JOURNAL OF
ECOLOGY AND ENVIRONMENT
http://www.jecoenv.org

Research Paper
J. Ecol. Environ. 37(1): 1-11, 2014

Impacts of dam discharge on river environments and phytoplankton communities in a regulated river system, the lower Han River of South Korea

Seung Won Jung[1,*], Oh Youn Kwon[2,4], Suk Min Yun[1,2], Hyoung Min Joo[3], Jung-Hoon Kang[4] and Jin Hwan Lee[2]

[1]Library of Marine Samples, Korea Institute of Ocean Science and Technology, Geoje 656-830, Korea
[2]Department of Life Science, Sangmyung University, Seoul 110-743, Korea
[3]Korea Polar Research Institute, Korea Institute of Ocean Science and Technology, Songdo Techno Park, Incheon 406-840, Korea
[4]South Sea Environment Research Division, Korea Institute of Ocean Science and Technology, Geoje 656-830, Korea

Abstract

To understand the effects of fluctuations in dam discharge due to river environments and phytoplankton communities, we monitored such environments and phytoplankton communities biweekly, from February 2001 to February 2002 and from February 2004 to February 2005, in the lower Han River (LHR), South Korea. The phytoplankton abundance during the dry season was approximately two times higher than that during the rainy season. In particular, fluctuations in diatom assemblages, which constituted over 70% of the total phytoplankton abundance, were affected severely by the changes in the discharge. When a large quantity of water in a dam was discharged into the LHR, the conductivity and the concentrations of total nitrogen (TN), total phosphorus (TP), and dissolved inorganic phosphorus (DIP) decreased rapidly, whereas the concentrations of suspended solids (SS), dissolved inorganic nitrogen (DIN), and dissolved silica (DSi) increased immediately. Time-delayed relationship also revealed that the dam discharge had an immediately significant negative relationship with phytoplankton abundance. On the whole, fluctuations in phytoplankton communities in the LHR were influenced much more by hydrodynamics such as dam discharge than by the availability of nutrients. Thus, the variability in these concentrations usually parallels the strength of river flow that is associated with summer rainfall, with higher values during periods of high river discharge.

Key words: dam discharge, lower Han River, phytoplankton succession, regulated river system, river hydrology, time-delayed influence

INTRODUCTION

The flow of most rivers worldwide is regulated by channelization or the construction of dams (Dynesius and Nilsson 1994). Diverse hydraulic conditions could be influenced by the control of a river's flow, thereby affecting the dynamics of aquatic organisms (Lamouroux and Capra 2002). In particular, fluctuations in the phytoplankton communities of many regulated rivers are affected by increases in the water flow due to dam discharge (Humborg et al. 1997). The release of water held behind a dam can wash away much of the phytoplankton biomass downstream of the dam. In contrast, stagnation of water flow can increase the density of phytoplankton abundances. However, this can impede the purification of water for human use and the toxicity that is shown by certain species

http://dx.doi.org/10.5141/ecoenv.2014.001

Received 03 September 2013, **Accepted** 19 November 2013

***Corresponding Author**
E-mail: diatoms@kiost.ac
Tel: +82-55-639-8430

pISSN: 2287-8327 eISSN: 2288-1220

of phytoplankton, such as *Anabaena circinalis*, can harm human populations (Webster et al. 2000). Thus, control of the level and flow of water by the regulation of dam discharge is important for water quality as well as for the dynamics of aquatic organisms.

Phytoplankton in rivers are sensitive aquatic organisms, the spatiotemporal distribution of which is controlled by both abiotic (water flow, nutrients, and water temperature, etc.) and biotic (competition and grazing, etc.) mechanisms (Hutchinson 1961). Although grazing by predators, including zooplankton and fish, contributes to changes in phytoplankton communities, spatiotemporal fluctuations of such communities are caused primarily by changes in abiotic variables (Sellner et al. 1993). Of these, high-velocity water flow (as a result of heavy precipitation or the discharge of dams) has been found to result in major shifts in the abundances and compositions of phytoplankton assemblages (Hallegraeff 1993). Each group of phytoplankton communities in a regulated river system can undergo different spatial and temporal changes due to nutrient levels as well as water flow. In a region downstream of the Three Gorges Dam (the world's largest dam), a small diatom, *Asterionella formosa*, was found to be dominant during the dry season, but *Chroomonas acuta* in Cryptophyta was dominant during the rainy season (Zeng et al. 2006). This spatiotemporal variability in the structure of phytoplankton communities plays a major role in the structure and function of aquatic ecosystems (Brett and Goldman 1996).

Given the current state of research, the objectives of the present study were to gain increased understanding of fluctuations in phytoplankton communities in the regulated river system and to characterize the association of these fluctuations with dam discharges and environmental factors. The results were then integrated over spatial and temporal scales to determine the impact of dam discharge on phytoplankton communities and environmental factors.

