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Daily Variation of Phytoplankton and Water Quality in the Lower Nakdong River

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Daily variation of phytoplankton community and environmental parameters were investigated at the lower Nakdong River (Mulgum) from January 2002 to December 2003 to investigate the dynamics of a phytoplankton community in detail. The daily results of water quality in this investigation showed pH (8.1 ± 0.7), DO (10.3 ± 2.7 $mg \cdot l^{-1}$), water temp. (18.8 ± 7.4°C), BOD (2.4 ± 1.0 $mg \cdot l^{-1}$), COD (5.3 ± 1.2 $mg \cdot l^{-1}$) and chl. a (43.5 ± 35.1 $mg \cdot m^{-3}$). The results of nutrient factors were the following: TN (3.1 ± 0.8 $mg \cdot l^{-1}$), NO_3-N (2.5 ± 0.5 $mg \cdot l^{-1}$), TP (90 ± 48 $\mu g \cdot l^{-1}$), PO_4-P (43 ± 30 $\mu g \cdot l^{-1}$). Dominant phytoplankton species during the study period were diatom (*Stephanodiscus hantzschii*, *Aulacoseira granulata* var. *angustissima* and *A. italica*) and cyanobacteria (*Microcystis aeruginosa*, *Aphanizomenon flos-aquae*). The small centric diatom, *Stephanodiscus hantzschii*, was repeatedly dominant from late fall to the following spring (mean and maximum cell density, $2.3 \times 10^3 \pm 3.8 \times 10^3$, 4.5×10^5 $cells \cdot ml^{-1}$, respectively). Pinnate diatom, *Aulacoseira granulata* var. *angustissima* and *A. italica*, were frequently observed all season except January to March. Cyanobacteria, *Microcystis aeruginosa* and *Aphanizomenon flos-aquae*, proliferated in summer of 2002 except in 2003 due to heavy precipitation. The dominant zooplankton species (March-early May) was rotifer (*Brachionus, Keratella, Polyarthra*) and cladocerans (*Diaphanosoma*). The daily observed dynamics of the phytoplankton community in the lower Nakdong River in this study may play an important role in increasing the detailed resolution of limnological information and serving as ecological data for future studies.

Key Words: Nakdong River, phytoplankton, water-bloom, water quality, zooplankton

INTRODUCTION

The Nakdong River is the second largest river system in South Korea containing a large drainage basin and a long main channel. The flow of the Nakdong River is highly regulated by 4 multi-purpose dams in the major tributaries and an estuary barrage, which were constructed in the mouth of the river to ensure efficient use of water resources. Especially, the lower Nakdong River shows a river-reservoir hybrid type due to the stagnation of water flow during the dry period. Also hypertrophication was occurring with in the Nakdong River over eutrophication because of the continuous inflow of raw nutrients from industries that have populated the middle part of the river (Joo *et al.* 1997). Since 1992, the low supply of water resources and the massive change in the aquatic community have caused cyanobacterial blooms every summer and the flourishing of diatoms during the dry winter period.

The development and succession of phytoplankton is governed by biological factors, such as decomposition, grazing and parasitism, and also by physical-chemical factors, such as climate, irradiance, precipitation, discharge, water temperature, pH, dissolved oxygen and nutrient availability (Reynolds 1984). The intensity and frequency of disturbances by precipitation and discharge are especially important to the regulation of phytoplankton dynamics (Reynolds 1988; Reynolds *et al.* 1993)

Numerous studies on the management and the status of the water quality in the Nakdong River since the 1990s have included the phytoplankton community (Kim and Lee 1991; Chung *et al.* 1994; Lee 1994; Ha *et al.* 1998), primary production (Kim *et al.* 1998), ecological studies (Joo 1995), water quality and zooplankton (Kim 1996), eutrophication (Heo *et al.* 1995; Kim 1996) and water quality (Park 1998; Shin and Cho 1999; Song *et al.* 2000). Also studies on the seasonal or weekly dynamics of the phytoplankton community in a hydrosphere have been

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conducted (Wetzel 1983; Harris 1986; Descy 1993; Garnier *et al*. 1995; Ha *et al*. 1998). However, daily variation of the phytoplankton community and other water quality factors have been rarely studied.

