor that worsened water quality. It was also determined that the intensification of algae blooms in the Nakdong River in 2013 was due to less precipitation and longer water retention time, which was compounded by higher temperatures and increased insolation.

Figure 6 The Committee announcing the evaluation results in December 2014. (Source: Korean Journalists Association) There have been many Board of Audit and Inspection results and committee evaluations related to the Four Major Rivers Project.

In July 2018, the National Audit Office released additional audit results and also disclosed the results of a water quality assessment after the Four Rivers project, which was commissioned by an external organization, the Korea Institute of Environmental Engineering. According to the Korea Institute of Environmental Engineering, it cannot be determined whether BOD and algae concentrations have improved since the Four Rivers Project, and COD has generally worsened in the Nakdong and Yeongsan rivers.

Since opening the weirs in 2017, the South Korean government has been announcing its effects through various materials. A summary of the published data based on actual observation results is as follows. (Ministry of Environment, 2021) First, it was confirmed that as the water flow was improved overall, GT decreased, anoxic bottom water disappeared, and sediment contamination level decreased. In the case of GT, it decreased compared to 2013-2017, before the opening of the weir, especially in the fully opened weir section. In addition, the frequency of occurrence of anoxic bottom water decreased due to the effect of water flow improvement and water layer mixing. The proportion of sand in the sediment was increasing and contaminants were decreasing. In addition, it was announced that the habitat environment for aquatic life has improved, such as the formation of rapids in the fully open weir section, and the habitat environment for terrestrial animals is also improving through the formation of various waterside spaces.

Figure 7 Number of occurrences of anoxic bottom water phenomenon (The figures are the annual average for each period.) (Ministry of Environment, 2021)

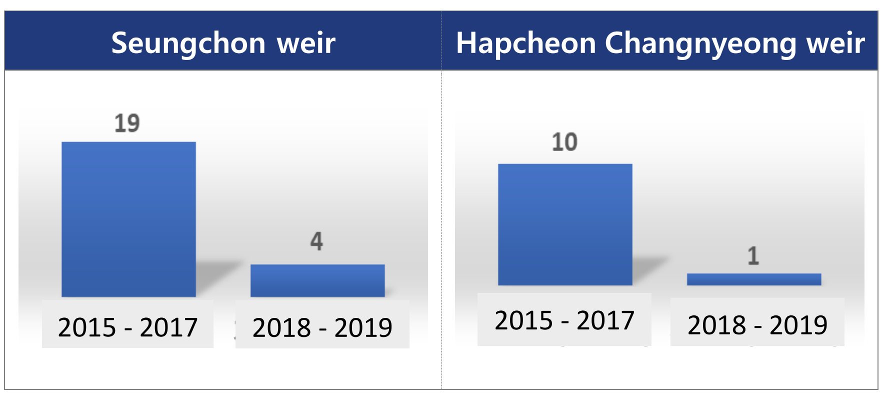
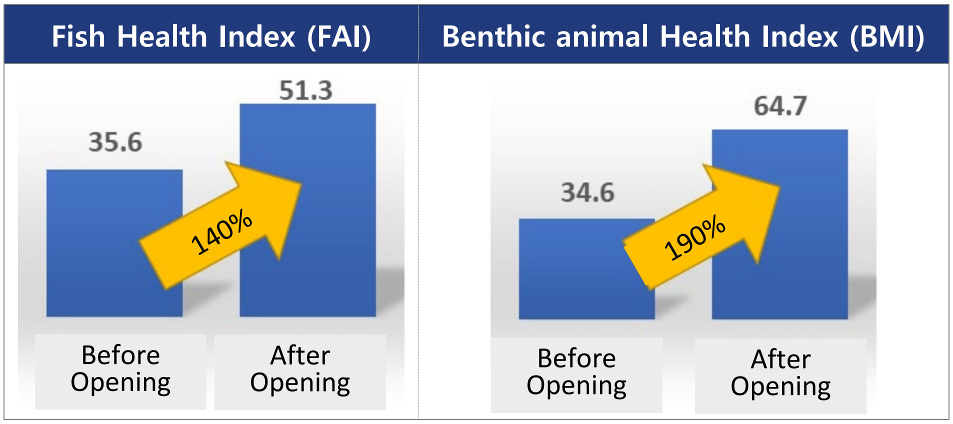


Figure 8 Changes in aquatic ecosystem health index before and after opening of Sejong weir[5] (Ministry of Environment, 2021)



Looking at the research results and literature so far, it is often possible to find time series analysis of the amount of GT at a specific time in a specific weir or water system. However, after the introduction and implementation of the policy of opening weirs, it was difficult to find cases of time-series comparative analysis of the impact of the policy by weir or river. Accordingly, my research question is to statistically compare the changes in GT of open and unopened weirs as of 2018, when the weirs were fully opened.

[5] In this table, before opening is from 2013 to October 2017, and after opening is from June 2018 to June 2021. Additionally, the closer FAI and BMI are to 100, the healthier the aquatic ecosystem is.