MATERIALS AND METHODS

Study area

The Han River is one of the longest and largest rivers in South Korea. The channel of the river is 482 km in length and it has a drainage basin with a total area of 26,018 km^2. The river is used as the main source of drinking water for more than 25 million residents in the Seoul metropolitan area. Jeong et al. (2007) reported that rainfall during the summer season (June to September) in South Korea provides 50–60% of the annual total, whereas limited precipitation during the winter (December to February) provides much less (approx. 10%). For flood control, supply of water, and hydropower generation, nine dams have been constructed along the Han River. Among these, the Paldang Dam (the dam furthest downstream) directly regulates flow and prevents flooding in the Seoul metropolitan area. The water in the Paldang Reservoir is retained for shorter periods (approx. 5–7 days) than that in the other reservoirs along the river. The LHR is defined as the part of the river located from downstream of the Paldang Dam to the entrance of Kyunggi Bay in the Yellow Sea, and it flows through the city of Seoul. During periods of heavy rainfall, when a large amount of water flows from the Paldang Reservoir into the LHR, the retention time in the LHR is approximately 1–2 days and the water flows rapidly into Kyunggi Bay in the Yellow Sea (Kim et al. 1998). The hydrological dynamics of the LHR are controlled mainly by the discharge schedules for the Paldang Dam. In the late 1980s, two small reservoirs (Jamsil and Shingok) were constructed downstream of the Paldang Dam to control water levels and for recreational activities.

Sample collection and analysis

Water samples for measurement of ambient physicochemical factors were obtained at six sites in the LHR at biweekly intervals (a total of 51 samplings) from February 2001 to February 2002 and from February 2004 to February 2005 (Fig. 1). The samples were collected at a depth of 0.5 m by using a 2 L horizontal Niskin sampler at each sampling site between 9:00 and 11:00 AM. Water temperature, dissolved oxygen (DO), pH, and conductivity were measured with subsampling using portable meters: YSI-85 and YSI-63 models (YSI Inc., Yellow Springs, OH, USA). Biological oxygen demand (BOD), chemical oxygen demand (COD), and SS were measured according to the method of the American Public Health Association (APHA 1995). To determine chlorophyll *a* concentrations, 500 mL of each sample were filtered through a Whatman® glass microfiber filters, Grade GF/F 47-mm filter (Whatman, Springfield Mill, UK) under low vacuum pressure. The filter was soaked in 15 mL of cold 90% acetone-distilled water (v/v), and then sonicated to break the cell walls and extracted for 24 hours in the dark at 4°C. Finally, chlorophyll *a* concentrations were measured using a Hewlett-Packard Model 8453 UV-Vis Spectrophotometer (Hewlett-Packard, Palo Alto, USA). Then, 250 mL of each sample of water were filtered through a GF/F filter (Whatman) to

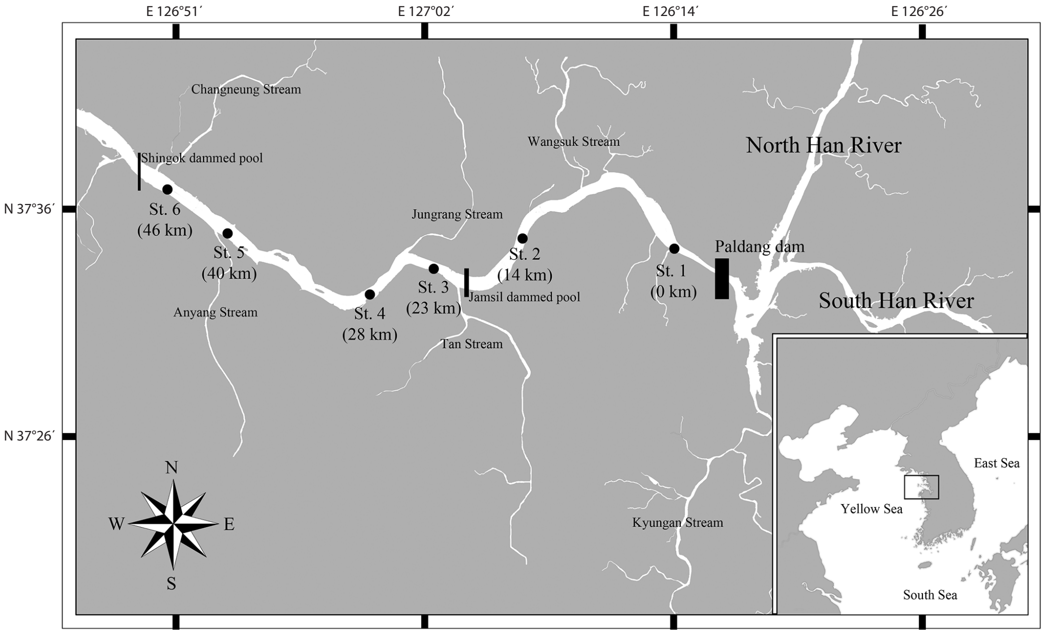

Fig. 1. Map showing investigated sites in the lower Han River. Sampling sites are described in terms of distance downstream (km) from St. 1 (0 km).

analyze inorganic nutrient concentrations (DIN, DIP, and DSi). Samples of water were also obtained for the analysis of TN and TP and were stored in a 300-mL acid-cleaned polyethylene bottle in a freezer (-80°C). The samples were analyzed using a nutrient auto-analyzer, Alpkem Flow Solution IV Autoanalyzer (Alpkem, Wilmington, DE, SA) according to the methods of the APHA (1995). Data on the precipitation in the drainage basin of the LHR, discharge of the Paldang Dam, and velocity of the LHR were obtained from the Korea Water Resources Corporation (http://www.kwater.or.kr) and Han River Flood Control Office (http://www.hrfco.go.kr).