In this investigation to evaluate the features of the Nakdong River in further detail, physico-chemical factors and the dominance and the abundance of phytoplankton were surveyed daily from January 2002 to December 2003 in Mulgum, which is located at the lower Nakdong River serving as the water supply resource of Busan Metropolitan City.

MATERIALS AND METHODS

Description of the study site

The Nakdong River is the longest river that reaches 521.1 km in its total length (river basin, 23,817.3 km^2), from Bonghwa, Kyung-buk province to the Nakdong estuary dam. The Nakdong River basin shows monsoon characteristics by frequent heavy rainfall from late June to early July every year. The mean annual precipitation is 1,272 mm at the lower Nakdong River. Over 60% of the annual rainfall is concentrated in summer (June-August) and the remaining period, especially winter (December-January), is classified as the dry period. The mean annual water temperature is 12-16°C. The mean annual cold water temperature is 2.5°C in January and the mean annual hot water temperature is 29-30°C in August (Kim *et al.* 2001).

In 1987, an estuary dam was constructed at the mouth of the Nakdong River to avoid salt-water intrusion. The lower part of the river became a river-reservoir hybrid due to these changes in hydrology (Joo *et al.* 1997; Kim *et al.* 1998). Because the channel slope is very slight and the flow rate is slow, the retention time assumes similar aspects of a reservoir. Also, considering the present condition of pollution in the lower part of the river, the pollution load of the Keumho River is 9.89 billion ton per day and is the principal depositer of pollution, occupying 39.2% of total pollution load in the lower Nakdong hydrosphere. Mulgum, the study site, is situated 27 km upstream from the estuary dam (maximum water depth, 10 m; mean depth, 4.5 m; river width, 250-350 m; Fig. 1).

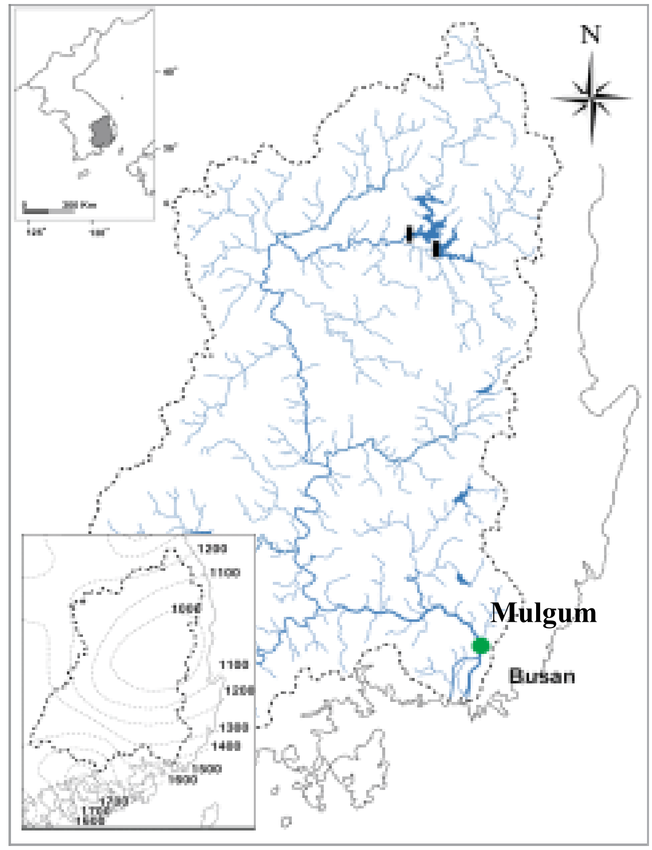

Fig. 1. Study area showing the location of sampling site (●: Mulgum).