4. Data Plan

1) Data Source

To analyze the association between the operation of weir gates and GT, I would like to use data from the water environment measurement network operated by the National Institute of Environmental Research. The National Institute of Environmental Research is a research institute affiliated with the Ministry of Environment of Korea that oversees investigations and research on environmental conservation and prevention of environmental pollution. Regarding GT, the National Institute of Environmental Research selects representative points of sixteen weirs once a week to measure and analyze them.

I plan to use 10 years of data from 2012 to 2023 to measure the population of harmful blue-green algae, and the data can be downloaded from the National Institute of Environmental Research's Water Environment Information System[6]. For reference, this system was launched in 2022 to integrate and provide various water-related measurement information such as water quality, quantity, aquatic ecology, and weather, which had been managed separately by each institution.

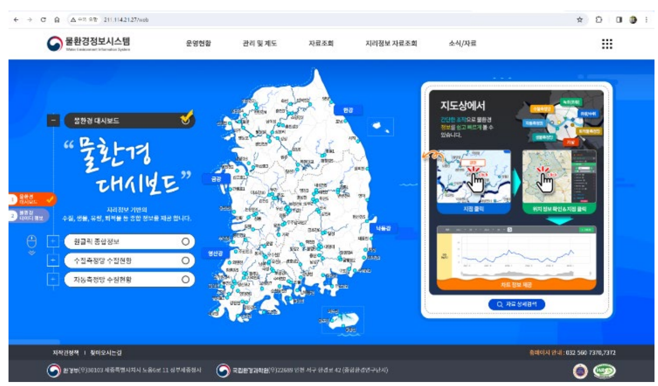


Figure 9 Homepage of Water Environment Information System

[6] http://211.114.21.27/web

2) Data content and analysis direction

The Ministry of Environment calculated and disclosed the opening rate for each weir from 2017 to 2021, which is shown in table 2 below. By water system, the three weirs of the Geum River have the highest openness rate of 88.6~100%, followed by the Yeongsan River and Nakdong River, and the Han River has the lowest openness rate of 0~3%. (Ministry of Environment, 2022)

Table 2 Weir opening rate by water system (2017-2021) (Ministry of Environment, 2022)

Water system	**Geum**			**Yeongsan**		**Nakdong**		
Weir Name	Sejong	Gongju	Baekje	Seungchon	Juksan	Sangju	Nakdan	Gumi
Opening Rate (%)	100	88.6	97.4	34.4	41.2	1.1	0	6.1
Water system	**Nakdong**					**Han**		
Weir Name	Chilgok	Gangjeong Goryeong	Dalseong	Hapcheon Changnyeong	Changnyeong Haman	Ipo	Yeoju	Gangcheon
Opening Rate (%)	2.3	12.6	6.2	27.1	51.9	0	0	3

※ How to calculate opening rate.

$$Opening\ rate(\%) = \left[\sum_{i=1}^{n} \frac{(Management\ water\ level - Open\ water\ level_i)}{(Management\ water\ level - \ Minimum\ water\ level)} \times 100(\%)\right] \div Days$$

- Open water level$_i$: Water level of the weir on the i th day
- Minimum water level: The water level when the water gate of the movable weir is fully opened.
- Management water level: The water level at the top of the fixed weir, which is the normal operating level before the weir is opened.

I would like to set the data in the following two directions, referring to the weir open rate. First, I would like to compare the population data of harmful blue-green algae by selecting weirs with high and low weir open rates in the Nakdong River and Geum River, which have many problems with GT during the summer (June to September). In addition, using different analysis methods, I would like to compare the trends in the population of harmful blue-green algae in three weirs in the Geum River with high weir opening rates and the trends in the population of harmful blue-green algae in all weirs in the Nakdong River and Han River with low weir open rates. In other words, I plan to proceed with a method of directly comparing the populations of harmful blue-green algae from river to river.

Table 3 Example of measurement data on harmful blue-green algae in Gongju weir in 2012 summer from Water Environment Information System

Weir name	River	Date (YYYY.MM.DD)	Harmful blue-green algae cell count (cells/㎖)	Dominant species and cell numbers of harmful blue-green algae (by genus)			
				Microcystis	Anabaena	Oscillatoria	Aphanizomenon
Gongju	Geum	2012.06.05	118	0	0	0	0
Gongju	Geum	2012.06.07	116	0	0	0	0
Gongju	Geum	2012.06.12	192	0	0	0	0
Gongju	Geum	2012.06.15	0	0	0	0	0
Gongju	Geum	2012.06.19	260	0	0	0	0
Gongju	Geum	2012.06.21	152	0	0	0	0
Gongju	Geum	2012.06.26	108	0	0	0	0
Gongju	Geum	2012.06.28	196	0	0	0	0
Gongju	Geum	2012.07.03	806	0	0	0	0
Gongju	Geum	2012.07.10	372	0	0	0	0
Gongju	Geum	2012.07.17	64	0	0	0	0
Gongju	Geum	2012.07.24	0	0	0	0	0
Gongju	Geum	2012.07.31	2024	0	0	0	0
Gongju	Geum	2012.08.07	676	0	0	0	0
Gongju	Geum	2012.08.10	3414	0	0	0	0
Gongju	Geum	2012.08.12	2888	0	0	0	0