Samples for the enumeration and identification of phytoplankton species were collected in a 1000 mL sterilized polyethylene bottle that contained 900 mL of subsample, and immediately fixed with a glutaraldehyde solution at a final concentration of 2%; then, they were concentrated by natural sedimentation for 24 hours. Over 500 phytoplankton cells in each sedimented sample were counted using a Sedgwick–Rafter counting chamber at ×400 magnification under a light microscope (Axioskop 40; Zeiss, Oberkochen, Germany). We recorded the relatively common species, which were defined as those that constituted more than 1% of the total and those with an abundance of more than 10^5 cells mL^{-1}. During the identification of phytoplankton species, the dataset of all phytoplankton communities was divided into six major taxonomic groups, which were identified in accordance with the commonly used nomenclature: Bacillariophyceae, Chlorophyta, Cryptophyta, Cyanophyta, Dinophyceae, and Euglenophyta.

Statistical analyses

Means and standard deviations were calculated for the data collected at the six sampling sites. To examine significant relationships between abundances of phytoplankton and environmental factors in the LHR, Pearson's correlation analysis and one-way ANOVA were used. Pearson's correlation analysis was used to reveal directly the correlation between environmental changes and phytoplankton abundance, and the ANOVA enabled us to determine the potential differences between rainy and dry seasons in terms of the abundance of phytoplankton and the effects of environmental factors. In the ANOVA, significant differences were tested by Scheffe's post hoc test. *P* values less than 0.05 were considered significant. Cross-correlation analysis enabled us to identify changes in the abundance of phytoplankton and abiotic factors over time after the introduction of variables that related to a rainfall season. These data were then transformed into normalized metadata, for which the time-series data ranged between -1 and 1. The statistical analyses were performed using the softwares: SPSS for Windows ver. 13 (SPSS Inc., Chicago, IL, USA) and XLSTAT 2011 (Addinsoft SARL, New York, NY, USA).

RESULTS

Hydrographic study

The mean values for precipitation were 7.06 ± 8.17 mm during the rainy season and 0.98 ± 1.26 mm during the dry season (Fig. 2). During the rainy season, the mean volume of water discharged by the Paldang Dam into the LHR was 1,108 m^{3} s^{-1}, but this fell to 157 m^{3} s^{-1} during the winter (dry season). There was a positive correlation between precipitation and discharge, with a coefficient of 0.76 (P < 0.001). Water velocity is controlled by the level of rain-

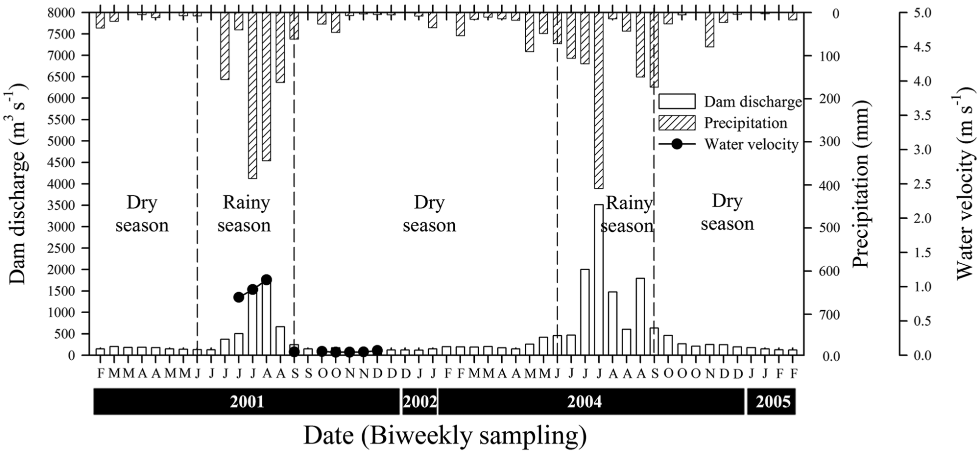

Fig. 2. Changes in precipitation, dam discharge, and water velocity in the lower Han River in the investigated periods.

Table 1. Differences between rainy and dry seasons in terms of environmental and biological factors in the lower Han River