Sampling and water quality analysis

Daily sampling was conducted from 1 January 2002 to 31 December 2003 at Mulgum before investigating basic water quality variables and abundance of dominant phytoplankton (Fig. 2). Total coliforms and nutrients were surveyed at weekly intervals. The daily precipitation data of the 5 representative meteorological stations within the Nakdong River basin (Andong, Taegu, Hapchun, Jinju and Milyang) were obtained from Busan Regional Meteorological Offices. Data on irradiance were also collected about the nearest study site from Busan Regional Meteorological Offices. Data on daily river discharge were collected about Jindong station (49 km upstream from the estuary dam), which directly influenced the variation in water level. Water temperature and dissolved oxygen (DO) were measured with DO meter (model 830, Orion, Germany) and pH with a pH meter (model 407A, Orion, Germany) on the spot. Chemical oxygen demand (COD), biological oxygen demand (BOD) and total nitrogen (TN), total phosphorus (TP) and phosphate (PO_4-P) were measured according to the standard method of APHA (1999) after collecting water samples with Van-Don sampler at 0.5 m depth at the river site and carried to the laboratory under frozen-dark conditions. Chlorophyll *a* concentrations (chl. *a*) were determined after a 500 m*l* sample was

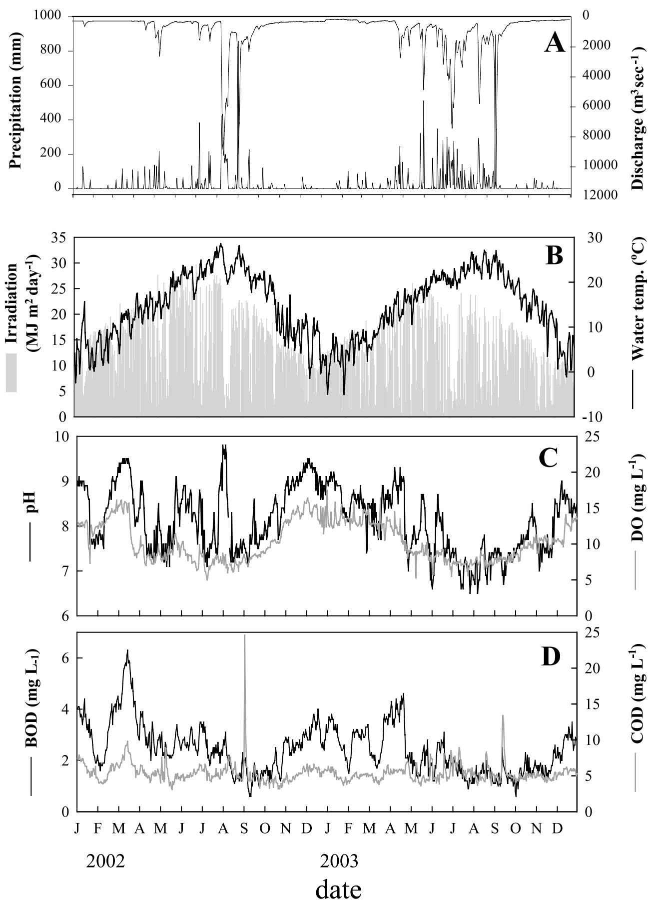

Fig. 2. Daily variations of meteorogical factors and environmental parameters in the lower Nakdong River basin.

filtered with 0.45 μm GF/C filters (Whatman, Cat. No. 1822047, UK), preserved in a refrigerator in the dark for a day and analyzed by the monochromatic method (Wetzel and Likens, 1991). Total coliforms were determined by MPN method after sampling aseptically with a sterilized 125 ml vial on the spot and delivered to the laboratory (APHA 1999).