Weir name	River	Date (YYYY.MM.DD)	Harmful blue-green algae cell count (cells/㎖)	Dominant species and cell numbers of harmful blue-green algae (by genus)			
				Microcystis	Anabaena	Oscillatoria	Aphanizomenon
Gongju	Geum	2012.08.13	728	0	0	0	0
Gongju	Geum	2012.08.16	368	0	0	0	0
Gongju	Geum	2012.08.20	362	0	0	0	0
Gongju	Geum	2012.08.23	292	0	0	0	0
Gongju	Geum	2012.08.27	1046	0	0	0	0
Gongju	Geum	2012.08.31	112	0	0	0	0
Gongju	Geum	2012.09.03	1618	0	0	0	0
Gongju	Geum	2012.09.07	2394	0	0	0	0
Gongju	Geum	2012.09.11	1436	0	0	0	0
Gongju	Geum	2012.09.14	120	0	0	0	0
Gongju	Geum	2012.09.18	1427	0	0	0	0
Gongju	Geum	2012.09.21	3124	0	0	0	0
Gongju	Geum	2012.09.25	3048	0	0	0	0

Here, I would like to exclude data from 2017 to 2018, when the weir began to be opened in earnest. According to the Ministry of Environment, it has been announced that disturbances such as resuspension of sediment may occur as the weir is opened. (Ministry of Environment, 2019) So, I would like to conduct a DID analysis by excluding the data from 2017 and 2018, when data began to be opened, and setting the previous years, 2012 to 2016, as the first period (before opening) and 2019 to 2023 as the second period (after opening).

5. Research Design

1) Analysis method 1: DID between weirs with high and low open rates

Before 2017, the weir gates were not open. After 2017~2018, the gates started to be opened, but due to different conditions, some gates were opened, and some were not. Among sixteen weirs, Gongju has been fully open since, so this data is selected. Chilgok Weir in the Nakdong River was selected for comparison. Chilgok Weir gates were not operated during most of the period.

Figure 10 Target weirs location for analysis method 1.

Between 2012 and 2023, a comparison is made between Gongju Weir, which fully opened the weir gate, and Chilgok Weir, which mostly closed the weir gate. Through Difference-in-Differences analysis, I want to verify whether weir gate operation has a causal relationship with blue-green algae.

The data will use the monthly status of the population of harmful blue-green algae during the summer (June to September) from the water environment information system operated by the National Institute of Environmental Research. Data can be searched on a yearly basis on the website, and the data was categorized, downloaded, and organized by month during the summer.

The model for DID analysis is as follows.

$y\_it = \beta0 + \beta1Treated\_i + \beta2Time\_t + \beta3*(Treated\_i * Time\_t) + \varepsilon\_it$

- y_it: Amount of harmful blue-green algae measured at time t in the i-th weir.
- Treated_i: Whether or not the i-th weir is opened (Gongju: 1, Chilgok: 0)
- Time_t: Post_t: whether it is after time t (after Gongju open: 1, before: 0)
- (Treated_i * Time_t): Treatment-effect (Multiplication of Treat_i and Time_t)
- β0, β1, β2, β3: regression coefficients
- ε_it: error term

As confirmed in the literature analysis, GT is generally said to be mainly affected by temperature, flow rate, and pollutants. Since opening the gates of a weir mainly affects the flow rate, my hypothesis is meaningful in comparing the GT situations of weirs with open and unopened gates.

However, the weirs are in different rivers. Gongju weir is in the middle stream of the Geum River, and Chilgok weir is located in the middle stream of the Nakdong River. I wanted to choose a river located upstream and downstream of the same river, but all three weirs of the Geum River were open, and none of the Nakdong River weirs were mostly open. There may be limitations in the analysis because the circumstances and proportions of factors affecting GT may differ for each river. This will be described after statistical analysis.

2) Analysis method 2: DID between rivers with high and low weirs open rates.

Because there may be errors in analysis method 1, plan 2 was structured as follows. As shown in Table 5, the Geum River (3 weirs) had a very high weir opening rate, but the Nakdong River (8 weirs) and the Han River (3 weirs) had very low opening rates. Therefore, I would like to perform DID analysis by dividing the Geum River-Nakdong River and Geum River-Han River into the early (2012-2016) and late (2019-2023) periods, respectively.

Figure 11 Target weirs location for analysis method 2.

DID analysis is as follows.

$$y_{it} = \beta_0 + \beta_1 Treated_i + \beta_2 Time_t + \beta_3 * (Treated_i * Time_t) + \varepsilon_{it}$$

- y_{it}: Amount of harmful blue-green algae measured at time t in the i th River.
- $Treated_i$: Whether or not it is a river with a high rate of weir opening. (Geum River: 1, Nakdong River, Han River: 0)
- $Time_t$: $Time_t$: whether it is after time t (after Weir open: 1, before: 0)
- ($Treated_i * Time_t$): Treatment-effect (Multiplication of $Treat_i$ and $Time_t$)
- $\beta_0, \beta_1, \beta_2, \beta_3$: regression coefficients
- ε_{it}: error term

6. Analysis results

I used the Stata/BE 17.0 program for analysis. For each analysis result, the coefficient and standard deviation for each variable were specified, and the multicollinearity verification results of the variables were derived and presented. The suitability of the research model was confirmed by presenting the R^2 value and F value. In addition, graphs were used to analyze each DID.