Factor	Rainy season (n = 102)	Dry season (n = 204)	*F* value
Environmental factors			
Water temperature (°C)	22.89 ± 2.23^{A}	9.59 ± 6.46^{B}	407.53***
pH	7.33 ± 0.33	7.49 ± 0.67	N.S.
Precipitation (mm)	7.06 ± 8.17^{A}	0.98 ± 1.26^{B}	108.57***
Discharge (m^{3} s^{-1})	973 ± 899^{A}	187 ± 76^{B}	154.25***
Dissolved oxygen (mg L^{-1})	5.88 ± 1.55^{B}	9.59 ± 3.24^{A}	120.47***
Chemical oxygen demand (mg L^{-1})	5.40 ± 2.30	5.58 ± 2.09	N.S.
Biological oxygen demand (mg L^{-1})	2.65 ± 1.68^{B}	3.47 ± 2.13^{A}	11.62***
Conductivity (μS cm^{-1})	187 ± 67	176 ± 72	N.S.
Suspended solids (mg L^{-1})	36.54 ± 48.54^{A}	19.25 ± 26.67^{B}	15.71***
Total nitrogen (mg L^{-1})	3.79 ± 1.69^{B}	5.77 ± 2.88^{A}	41.09***
Total phosphorus (μg L^{-1})	156 ± 145^{A}	259 ± 200^{B}	21.56***
Dissolved inorganic nitrogen (mg L^{-1})	6.24 ± 3.97	6.67 ± 3.31	N.S.
Dissolved inorganic phosphorus (mg L^{-1})	0.10 ± 105^{B}	0.14 ± 145^{A}	7.74**
Dissolved silica (mg L^{-1})	1.44 ± 0.98^{A}	0.53 ± 0.46^{B}	119.70***
Biological factors			
Chlorophyll *a* (μg L^{-1})	19.1 ± 18.9^{B}	28.3 ± 20.3^{A}	14.58***
Phytoplankton (cells mL^{-1})	5770 ± 5431^{B}	9524 ± 10127^{A}	10.55**
Bacillariophyceae (cells mL^{-1})	4638 ± 4482^{B}	6457 ± 4896^{A}	9.92**
Cyanophyta (cells mL^{-1})	379 ± 1537	1639 ± 6628	N.S.
Chlorophyta (cells mL^{-1})	467 ± 755	730 ± 2408	N.S.
Other phytoplankton (cells mL^{-1})	287 ± 402	428 ± 576	N.S.

Letters (A and B) indicate significant differences among experimental groups (P < 0.05).
*, P < 0.05; **, P < 0.01; ***, P < 0.001; N.S., no significance.
Values represent mean ± standard deviation (SD).

fall and the inflow of water: during the rainy season, the water moved rapidly into Kyunggi Bay in the Yellow Sea at a mean velocity of 0.92 m s^{-1}, but during the dry season, this value was lower at 0.05 m s^{-1}. Thus, changes in water discharge and velocity showed patterns similar to that of precipitation (Fig. 2).

Changes in environmental factors

The LHR was eutrophic on the basis of TN (mean value: 4.78 mg L^{-1}), TP (0.21 mg L^{-1}), and chlorophyll *a* concentrations (23.7 μg L^{-1}) (Fig. 3 and Table 1). There were clear differences in some environmental factors between the