Phytoplankton samples (1.0 *l*) were immediately preserved with Lugol's solution and concentrated on 20 m*l* sample in 20 m*l* scintillation vial with 10 μm pore-size sieve. 1.0 m*l* out of the concentrated sample on a Sedgwick Rafter Chamber was repeatedly identified and enumerated with an inverted microscope (× 400, ZEISS, Axiovert 135M, Germany). Subsamples were identified on a slide glass at 1,000 fold magnification. Identification of individual species was referred to Cassie (1989), Round *et al.* (1990) and Prescott (1973).

Zooplankton were collected by 4 or 8 *l* of water using a 3.2 *l* Van Dorn bottle at 0.5 m depth. Retained zooplankton through a 35 m nylon mesh were preserved with 10% formalin (4% of final concentration). Large (> 0.2 mm or copepods and cladocerans) and small (< 0.2 mm or nauplius and rotifers) zooplankton were counted separately because they differed substantially in their numerical densities. Zooplankton taxa were identified to the genus or species level, except for juvenile copepods, using Koste (1978) and Einsle (1993) as references.

RESULTS AND DISCUSSION

Meteorology of the lower Nakdong River

About 10 dams were constructed within the Nakdong River basin to ensure water supply because precipitation is heavily concentrated in summer with over 50% of the mean annual precipitation. Heavy rainfall in summer primarily stored at the dams, and regulation of dam discharge is highly influenced in flow and water quality by the lower Nakdong River.

The means of annual precipitation in 2002 (1,522.7 mm) and 2003 (1,805.7 mm) were higher than the annual average of the last seven years (1,224 mm) (Jung 2004). In 2002 and 2003, heavy rainfall in summer was mean 220 mm for 10 d (6 August-16 August, especially maximum 857.5 mm consisting of 56% of mean annual precipitation, 31 August) and mean 120 mm for 14 d (1 July-14 July, especially maximum 894.5 mm consisting of about 50% of mean annual precipitation, 12 September), respectively, which was about a month earlier than in 2002 (Fig. 2-A). Precipitation frequency over 50 mm was observed more in 2003 than in 2002 (maximum 13 times in August out of total 39). The frequency of precipitation was higher in 2003 (145 d) than in 2002 (131 d). Precipitation in the mid Nakdong River area highly influenced the water quality at Mulgum in the lower Nakdong River. Especially, water quality was influenced more by days of rainfall than by precipitation.

The variation of mean monthly irradiance ranged from maximum 20.2 $MJ \cdot m^{-2}$ (June 2002) to minimum 7.4 $MJ \cdot m^{-2}$ (November 2003) and was especially higher in May and June (Fig. 2-B). Mean annual irradiance was higher in 2002 (14.5 $MJ \cdot m^{-2}$) than in 2003 (12.1 $MJ \cdot m^{-2}$). The variation in water temperature differed little with the variation in irradiance. The variation of monthly water temperature was minimum 2.5°C (January 2003) and maximum 24.3°C (August 2002).

Physico-chemical factors of water quality

The variation of pH (8.1 ± 0.4, monthly average 7.1-9.1) was seasonally higher in winter than in summer on a weak alkali state, displaying a lower pH in 2003 (7.9 ± 0.5) than in 2002 (8.3 ± 0.4). The annual and seasonal variations in pH showed correlation with variations of phytoplankton abundance. Daily variation of pH showed a maximum in the cyanobacterial bloom period (26 July-7 August in 2002, pH 8.7-9.8) and maintained high values all winter with a diatom bloom (Fig. 2-C).

Water temperature (1.5 ± 7.2-28.9 ± 7.8°C) was lower during the study period than that of previous years, considering frequent precipitation. Especially in August 2002 and July 2003, water temperature showed 3-5°C lower than that of previous years (Bahk *et al.* 2001; Jung 2004). Seasonal variation of DO was clearly higher in winter than in summer. Frequent precipitation in 2003 caused lower DO than in 2002 (Fig. 2-C). High DO at the end of October (27 October 2002) to the middle of April (17 April 2003) changed steadily to low values in spring and summer. DO was higher in fall and winter than in spring and summer. Low DO in summer was probably due to the influx of washout and nutrients by frequent rainfall.