1) Analysis method 1: DID between weirs with high and low open rates

The DID analysis results are shown in Table 4 and Figure 12. The analysis of the results is as follows.

Table 4 Effect of weir opening on GT of Gongju weir.

Independent Variable	**Coef.**	**S.E.**	**t**
Time(ref.=2012~2016)	-2,019.475	2,637.176	-0.77
Treated(ref.=Chilgok)	-5249.522*	2,298.794	-2.28
DID	-426.6202	3,677.009	-0.12
cons	8,701.639***	1,609.848	5.41
R^2	0.025		
Adj.R^2	0.018		
F(sig.)	3.64*		
N	429		

*p<0.05, **p<0.01, ***p<0.001

I conducted a Difference in Difference analysis to determine the effect of weir opening on the GT of the Gongju weir in the summer. The explanatory power of the independent variables for the dependent variable, GT (harmful algal bloom), is 2.5% (R^2=.025), and the research model was found to be adequate (F=3.64, p<.05). I also checked the VIF of the variables for multicollinearity, which is greater than ten, and the results were between 1.64 and 2.77, which is not a problem.

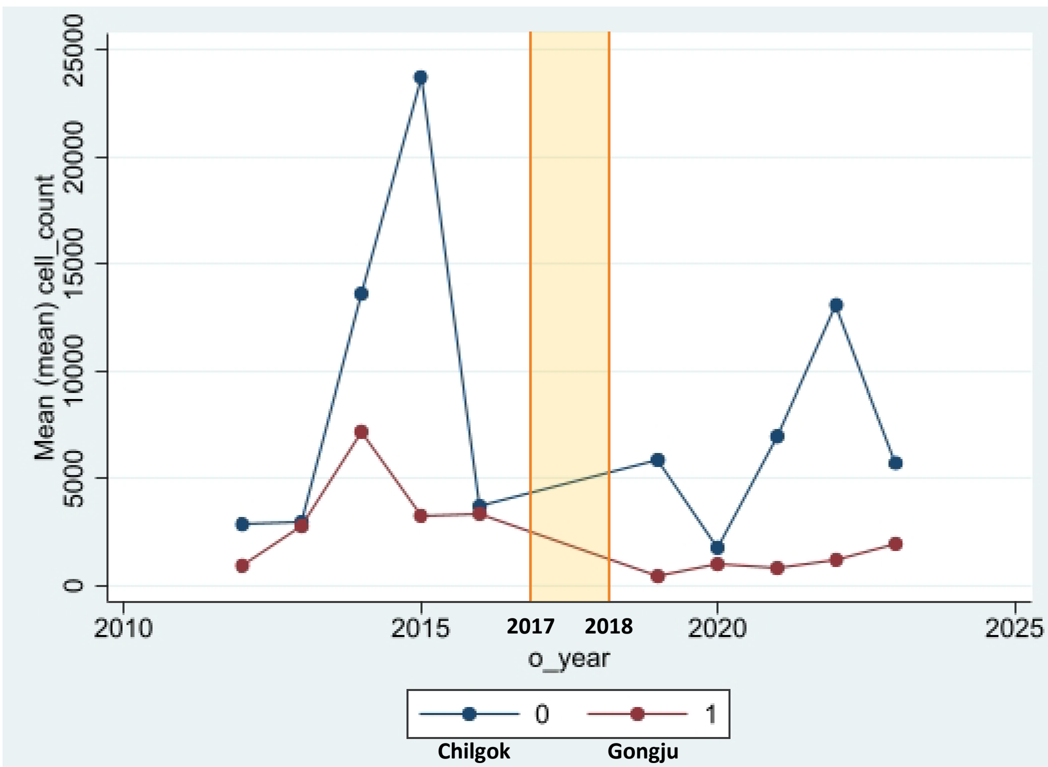


Figure 12 Average GT value by year for Gongju weir (1) and Chilgok weir (0)

First, the coefficient of the "Time" variable is -2,019.475, which indicates that the amount of GT generated after the opening of the weir gate in 2017-2018 decreases by about 2,019.475 compared to before 2017. However, since the P-value is 0.444, which is greater than the significance level of 0.05, this effect can be said to be not statistically significant.

Second, the coefficient of the “Treated” variable is -5,249.522, which indicates the GT generated in Gongju weir was less than that in Chilgok weir by about 5,249.522 on average. Since the P-value is 0.023, which is less than the significance level of 0.05, this effect can be said to be statistically significant.

Third, the Difference-in-Differences analysis depends on the treated_Time(did) variable. The coefficient of the “did” variable is -426.6202, which is the result of comparing the period after the weir gates were opened at 'Gongju Weir' with 'Chilgok Weir'. However, since the P-value is very high at 0.908, it can be said to be not statistically significant.

In summary, it can be said that statistically, the amount of GT in the summer at Gongju weir was clearly smaller than that at Chilgok weir. However, I could not find strong evidence in this DID analysis as to whether the opening of the Gongju Weir's floodgates since 2017 had an effect on the difference.