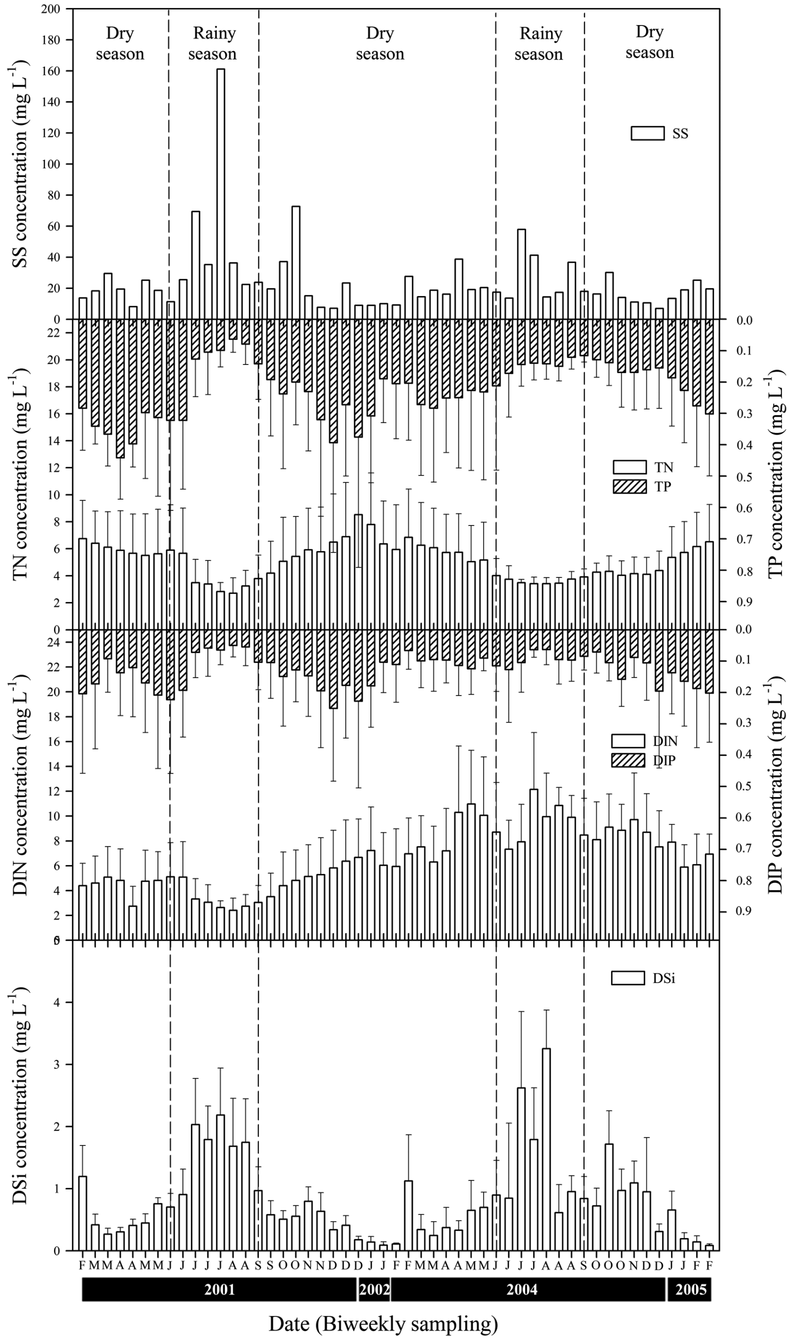

Fig. 3. Changes in total nitrogen (TN), total phosphorus (TP), suspended solids (SS), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and dissolved silica (DSi) in the lower Han River in the investigated periods. Error bar represents standard deviation.

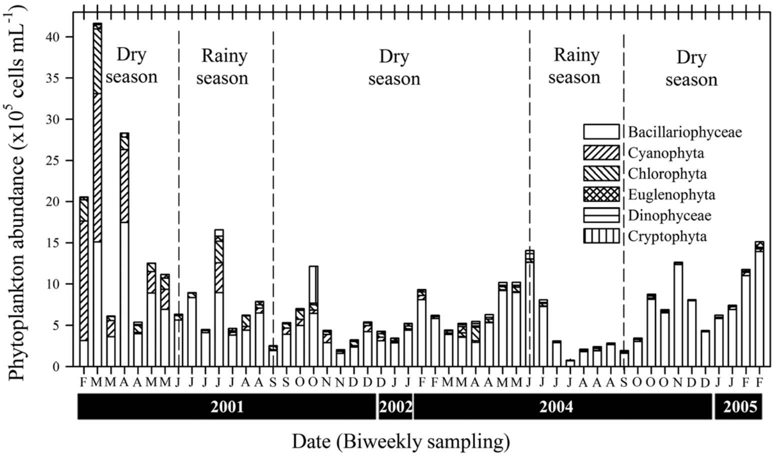

Fig. 4. Changes in phytoplankton abundance in the lower Han River in the investigated periods.

rainy and dry seasons: water temperature and precipitation were increased during the rainy season in association with some climatic features, such as monsoons ($P < 0.0001$, ANOVA). The pH value, which was correlated positively with the proliferation of phytoplankton ($r = 0.31$, $P < 0.05$), was highest in early spring during the phytoplankton blooms, whereas the pH value fell during the rainy season. The conductivity of the water was more than 160 μS cm^{-1}, and showed no significant difference between the seasons (Table 1). The concentration of SS increased during periods of rainfall following upwelling of bottom sediments and inflow of organic particles by run-off after release from the land by summer storms. The concentrations of BOD, DO, TN, and DIP were lower during the rainy season as a result of dilution by rainfall. Changes in TP and DSi concentrations were associated inversely with changes in TN concentration. The concentration of DSi was correlated positively with precipitation. In particular, the DSi concentration decreased rapidly when *Stephanodiscus hantzschii* bloomed in the winter. The concentration of DIN concentration was not significantly different among the seasons. Thus, the BOD, DO, TN, and DIP concentrations were associated negatively with precipitation, whereas the TP, DSi, and SS concentrations were associated positively with it.

Phytoplankton communities

A total of 437 phytoplankton taxa were identified in the LHR, and were distributed among the following taxonomic groups: Bacillariophyceae (203), Chlorophyta (169), Cryptophyceae (6), Cyanophyta (37), Dinophyceae (5), and Euglenophyta (17). The mean density of the total abundance of phytoplankton was 5.80 ± 4.48 × 10^5 cells mL^{-1} during the rainy season, whereas the abundance was higher during the dry season at 9.14 ± 7.70 × 10^5 cells mL^{-1} (Fig. 4). A change in chlorophyll *a* concentration was correlated significantly with a change in total phytoplankton abundance ($r = 0.46$, $P < 0.01$). Diatoms were present at the highest density in the phytoplankton communities. The mean density of diatoms was 5.77 × 10^5 cells mL^{-1} and they constituted 72% of the total phytoplankton abundance. Diatom abundances were lower during the rainy season, from summer to early autumn, than during the dry season, from winter to spring, with mean densities of 4.68 ± 3.31 × 10^5 cells mL^{-1} and 6.38 ± 3.85 × 10^5 cells mL^{-1}, respectively. Cyanobacteria were present at a density of 3.56 ± 8.85 × 10^4 cells mL^{-1} during the rainy season, but they bloomed to a peak density of 1.8 × 10^7 cells mL^{-1} on 10 March 2001 (in the dry season). Thus, cyanobacteria constituted 17.61% of the total phytoplankton community when their numbers peaked during the dry season, whereas other groups, including Chlorophyta, Dinophyceae, Cryptophyceae, and Euglenophyta, usually each constituted less than approximately 10% of the total. A total of nine common species were found during the rainy season (65.63% of the total phytoplankton abundance): *Fragilaria crotonensis* (mean value 28.57%) and *Aulacoseira granulata* (12.17%) were the most common diatoms, at more than 10%. Besides the above two species, five diatoms such as *Aulacoseria granulata* var. *angustissima*, *Cyclotella comta*, *Cyclotella meneghiniana*, *Nitzschia palea* and *Synedra acus*, one cyanobacterium (*Osillatoria limosa*), and one dinoflagellate (*Peridinium cinctum*) each constituted more than 1% of the total phytoplankton abundance. During the dry season, *Stephanodiscus* *hantzschii* (17.06%), *Oscillatoria limosa* (12.69%), and *Synedra acus* (11.05%) were the most common species, totalling 40.80% of the total phytoplankton abundance. Besides these species, eight diatoms (*Asterionella formosa*, *Aulacoseria granulata*, *Aulacoseria granulata* var. *angustissima*, *Aulacoseria italica*, *Cyclotella comta*, *Cyclotella* sp., *Fragilaria crotonensis*, and *Synedra ulna*), one cyanobacterium (*Croococcus turgidus*), one Chlorophyta (*Spirogyra crassa*), one Euglenophyta (*Euglena* sp.), and one Cryptophyta (*Cryptomonas* sp.) were found at abundances of more than 1%.

