OCCURRENCE CHARACTERISTICS OF *STEPHANODISCUS* AND *SYNEDRA* IN RELATION TO WATER TEMPERATURE AND CONCENTRATIONS OF NUTRIENTs DURING SPRING DIATOM BLOOM IN LAKE PALDANG, KOREA

YOUN, S. J. – YU, S. J. – BYEON, M. S.*

Han River Environmental Research Center, National Institute of Environmental Research
42, Dumulmeori-gil68beon-gil, Yangser-myeon, Yangpyeong-gun, Gyeonggi-do 12585, Republic of Korea
(phone: +82-31-770-7270; fax: +82-31-773-2268)

**Corresponding author*
e-mail: zacco@korea.kr; phone: +82-31-770-7271

(Received 6th Dec 2019; accepted 6th May 2020)

Abstract. Physicochemistry was measured weekly from 2014–2017 at sites PD1, PD2, and PD3 in Lake Paldang, Korea. The effects of temperature and nutrients on the growth of the freshwater diatoms *Stephanodiscus* and *Synedra* were determined. PD2 had higher water temperature, dissolved oxygen, and conductivity than PD3. Total phosphorus and nitrogen at PD2 were the highest (0.038 mg/L and 2.181 mg/L, respectively). However, PD3 had more silicon (1.396 mg/L) than PD2 (1.027 mg/L). *Stephanodiscus* and *Synedra* bloomed mainly between March and May. At all three sites, *Stephanodiscus* was detected at 1.2–22.7°C and its density was the highest at 6.7°C. *Synedra* was detected at 1.2–32.8°C and its density was the highest at 13–15°C. *Stephanodiscus* and *Synedra* proliferated when TP was ≥ 0.020 mg/L and ≤ 0.020 mg/L, respectively, and Si was ≤ 0.4 mg/L and ≥ 0.4 mg/L, respectively. Therefore, temperature, phosphorus and silicon significantly influenced diatom growth.
Keywords: *phosphorus, silicon, Si:P ratio, springtime*

Introduction

Spring diatom bloom frequently occurs in eutrophic rivers, lakes, and seas around the world. The mass growth of *Asterionella* or *Stephanodiscus* is accompanied by malodor (Jüttner, 1983; Deng et al., 2013). When large volumes of these diatoms flow into water purification plants, they clog filter basins (Joh et al., 2011). Diatom overpopulation also causes many other problems. These problems lead to a reduction of dissolved oxygen transparency, which results in clogging and sedimentation issues in water-treatment processes and drinking water supply systems, with high diatoms biomass (Hijnen et al., 2007; Reavie et al., 2016).

Spring diatom bloom is affected by various environmental factors like light, rainfall, water temperature, and nutrient levels (Bleiker and Schanz, 1989; Marshall and Peter, 1989; Muylaert and Sabbe, 1999; Ye et al., 2007). These factors modify phytoplankton development and sustainability. They also determine species composition and seasonal succession (McCauley and Downing, 1991; Teubner and Dokulil, 2002; Lv et al., 2014). Water temperature is a major factor influencing phytoplankton growth (Masaki and Seki, 1984; Tsuchida et al., 1984). A rise in water temperature may accelerate phytoplankton growth. Nevertheless, temperature fluctuations may cause stress and reduce phytoplankton populations (Round et al., 1990; Reynolds, 2006). It was reported that a change in water temperature caused the existing predominant species to be replaced by another more competitive one at the new temperature (Tilman et al., 1981).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

Motile freshwater flagellate algae changed their locations according to water temperature (Clegg et al., 2003). Nutrients and water temperature affected the springtime growth of phytoplankton (Wu et al., 2013). Phosphorus and silicon have significant effects on the development and succession of phytoplankton, especially diatoms. A low Si:P ratio may partially constrain diatom growth in eutrophic lakes (Schindler et al., 1996; Schindler, 2006; Reynolds, 2006). The centric freshwater diatoms *Cyclotella* and *Stephanodiscus* are known to compete with other diatom genera for silicon (Tilman et al., 1986). They grow continuously in the springtime until the silicon is almost exhausted. Their growth is not affected by silicon concentration (cited in Shatwell et al., 2013). Contrarily, *Synedra*, *Asterionella*, and other linear Fragilariaceae prefer high silicon concentrations and are more competitive at low phosphorus levels (Tilman et al., 1982). Sommer (1985) reported that *Asterionella* was a better competitor for phosphorus than *Stephanodiscus*, and *Synedra acus* is the most successful competitor for phosphorus when the silicon levels were not limiting. Constraints on the availability of silicon restrict diatom growth to a short springtime duration. However, the interactions between physicochemical factors like water temperature and Si:P play important roles in determining diatom species distributions (Shatwell et al., 2013). Analysis of the interaction between phytoplankton and environmental factors will help us understand phytoplankton species composition under various conditions. It will improve predictions about the growth, development, and dynamics of diatoms.