2) Analysis method 2: DID between rivers with high and low weirs open rates.

Regarding Analysis method 2, the first is a comparison of the Geum River and the Nakdong River. I conducted a Difference in Difference analysis to determine the effect of weirs opening on the GT of the Geum River in the summer. The explanatory power of the independent variables for the dependent variable, GT (harmful algal bloom), is 2.5% (R^2=.025), and the research model was found to be adequate (F=20.63, p<.001). I also checked the VIF of the variables for multicollinearity, which is greater than ten, and the results were between 1.37 and 2.07, which is not a problem.

Table 5 Effect of weir opening on GT of Geum River (comparison with Nakdong River)

Independent Variable	Coef.	S.E.	t
Time(ref.=2012~2016)	-967.625	1,805.718	-0.54
Treated(ref.=Nakdong)	-11,611.74***	2,201.698	-5.27
DID	-3,570.464	3,476.198	-1.03
cons	17,114.26***	1,107.831	15.45
R^2	0.025		
Adj.R^2	0.024		
F(sig.)	20.63***		
N	2,429		

*p<0.05, **p<0.01, ***p<0.001

First, the coefficient of the “Time” variable is -967.625, which indicates that the amount of GT generated after the opening of the weirs in 2017-2018 decreases by about 967.625 compared to before 2017. However, since the P-value is 0.592, which is greater than the significance level of 0.05, this effect can be said to be not statistically significant.

Second, the coefficient of the “Treated” variable is -11,611.74, which indicates the GT generated in the Geum River weirs was less than that in the Nakdong River weirs by about 11,611.74 on average. Since the P-value is <0.001, which is less than the significant level of 0.05, this effect can be said to be statistically significant.

Third, the Difference-in-Differences analysis depends on the treated_Time(did) variable. The coefficient of the 'did' variable is -3,570.464, which compares the periods before and after the weirs opening of the Geum and Nakdong rivers. However, since the P-value is high at 0.304, it can be said to be not statistically significant.

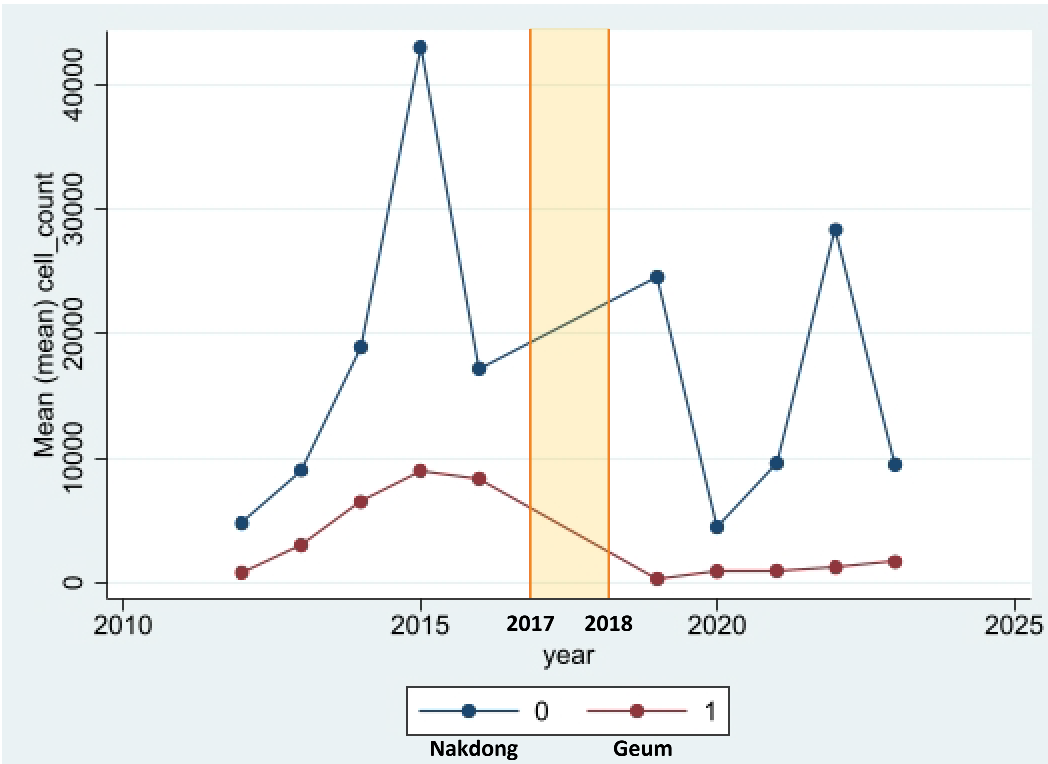


Figure 13 Average GT value by year for Geum River weirs (1) and Nakdong River weirs (0)

In summary, it can be said that statistically, the amount of GT in the weirs section of the Geum River is definitely lower in summer than in the Nakdong River. However, I have not found any strong evidence that this is due to opening weirs.

The second is a comparison between the Geum and Han River.