Time-delayed effect of dam discharge on environmental factors and phytoplankton communities

Significantly, dam discharge was correlated positively with precipitation and concentrations of SS ($r = 0.27$, $P < 0.001$), DIN ($r = 0.19$, $P < 0.01$), and DSi ($r = 0.55$, $P < 0.001$). However, the discharge was associated negatively with other environmental variables, including conductivity ($r = -0.16$, $P < 0.01$) and concentrations of TN ($r = -0.29$, $P < 0.001$), TP ($r = -0.24$, $P < 0.001$), and DIP ($r = -0.18$, $P < 0.01$), as well as total abundances of phytoplankton ($r = -0.21$, $P < 0.001$) and diatoms ($r = -0.24$, $P < 0.001$). When cross-correlation analysis was applied to the same set of metadata, a significant time-delayed relationship between dam discharge and phytoplankton could be identified (Table 2). Dam discharge showed high cross-correlation factors (CCFs) with phytoplankton and diatom assemblages at a lag time of 0: in other words, their abundances decreased immediately when the floodgates of the Paldang Dam were opened. Subsequently, the CCF with phytoplankton abundances increased slightly at 22 weeks after the dam discharge (11th sampling time), but CCFs with diatoms had increased sharply already at the third or fourth sampling time. The trend of the correlation between diatoms and dam discharge switched from negative to positive at 6 weeks after the Dam discharge. This shows that the phytoplankton, including diatom assemblages, were affected immediately and negatively by the dam discharge, and that their abundances could recover after six weeks. Fluctuations in cyanobacteria and Chlorophyta were not significant. When a significant relationship between dam discharge and environmental factors was found, the length of the time lag, if any, could be identified (Table 2). The combinations of dam discharge and conductivity, as well as the concentrations of TN, TP, and DIP, showed negative CCFs immediately after dam discharge. In contrast, dam discharge showed a positive cross-correlation with SS and DIN at immediately after dam discharge (lag

Table 2. Summary of significant cross-correlation between dam discharge and biotic/abiotic factors. Significant cross-correlation coefficients factor (CCF) is given as *r* and its sign (n = 51)

Input variable	Output variable	Lag time (week)	Sign	CCF	*r* for $P < 0.05$
Dam discharge	Phytoplankton	0	-	-0.254	0.233
	Diatom	0	-	-0.320	0.233
	Other phytoplankton	36	+	0.557	0.233
	Total nitrogen	0	-	-0.583	0.233
	Total phosphorus	0	-	-0.498	0.233
	Dissolved inorganic nitrogen	0	+	0.264	0.233
	Dissolved inorganic phosphorus	0	-	-0.474	0.233
	Dissolved silica	0	+	0.653	0.233
	Conductivity	0	-	-0.325	0.233
	Suspended solids	0	+	0.415	0.233
	Chemical oxygen demand	10	+	0.338	0.233
	Biological oxygen demand	12	+	0.432	0.233
Phytoplankton	pH	0	+	0.617	0.233
Diatom	pH	0	+	0.757	0.233
Suspended solids	Phytoplankton	2	-	-0.641	0.506
	Cyanophyta	2	-	-0.856	0.506
	Chlorophyta	2	-	-0.803	0.506
	Other phytoplankton	2	-	-0.645	0.506
Dissolved inorganic nitrogen	Phytoplankton	2	-	-0.511	0.506
	Chlorophyta	0	+	0.724	0.506

time of 0), whereas positive cross-correlations for COD occurred at ten weeks after the dam discharge and with BOD at the sixth sampling time. With regard to the cross-correlation between these phytoplankton communities and abiotic factors (Table 2), DIN had a delayed negative association with total phytoplankton and Chlorophyta at the first sampling time and a positive one at a lag time of 0. Total phytoplankton, cyanobacteria, and Chlorophyta communities were affected negatively by increased SS concentrations. Other environmental factors hardly affected the phytoplankton communities.