Mean annual variations of BOD and COD were, respectively, 2.7 $mg \cdot l^{-1}$ and 5.6 $mg \cdot l^{-1}$ in 2002 and 2.2 $mg \cdot l^{-1}$ and 5.3 $mg \cdot l^{-1}$ in 2003. Both BOD and COD showed lower values in 2003 than in 2002. Mean monthly variation of BOD and COD was higher in winter (2.7-4.8 $mg \cdot l^{-1}$ and 4.9-7.1 $mg \cdot l^{-1}$, respectively) than in summer (1.5-2.7 $mg \cdot l^{-1}$ and 5.1-6.2 $mg \cdot l^{-1}$, respectively) (Fig. 2-D). In 2002, BOD was reduced to 1.8 $mg \cdot l^{-1}$ due to heavy rainfall on 6 August and maintained until 26 October. During this period, however COD increased and especially, showed temporally 12.8 $mg \cdot l^{-1}$ on 31 August having 857.5 mm precipitation. In 2003, low BOD was maintained from 1 July to 25 November but COD was the very reverse. Especially, on 12 September 2003 having 894.5 mm precipitation, COD showed maximum 13.4 $mg \cdot l^{-1}$ (Fig. 2-D). Those results were considered to be caused by the influx of massive organic nutrients from the upper stream, not by the algae abundance during heavy rainfall. Mean annual concentration of TN was similarly 3.23 $mg \cdot l^{-1}$ in 2002 and 3.00 $mg \cdot l^{-1}$ in 2003, and was lower in the study period than in 1995-1999 (Jung 2004). Mean monthly TN concentration ranged in 1.75-5.59 $mg \cdot l^{-1}$ and showed minimum 1.8 $mg \cdot l^{-1}$ in September 2002 and maximum 4.2 $mg \cdot l^{-1}$ in March 2002. Variation in concentration of TN was lower in summer (June-September) and higher in winter (October-March) (Fig. 3-A). Mean annual concentration of TP was 117 $\mu g \cdot l^{-1}$ in 2002 and 77 $\mu g \cdot l^{-1}$ in 2003 which was lower than that of previous years. Variation in monthly concentration of TP was low in August and September 2002 because of heavy rainfall and low all year of 2003 (Fig. 3-B). N/P ratio showed high variation of 16-115 and maximum in March 2003. Seasonal variation of N/P ratio was low in summer and high in winter to spring (Fig. 3-C). This pattern of values was similar to that of Andong dam, which is located in the upper Nakdong River, and was lower than that of Paldang dam (Han *et al.* 1993; Heo *et al.* 2000).