I conducted a Difference in Difference analysis to determine the effect of weirs opening on the GT of the Geum River in the summer. The explanatory power of the independent variables for the dependent variable, GT (harmful algal bloom), is 5.4% (R^2=.054), and the research model was found to be adequate (F=19.88, p<.001). I also checked the VIF of the variables for multicollinearity, which is greater than ten, and the results were between 1.65 and 3.28, which is not a problem.

Table 6 Effect of weir opening on GT of Geum River (comparison with Han River)

Independent Variable	Coef.	S.E.	t
Time(ref.=2012~2016)	2.872	1,053.279	0.00
Treated(ref.=Han)	5,485.309***	843.639	6.50
DID	-4,540.961***	1,346.507	-3.37
cons	17.209	650.390	0.03
R^2	0.054		
Adj.R^2	0.051		
F(sig.)	19.88***		
N	1,058		

*p<0.05, **p<0.01, ***p<0.001

First, the coefficient of the “Time” variable is 2.872, which indicates that the amount of GT generated after the opening of the weirs in 2017-2018 increases by about 2.872 compared to before 2017. However, since the P-value is 0.998, which is greater than the significance level of 0.05, this effect can be said to be not statistically significant.

Second, the coefficient of the “Treated” variable is 5485.309, which indicates the GT generated in the Geum River weirs was more than that in the Han River weirs by about 5485.309 on average. Since the P-value is <0.001, which is less than the significant level of 0.05, this effect can be said to be statistically significant.

Third, the Difference-in-Differences analysis depends on the treated_Time(did) variable. The coefficient of the 'did' variable is -4,540.961, which compares the periods before and after the weirs opening of the Geum and Han rivers. Since the P-value is 0.001, which is less than the significance level of 0.05, this effect can be said to be statistically significant.

In summary, this result appears to be that the weir opening policy in the Geum River can be statistically significant in reducing GT in the summer compared to the Han River.

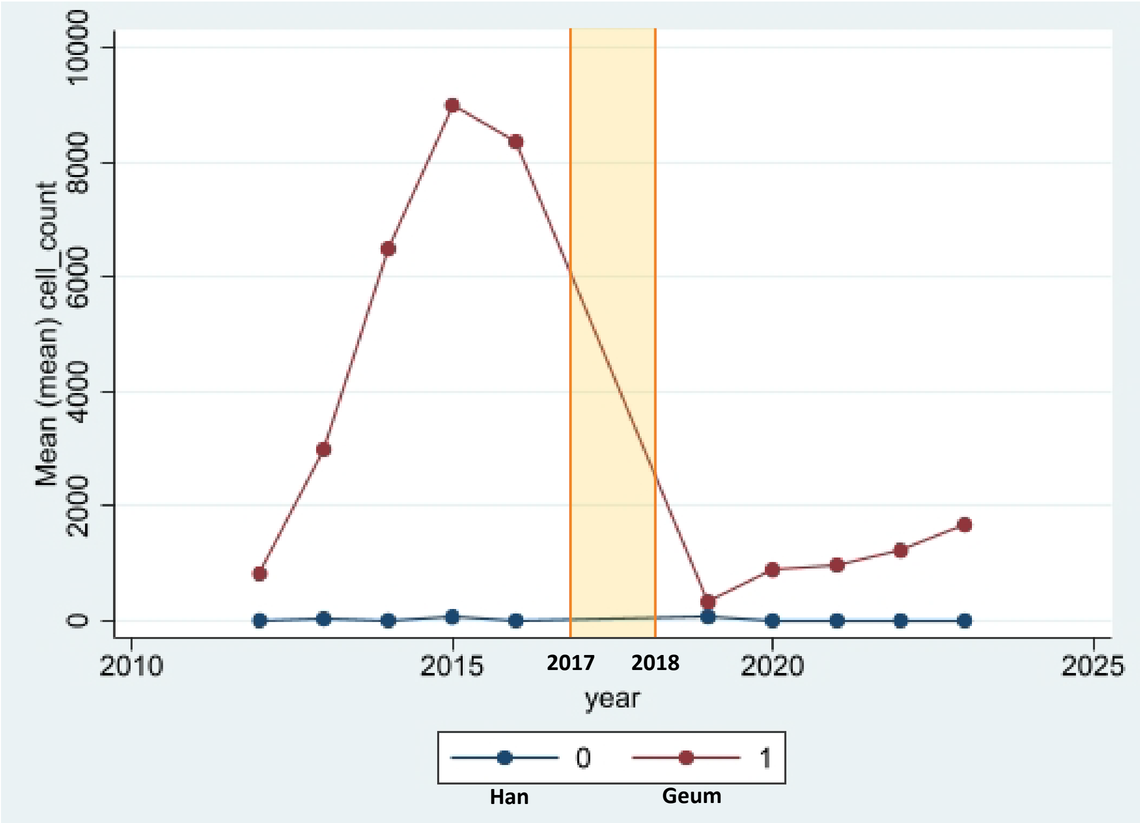


Figure 14 Average GT value by year for Geum River weirs (1) and Han River weirs (0)

7. Discussion and Policy implications

There is evidence for the effect of weir openings in one of the three river comparisons.