The objective of this study was to identify the environmental factors affecting the growth of *Stephanodiscus* and *Synedra* by investigating the development of spring diatom blooms (*Stephanodiscus* and *Synedra*) in Lake Paldang at the confluence of the physicochemically different Bukhan and Namhan Rivers, in South Korea.

Materials and methods

Study site

Lake Paldang is located in the upper region of the Han River running through Seoul, the capital city of South Korea, in East Asia. Lake Paldang is a man-made lake constructed in 1973 at the confluences of the Bukhan and Namhan Rivers. In 1975, it was designated a protected watercourse area. It provides water to 2.4 million people, and is the largest drinking water source in South Korea. The surface area is 36.5 km^2 and the total basin area is ~23,800 km^2. The Bukhan River catchment occupies 37%, while the Namhan River catchment accounts for ~60% of the total basin area. The average depth of Lake Paldang is ~6.5 m. Therefore, the vertical distributions of both water temperature and DO are more or less uniform and no distinct stratification is observed. The Bukhan and Namhan Rivers account for 35.5% and 62.9% of the total inflow into Lake Paldang, respectively. The tributaries of Lake Paldang have different water quality characteristics. The continuous inflow of domestic sewage and livestock wastewater cause eutrophication, and, consequently, algal blooms (Park et al., 2004; Park and Jheong, 2003).

Analytical methods

A field survey was conducted at three different sites; PD1, PD2, and PD3. PD1 (N 37°31'24.5" E 127°16'56.6") was located in front of the Paldang Dam. PD2

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

(N 37°30'00" E 127°15'00") was under the influence of the Namhan River. PD3 (N 37°35'25.2" E 127°20'24.5") was in the trajectory of the Bukhan River (*Fig. 1*). Water samples were collected weekly from March 2014 to October 2017 except when the water was frozen, and continuously measured 40 times or more each year. In our analysis, Springtime was set between March to May. Water samples were taken at a depth of 0.5 m using an 8 L water sampler (Wildco, Yulee, FL, USA).

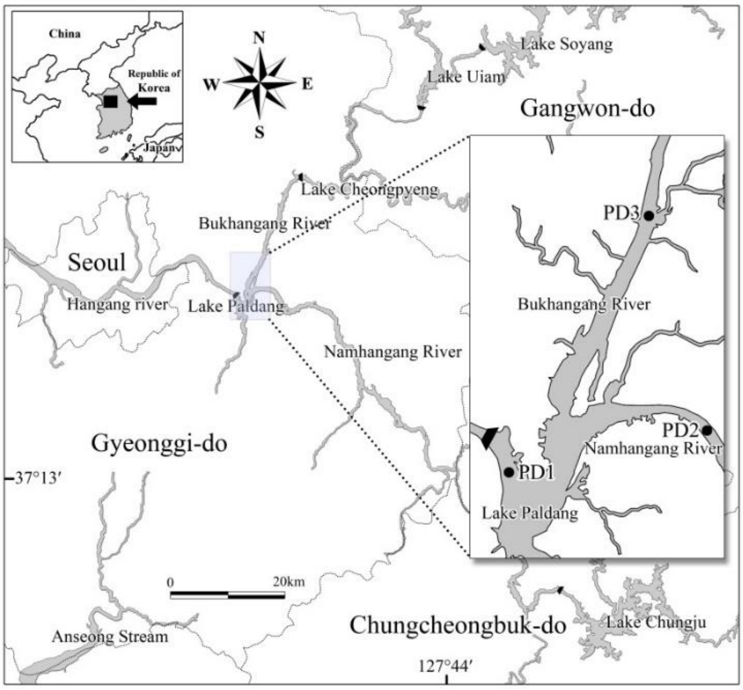

Figure 1. *Location of sampling sites in Lake Paldang*

At each sampling, water temperature (T), dissolved oxygen (DO), and conductivity (C) were measured with a multi water quality checker (YSI EXO; YSI Inc., Yellow Springs, OH, USA). An 8-L water sampler (Wildco, Yulee, FL, USA) was used and the collected samples were stored in the cold (~4°C) and dark until they were transported to the laboratory. For certain samples, total phosphorus (TP, mg/L), dissolved total phosphorus (DTP), total nitrogen (TN), dissolved total nitrogen (DTN), and silicon (Si) were measured in accordance with the Korean standard methods (ME, 2016). TP and DTP were calculated from the absorbance of molybdic acid measured by continuous flow at 880 nm. TN and DTN were determined from the absorbance of NO_2-N (nitrite nitrogen) measured by continuous flow at 550 nm. From March 2015 to October 2017, Si was analyzed using the color reactions of supersaturated oxalic acid and the absorbance was measured at 630 nm. N:P and Si:P were reported as mass ratios using the values of TN and TP. Si:P was calculated from Si and TP.