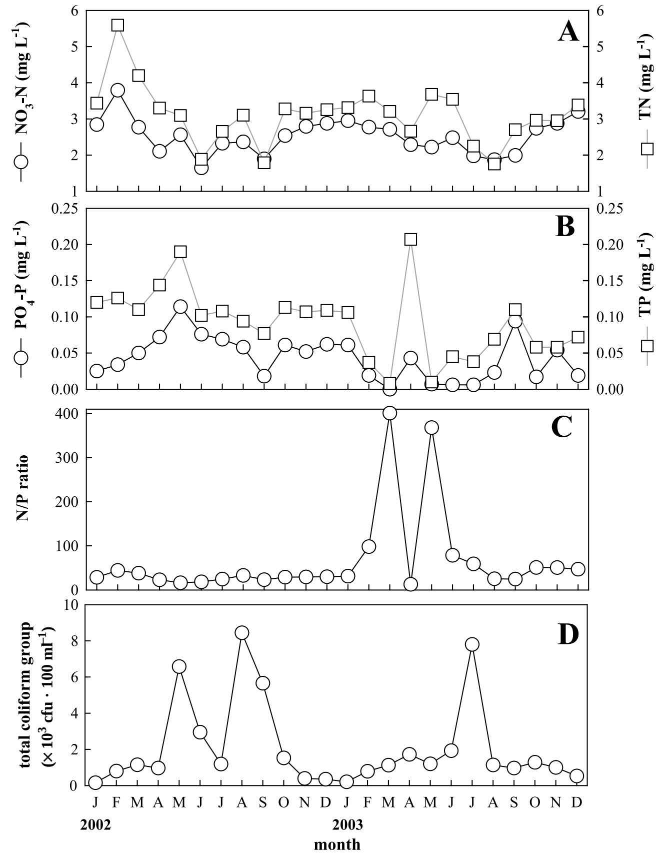

Fig. 3. Monthly variations of environmental parameter in the lower Nakdong River.

Variation of total coliforms was 1.6×10^2-8.4×10^3 MPN/100 m*l* displaying lower number in winter than in summer, which was more than a third class drinking water source. Especially, those reverse results were observed with monthly variations in the abundance of phytoplankton (Fig. 3-D).

Dynamics of dominant phytoplankton

Means of annual abundance of phytoplankton (chl. *a*) were 41.7 $mg \cdot m^{-3}$ (n = 365, max.: 213.6 $mg \cdot m^{-3}$) in 2002 and 39.0 $mg \cdot m^{-3}$ (n = 365, max.: 130 $mg \cdot m^{-3}$) in 2003. According to Vollenweider and Kerekes (1980), mean

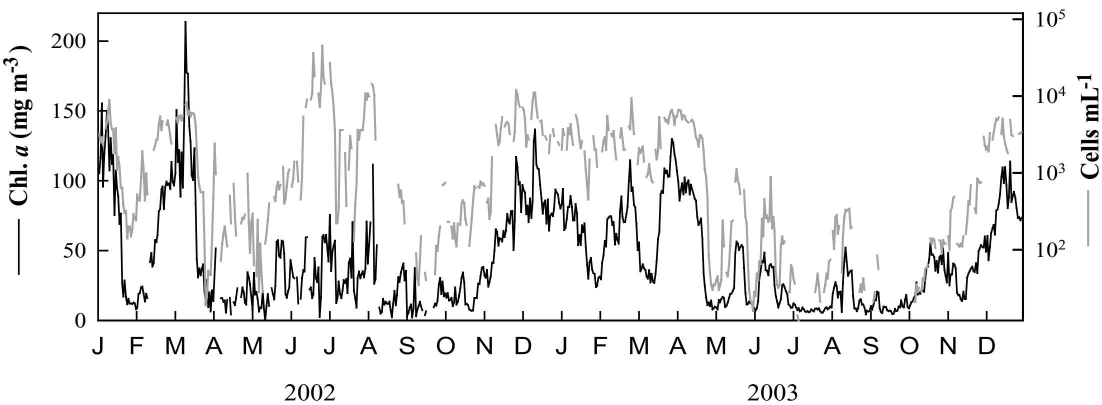

Fig. 4. Daily variations of chl. *a* and abundance of phytoplankton dominance species in the lower Nakdong River (Mulgum).

Table 1. Change of dominant species of phytoplankton at Mulgum in lower Nakdong River during January 2002 to December 2003