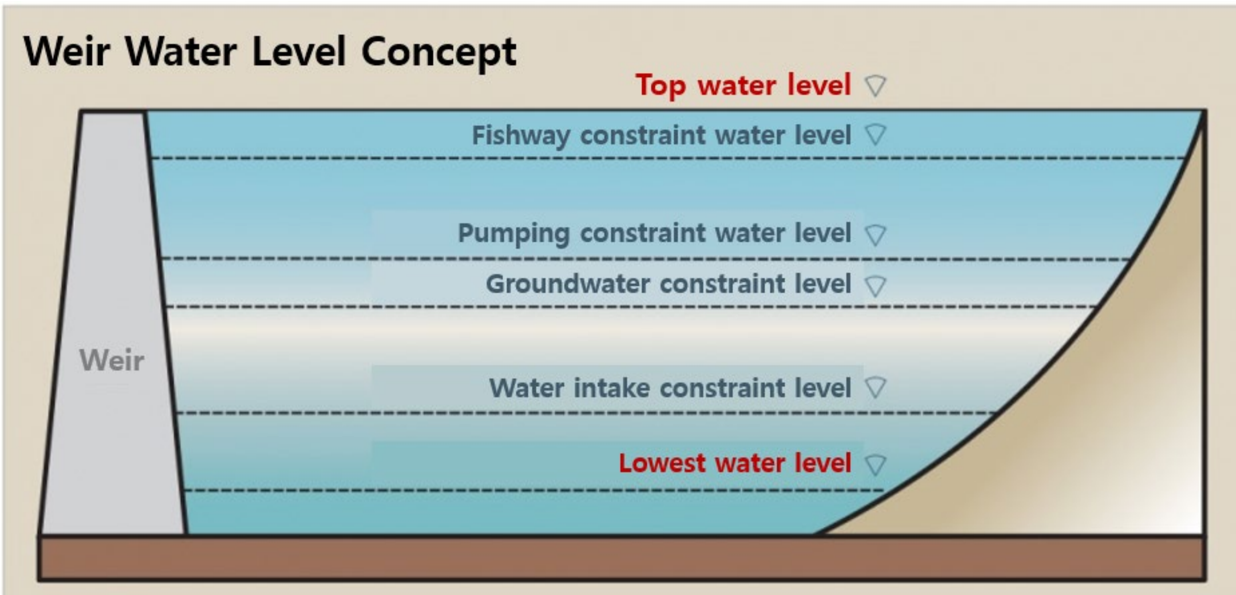
In Analysis 1, the Gongju weir of the Geum River with a high weir opening rate had a lower GT than the Chilgok weir of the Nakdong River with a low weir opening rate, but statistical evidence does not find a significant effect of weir opening. In Analysis 2-1, the Geum River, which has a high weir opening rate, had a lower GT than the Nakdong River, which has a low weir opening rate, but again there is no statistically significant effect of weir opening. In Analysis 2-2, compared to the Han River, weir opening in the Geum River was statistically significant in reducing GT in the later period (2019-2023) compared to the earlier period (2012-2016).

As identified in the literature review, temperature, nutrients, and retention time are the main factors affecting GT reproduction. The significance of this study is that it confirmed the statistical possibility that weir opening affects retention time, resulting in a decrease in GT in one of the three analyses. However, there are the following limitations.

First, as mentioned earlier, it would have been nice to be able to make statistical comparisons within the same water system, but this was not possible. As shown in Table 5, only three weirs in the Geum River had an opening rate of more than 80%, and thirteen weirs in the other three rivers had an opening rate of less than half. Although the Changnyeong Haman weir was 51% open, it was mostly open in winter, and summer (June-September) opening, which is the period included in the study, only started in 2022, so summer opening in the three rivers was rare. In the future, if more weirs are opened in summer when GTs thrive, it will be possible to conduct comparative studies within the same water system.

The second is related to the explanatory power of the study model. Although retention time does affect GT reproduction, it would have been better to add temperature and nutrient factors to the analysis. Due to time and physical limitations, it was not possible to add these two factors to this study, but it would be good to consider them in future studies.

Figure 15 Conceptual diagram of weir water level (Source: Ministry of Environment)



- Top Water level: A water level when the weir gates are fully closed.
- Fishway constraint water level: A water level that does not affect fishway operations.
- Pumping constraint water level: A water level that does not affect agricultural pumping station intakes.
- Groundwater constraint level: A water level that does not affect surrounding groundwater.
- Water intake constraints: A water level that do not affect drinking water intakes.
- Lowest water level: A water level when the weir gates are fully opened.

The policy implications of this study are as follows. Since the completion of the Four Rivers Project in 2011, weir operations have aimed to maintain the top water level of the weirs by closing them. (See Fig. 15.) However, since then, as GT became an issue, the alternative of operating the weirs flexibly was proposed, but due to the existence of various water level constraints such as fishways, agricultural pumping facilities, and water intake facilities, the weirs were not operated.