DISCUSSION

In the LHR, the density of phytoplankton during the dry season was approximately two times higher than that during the rainy season. Many reports of studies in channelled river systems have shown the importance of the control of the flow and amount of water by a dam for the increase (dry season) or decrease (rainy season) of phytoplankton abundance. For example, fluctuations in the biomass of *Microcystis aeruginosa* (a cyanobacterium) in the Nakdong River of South Korea were affected strongly by dam discharge: *M. aeruginosa* increased in biomass when there was a low level of discharge, whereas it decreased in biomass during periods of high rainfall (Jeong et al. 2007). This finding is similar to results reported by Park et al. (2002), such that that the timing of dam discharge during periods of summer typhoons is important for fluctuations in cyanobacterial density. Søballe and Kimmel (1987) stated that high discharge causes a decrease in phyto- and zooplankton biomass in a lotic system supplied by a large mass of water. These previous results strongly support the assertion that increased quantities of discharge lead to a reduction in phytoplankton abundances. In particular, in the present study, fluctuations in diatom assemblages, which constituted over 70% of the total phytoplankton abundance, were affected severely by the changes in the discharge. Interestingly, diatom abundances showed rapid recovery within 6 weeks (data not shown). This time lag is consistent with the end of periods of rainfall. Moreover, in a regulated river, diatoms can be the main constituent of the phytoplankton community (Domingues et al. 2012). Thus, rapid recovery of diatom assemblages can be assumed to be one of the eco-physiological characteristics that tend to occur with falling temperature in autumn and nutrient loading due to a low water velocity (Jung et al. 2011).

Eutrophication in an ecosystem causes phytoplankton abundance to increase, species diversity to decrease, and dominant biota to change. In particular, more species were present during the dry season, which may serve as an indicator of the strong eutrophication of a body of water (Mason 2002). Diatom blooms tend to occur in spring and autumn, whereas an admixture of Chlorophyta and cyanobacteria appears during summer (Gosselain et al. 1994). In the LHR, Chlorophyta and cyanobacteria cannot accumulate in blooms during summer because of the fast flow of the river due to high precipitation and discharge. As mentioned above, the Nakdong River exhibits frequently *M. aeruginosa* blooms during the dry summer season. Hötzel and Croome (1994) reported that the occurrence of cyanobacterial blooms is an opportunistic response to conditions of slow flow with high nutrient status. In the Warnow River in Germany (a lowland river-lake system), tendencies were observed for cyanobacteria to be the most abundant group during summer, and centric diatoms the most common group during autumn (Bahnwart et al. 1999). It is illuminating to analyse the dynamics of phytoplankton communities in the LHR by comparison with that of a lacustrine system because lotic systems have hydrological characteristics, such as a high-velocity flow and a short retention time, that are associated with the inflow of a significant amount of water due to dam discharge. Consequently, Chlorophyta and cyanobacteria in the LHR cannot grow during summer because of the high velocity caused by a high level of discharge. Diatoms could be better adapted to the channelled flow regime and seasons that prevail in a regulated river.

Dam discharge had a direct influence on the water quality, such as levels of turbidity and nutrients; however, these effects are unusual and are unlikely to occur in most channeled rivers. The quantity of dam discharge, and the interval and frequency of discharge, are important for the control of water quality. When a large quantity of water was discharged into the LHR, the conductivity and the concentrations of TN, TP, and DIP decreased rapidly, whereas the concentrations of SS, DIN, and DSi increased immediately. Shapiro and Wright (1984) reported that the TN and TP concentrations in Round Lake in the USA increased in summer during the period of high rainfall. These increases may be associated with the accumulation of particulate nutrients, including manure, and/or aquatic organisms entering the lentic ecosystem. However, in the lotic system studied herein the concentrations of TN and TP were reduced rapidly during seasons of rainfall. Ha et al. (1998) found that the concentrations of TN and TP in the rainfall run-off were decreased rapidly in the Nakdong River. The increase in the concentrations of SS,