Year	Month	Dominance species	Year	Month	Dominance species
2002	Jan.	*Stephanodiscus hantzschii*	2003	Jan.	*Stephanodiscus hanzschii*
	Feb.	*Stephanodiscus hantzschii*		Feb.	*Stephanodiscus hanzschii*
	Mar.	*Cyclotella meneghiniana*		Mar.	*Stephanodiscus hanzschii*
		Nitzschia palea			
		Stephanodiscus hantzschii			
	Apr.	*Actinastrum hanzschii*		Apr.	*Cyclotella meneghiniana*
		Aulacoseira granulata var. *angustissima*			*Stephanodiscus hanzschii*
		Aulacoseira italica			
		Cyclotella meneghiniana			
		Dictyospaerium pulchellum			
		Scenedesmus quadricauda			
		Stephanodiscus hantzschii			
	May	*Aulacoseira granulata* var. *angustissima*		May	*Asterionella formosa*
		Aulacoseira italica			*Aulacoseira granulata var. angustissima*
		Scenedesmus quadricauda			*Aulacoseira italica*
					Cyclotella meneghiniana
	Jun.	*Aulacoseira granulata* var. *angustissima*		Jun.	*Aulacoseira granulata* var. *angustissima*
		Aulacoseira italica			*Aulacoseira italica*
		Microcystis aeruginosa			*Nizschia palea*
	Jul.	*Aulacoseira granulata* var. *angustissima*		Jul.	*Aulacoseira granulata* var. *angustissima*
		Aulacoseira italica			*Aulacoseira italica*
		Microcystis aeruginosa			*Synedra acus*
	Aug.	*Aulacoseira granulata* var. *angustissima*		Aug.	*Aulacoseira granulata* var. *angustissima*
		Aulacoseira italica			*Aulacoseira italica*
		Microcystis aeruginosa			
	Sep.	*Aulacoseira granulata* var. *angustissima*		Sep.	*Aulacoseira granulata* var. *angustissima*
		Aulacoseira italica			*Aulacoseira italica*
		Aphanizomenon flos-aquae			
	Oct.	*Aulacoseira granulata* var. *angustissima*		Oct.	*Aulacoseira granulata* var. *angustissima*
		Aulacoseira italica			*Aulacoseira italica*
	Nov.	*Aulacoseira granulata* var. *angustissima*		Nov.	*Aulacoseira granulata* var. *angustissima*
		Aulacoseira italica			*Aulacoseira italica*
		Stephanodiscus hanzschii			*Stephanodiscus hanzschii*
					Synedra acus
	Dec.	*Stephanodiscus hanzschii*		Dec.	*Stephanodiscus hanzschii*

annual chl. a concentration over 25 mg · m^{-3} was assessed as hypertrophication because the study site exceeded 0.6-0.7 times of the hypertrophic standard. From 1995 to 2001, mean annual by Jung (2004) was 44.1-96.0 mg · m^{-3} at the same site, which was slightly higher than the study period. Abundance of phytoplankton was generally high during the cyanobacterial bloom in summer (June-September) and during the diatom bloom in winter (December-March). *Microcystis* dominated for about 1 month (11 June-12 July 2002) but showed no massive bloom. Mean chl. a concentration in this period was 40.4 mg · m^{-3}, which was 2-6 times lower than that of previous cyanobacterial bloom periods (Ha *et al.* 1999; Jung 2004). Chl. a concentration was high due to the diatom bloom until the middle of March but was reduced sharply as zooplankton increased of in early May. Abundance of phytoplankton was higher in winter than in summer, which was caused by the maintenance of higher abundance of diatoms during 3-4 months of winter in spite of a short cyanobacterial bloom for 14 d. A cyanobacterial bloom in summer was not clearly observed during this study period.

Repeated heavy rainfall occurred at intervals of 7-10 d from April to October 2002 in all basins and caused low abundance of phytoplankton 12.7-35.1 mg · m^{-3}. In the dry period of short discharge, abundance of phytoplankton showed a clear increase in Mulgum of the lower Nakdong River by an influx of increasing nutrients from the upper stream and closure of the estuary gate.

Especially, abundance of phytoplankton showed a negative correlation with precipitation and discharge. Abundance of phytoplankton in a heavy rainfall period showed a minimum of 3.2 mg · m^{-3} in 31 August 2002 and 5.3 mg · m^{-3} in 12 September 2003.