Figure 16 An example of a pumping constraint water level. The opening of the Hapcheon Changnyeong Weir on the Nakdong River in January 2022 reveals the intake of an agricultural pumping station upstream. (강찬수, 2023)

Figure 15 is a schematic showing the factors that currently constrain hydrologic operations at weir sections of the Four Rivers. The top water level, shown in red, is the water level when the gates of the weir are closed. In principle, it should be possible to adjust the water level from the top water level to the lowest water level by opening the sluice gate of the weir. However, if the weirs of the four major rivers are opened in this state, the water level will decrease, causing constraints as shown in Figure 15, and the weirs cannot be opened below that level. It is understood that the weirs should have been constructed so that they can be opened to the maximum extent during the past Four Rivers project, but the above-mentioned constraints of fishways, water intake facilities, etc. were not considered.

Through the DID analysis of this study, I confirmed the possibility that weir opening may be statistically significant in reducing GT. Of course, in the future, I would like to expand the weir opening range to obtain better data and perform a more accurate DID analysis. In fact, in the summer in South Korea, there is no reason to keep the weir water level at the top because there is a lot of precipitation such as rainy season and there is not much demand for water utilization. If the necessary facilities to lower the water level from the top of the weir to the lowest water level are improved, a flexible weir operation plan can be developed to help reduce GT in summer. In other words, if the weir gates can be freely opened from the top to the lowest water level without any constraints, it will be beneficial not only for GT reduction in summer but also for future research.

References

Kim, B. (2017). 녹조현상의 원인과 대책. *물과 미래*, 8.

Ministry of Environment. (2019). *2018 조류(녹조) 발생과 대응 연차보고서.* Ministry of Environment.

Ministry of Environment. (2019, 8 21). *조선일보 2019.8.21 일자 기사에 대한 해명.* Retrieved from 환경부 홈페이지: http://27.101.216.209/home/web/board/read.do;jsessionid=htL70QF5AL7HsqpSSaDR0AI5.mehome1?pagerOffset=4720&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=286&orgCd=&boardMasterId=1&boardCategoryId=&boardId=1031510&decorator=

Ministry of Environment. (2020, 08 25). *녹조현상은 왜 생길까?* Retrieved from Ministry of Environment: http://www.me.go.kr/home/web/board/read.do;jsessionid=Z0DHlU8NuowhRx0Rzp2A2HX2.mehome1?pagerOffset=240&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=&orgCd=&boardId=1392740&boardMasterId=713&boardCategoryId=&decorator=

Ministry of Environment. (2021, 9 15). *장기간 완전개방한 금강 보 구간, 생태계 건강성 개선.* Retrieved from 환경부 홈페이지: https://me.go.kr/home/web/board/read.do?pagerOffset=0&maxPageItems=10&maxIndexPages=10&searchKey=title&searchValue=&menuId=10525&orgCd=&condition.createDeptName=%EB%AA%A8%EB%8B%88%ED%84%B0%EB%A7%81&boardId=1476770&boardMasterId=1&boardCategoryId=&decorato

Ministry of Environment. (2022). *보 개방 모니터링 종합 분석 보고서(2017.6~2021.12).* 세종: 환경부.

Ministry of Environment. (2023, 2 8). *환경부 홈페이지.* Retrieved from 사전정보공표: http://27.101.216.208/home/web/public_info/read.do;jsessionid=SG5rmqbBe9TwMjwWy+DrXtwa.mehome1?pagerOffset=70&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=10357&orgCd=&condition.publicInfoMasterId=3&condition.deleteYn=N&publicInfoId=64&

National Institute of Environmental Research. (n.d.). *보모니터링 종합정보.* Retrieved from Water Environment Information System: http://water.nier.go.kr/web/bo/dashBoard?pMENU_NO=20

Shin, J.-h. (2012, 8 26). Development and Implementation of the Green Infrastructure Paradigm - Based on the Korean River Restoration Projects - . Seoul, Korea.

고성표. (2017, 5 8). *[팩트체크] 문 "녹조 심한 건 4 대강 사업 때문" VS 홍 "오염물질과 높은 기온 탓" 누구 말이 맞나*. Retrieved from The Joongang: https://www.joongang.co.kr/article/21538464#home

구정모. (2023, 4 30). *연합뉴스*. Retrieved from [팩트체크] 4 대강 사업 과거 정부서 어떤 평가를 받았나: https://www.yna.co.kr/view/AKR20230428163800518

김동욱. (2021, 5 6). *“하천생태계의 현실적 총인 수질기준 설정 필요”*. Retrieved from 워터저널: http://www.waterjournal.co.kr/news/articleView.html?idxno=54900

김평화. (2018, 7 4). *낙동강 '녹조라떼' 주범 4 대강?...감사원 "인과관계 상당"*. Retrieved from 머니투데이: https://news.mt.co.kr/mtview.php?no=2018070416247619721

미래생태(주), 해양환경연구소(주), 한국생명공학연구원, 응용생태공학회. (2021). *Intensive Monitoring on the Regional Distribution of Phytoplankton in the Weir Areas(4).* National Institute of Environmental Research.

선정민. (2021, 10 13). *낙동강 보 열었는데도, 10 년만에 최악 녹조*. Retrieved from The Chosunilbo: https://www.chosun.com/national/transport-environment/2021/10/13/75IXYLHHCBHODEJBCZEXR4WN7Y/