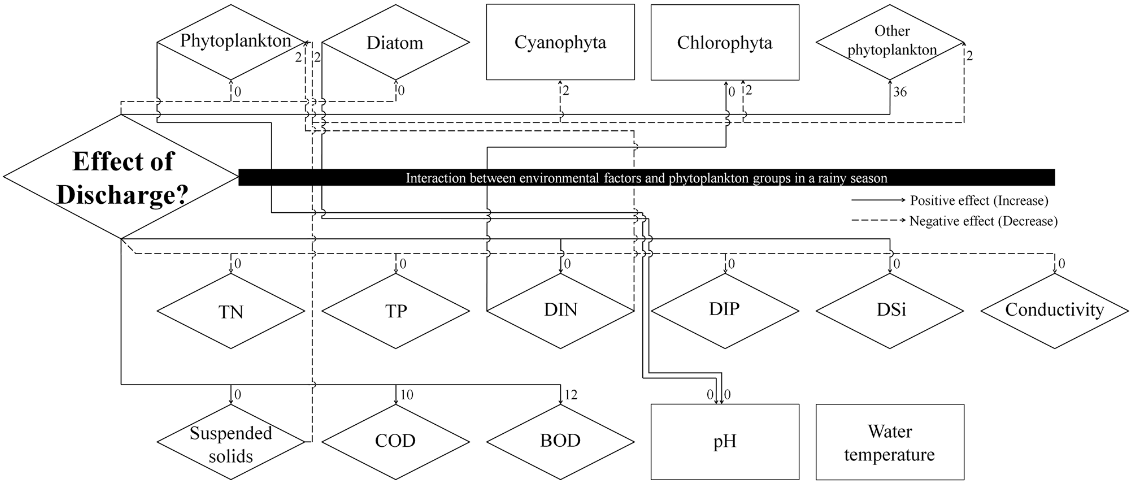

Fig. 5. Schematic diagram that summarizes the variations in phytoplankton populations and environmental factors associated with discharge of the Paldang Dam by cross-correlation analysis. The solid and dotted lines indicate positive (increase) and negative (decrease) correlations, respectively. Diamonds and rectangles indicate the significant interaction with dam discharge and no significant interaction between the discharge, respectively. Water temperature is not significantly correlated with any biotic and abiotic factors. TN, total nitrogen; TP, total phosphorus; DIP, dissolved inorganic phosphorus; COD, chemical oxygen demand; BOD, biological oxygen demand. The numerals on the arrows are time lags (weeks after discharge).

DIN, and DSi might be due to upwelling from bottom sediments by the high-velocity flow or release from the land by rainfall. McKee et al. (2001) stated that the concentrations of nitrogen and phosphorus in the Richmond River of Australia varied seasonally, with greater proportions of inorganic nitrogen and phosphorus during the rainy season, whereas the minimum nutrient concentrations were found 2–3 months after flood discharge. These changes in factors are similar to the finding of Humborg et al. (1997), such that hydrolytic factors, including discharge and precipitation, are among the most important factors that influence fluctuations in nutrient levels. Thus, the variability in these concentrations usually parallels the strength of river flow that is associated with summer rainfall, with higher values during periods of high river discharge (Domingues et al. 2012).

The time interval between a dam discharge and its effect on phytoplankton, environmental factors, and their interaction remains an important issue. Fig. 5, produced by a result of cross-correlation analysis (Table 2), shows the effect of dam discharge on phytoplankton communities and abiotic factors related to the river, as well as the interaction between phytoplankton and abiotic factors. The results show that dam discharge caused a rapid decrease in the total phytoplankton, diatom abundances, and concentrations of TN, TP, and DIP, but a rapid increase in the concentrations of SS, DIN, and DSi. On the whole, fluctuations in phytoplankton communities in the LHR were influenced much more by hydrodynamics than by the availability of nutrients. In relation to the interaction between phytoplankton communities and nutrients, DIN concentrations were only associated with a change in the abundance of Chlorophyta, which is a minor taxon that contributes little to the total phytoplankton abundance, in particular during the rainy season. Domingues et al. (2012) stated that diatoms abundance was correlated positively with nitrate concentration, which was in turn regulated by river flow. However, in our results, diatom assemblages were less abundant during the rainy season, even though the nitrate concentration increased during this period. Our results indicate that soluble nutrients may be taken up less effectively by phytoplankton in rivers with a rapid flow. When discharge from a dam occurs, phytoplankton abundance in the river decreases rapidly due to the short hydraulic retention time. In contrast, phytoplankton abundance in the river increased due to the long retention time (Dynesius and Nilsson 1994). For example, after the Columbia River in the USA was dammed, phytoplankton biomass increased due to the combined effects of reduced flow velocity, increased water retention time, and decreased vertical mixing intensity (Sullivan et al. 2001). A similar situation has been observed in some reservoirs and regulated rivers, as well as rapidly flushed impoundments (Søballe and Kimmel 1987).

CONCLUSION

The status of phytoplankton downstream of the Paldang Dam on the LHR can be categorized in terms of four key temporal periods that are related to changes in the water inflow as a result of dam discharge. First, towards the end of winter (dry season), small centric and pennate diatoms, as well as cyanobacteria, develop in response to increased nutrient availability, light intensity, and water temperature, as well as a long retention time. Second, when discharge from the dam occurs during summer, with its heavy rainfall, the crop of phytoplankton is swept away by the high-velocity flow. At the same time, concentrations of SS, DIN, and DSi are increased rapidly by run-off from the land. As a consequence, phytoplankton decreases in abundance rapidly. Third, after the rainy season, autumn phytoplankton crops start to accumulate. Among them, *Aulacoseira granulata*, a chain-form diatom, becomes increasingly abundant with the progression of autumn. Finally, with the reduction of light energy and high nutrient sources associated with winter, *Stephanodiscus hantzschii*, a small centric diatom, blooms. This blooming leads to depletion of DSi during the dry winter season.

ACKNOWLEDGMENTS

This study was supported by a research fund from the Korea Institute of Ocean Science and Technology (The Study on the impact of the Yellow Sea Bottom Cold Water Mass to the ecosystem: PE99233) and from Korea Ministry of Environment (#416-111-008, Industrialization of Algae of The Eco-Innovation project in 2013).

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