The phytoplankton community showed clear dominance of diatoms during the study period (Table 1). According to the previous surveys, cyanobacteria thrived distinctly in summer, and diatoms in winter (Ha *et al.* 1998; Jung 2004). During this study period, *Microcystis aeruginosa, M. viridis, M. wesenbergii, Anabaena spiroides, A. macrospora*, and *Aphanizomenon flos-aquae* were frequently observed in summer, but *Stephanodiscus hantzchii, Cyclotella meneginiana, Aulacoseira granulata* var. *angustissima* and *A. italica* dominated at many periods in winter. Also, higher densities of diatoms were observed than other populations in summer due to precipitation. *Stephanodiscus hantzschii*, a small diatom, occurred as the single most dominant species during the dry period of winter and early spring (December-March), similar to previous surveys (Ha *et al.* 1998; Jung 2004).

Stephanodiscus hantzschii has been known to dominate at low water temperatures during the dry period (about 10-15 d) in eutrophic rivers in Europe, Australia and Japan. But during periods of much lower water temperature (4-8°C), the density of *Stephanodiscus hantzschii* was 3-4 times higher in Korean river than that of other rivers in the world (Ha *et al.* 1998). This was probably because of the accumulation of nutrients and other pollutants from the midstream as well as stagnation of the hydrosphere, decreased flow rate due to the construction of an estuary barrage in 1987, and increased water supply for agricultural and industrial water. Especially, deteriorated water quality in winter was thought to be caused mainly by intense diatom blooms in the downstream, forming a reservoir-like pattern by severely decreasing discharge and flow rate during the dry winter and spring.

Variation of dominance and standing crops in 2002 showed 140-8,800 cells · ml^{-1} of *Stephanodiscus hantzschii* from January to the middle of April. Diatoms were temporally succeeded by chlorophyceae (*Dictyosphaerium puchellum, Actinastrum hantzschii, Scenedesmus quadricauda*) to the middle and the end of April. From May, diatom *Aulacoseira granulata* var. *angustissima* dominated again. As water temperature increased, cyanobacteria, *Microcystis aeruginosa*, dominated from the middle of June to the middle of July 2002, but standing crops were 3,600-36,000 cells · ml^{-1} with no water bloom. During the same period, *Aphanizomenon flos-aquae* occurred simultaneously but dominated temporally at the end of September (about 7 d). Cyanobacteria disappeared due to precipitation in early August, and diatom, *Aulacoseira granulata* var. *angustissima*, dominated until early November. Various dominant phytoplankton species appeared, beginning with *Cyclotella meneghiniana*, from the middle of April to early May, and succeeded by *Asterionella gracillima* to the end of May. Variation in dominance of phytoplankton in 2003 was different from that of 2002. In the summer of 2003, a cyanobacterial water bloom did not appear due to the frequent precipitation. Selective grazing by zooplankton was to related to seasonal succession of phytoplankton. Most rotifers, cladocerans and copepodas had the ability to improve water quality by removing particulate organic matter in the water with filtration (Wetzel and Likens 1991). The zooplankton community during the study period consisted of rotifers (*Brachionus calyciflorus, Keratella cochlearis* and *Polyarthra* *vulgaris*) and cladoceran (*Diaphanosoma brachyurum*). From 17 March 2002 to early May, a massive appearance of zooplankton caused the grazing of phytoplankton. During that period, standing crops of phytoplankton and most factors of water quality maintained low values. Dominant species of zooplankton in the lower Nakdong River (Mulgum) were rotifers and small cladocerans, which were similar to the survey by Kim and Joo (2000). Especially, *Brachionus calyciflorus* was distributed widely in spring (March-April) and fall (September-October). Standing crops of zooplankton in 2003 were less than that in 2002. Rotifers appeared for a long term from the end of March to the end of June 2003 but disappeared once the rainy season of July began.

In this study, the abundance of phytoplankton and water quality in the lower Nakdong River appeared to be influenced more by precipitation, discharge and abundance of zooplankton. Consequentially, regulation of dam discharge in the midstream and an open estuary gate in the lower Nakdong River seemed to influence the dynamics of phytoplankton community and improved water quality in the downstream.

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