The samples for analyzing the cell counts of *Stephanodiscus* and *Synedra* were fixed by adding Lugol’s iodine solution (final concentration: 2% w/v). They were then used unmodified, concentrated, or diluted depending on the phytoplankton density. One milliliter of the fixed sample was placed into a Sedgwick-Rafter counting chamber, left to settle for ≥30 min, then viewed under a microscope. Cell counts per unit area were calculated using an ECLIPSE Ni phase-contrast microscope (Nikon Instruments, Tokyo,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

Japan). The diatoms were identified based on the methods of John et al. (2002), Joh (2010), and Joh et al. (2010). *Stephanodiscus* and *Synedra* were differentiated from other diatoms by structural characteristics at the genus level. A Pearson correlation analysis was used to examine the relationship between environmental factors and *Stephanodiscus* and *Synedra* cell counts. Data were processed with SPSS v. 12.0 (IBM Corp., Armonk, NY, USA).

Results

Environmental characteristics of Water quality

Average annual water temperature, DO and conductivity measurements were higher at PD2 than at PD3 every year (*Table 1*). The average annual water temperature of the three sites was 16.8–20.0°C (*Table 1*). The lowest water temperatures were recorded in March (≤10°C). In July and August, the water temperature rose to ≥20°C (*Fig. 2*). The average annual DO ranged from 10.2 to 11.0 mg/L at PD1, 11.5 to 12.7 mg/L at PD2 and 9.8 to 10.4 mg/L at PD3. The average annual conductivity at PD2 was 236 to 271 μS/cm, whereas that at PD3 was 119 to 137 μS/cm. Electrical conductivity at PD2 was twice that of PD3. The conductivity at PD1 was intermediate relative to those at the other two sites (206 to 220 μS/cm). There were clear differences in some nutrients among three sites (ANOVA, $P < 0.01$): TN, TP, DTN, and DTP values were higher in PD2 compared to PD3 in all years of the survey period (*Table 1*). The average annual TP in PD3 ranged from 0.012 to 0.017 mg/L (i.e., less than 0.020 mg/L), and it had a broader range in PD2 that was typically greater than 0.030 mg/L (0.035 to 0.048 mg/L). The average annual TN was 1.857 to 2.095 mg/L at PD1, 1.959 to 2.404 mg/L at PD2 and 1.636 to 1.828 mg/L at PD3 (*Table 1*). Trends in DTN and DTP were similar to those of TN and TP, respectively. At PD1, the average annual DO ranged from 10.2 to 11.0 mg/L. Si concentrations were higher at PD3 (0.966 to 1.774 mg/L) compared to PD2 (0.922 to 1.460) (*Table 1*).

Table 1. *Differences in the values of environmental parameters at three sites in Lake Paldang from 2014 to 2017*

Site	Year	WT (°C)	DO (mg/L)	Cond. (μS/cm)	TP (mg/L)	DTP (mg/L)	TN (mg/L)	DTN (mg/L)	Si (mg/L)
PD1	2014	18.4	11.0	206	0.024	0.014	1.929	1.835	-
	2015	18.2	10.2	220	0.023	0.013	1.857	1.786	0.731
	2016	18.3	10.4	215	0.024	0.011	2.027	1.961	1.175
	2017	18.9	10.5	211	0.027	0.011	2.095	2.018	1.511
PD2	2014	18.9	12.7	236	0.038	0.020	2.173	2.046	-
	2015	19.3	12.0	271	0.035	0.019	1.959	1.862	0.922
	2016	19.1	11.6	265	0.035	0.015	2.250	2.152	1.306
	2017	20.0	11.5	263	0.048	0.023	2.404	2.299	1.460
PD3	2014	16.8	10.4	119	0.012	0.006	1.705	1.636	-
	2015	17.7	10.1	135	0.013	0.008	1.804	1.730	0.966
	2016	17.5	9.8	137	0.016	0.007	1.879	1.828	1.548
	2017	17.6	10.4	121	0.017	0.007	1.810	1.749	1.774

WT: Water temperature, DO: Dissolved oxygen, Cond.: Conductivity, TP: Total phosphorus, DTP: Dissolved total phosphorus, TN: Total nitrogen, DTN: Dissolved total nitrogen, Si: Silicon

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

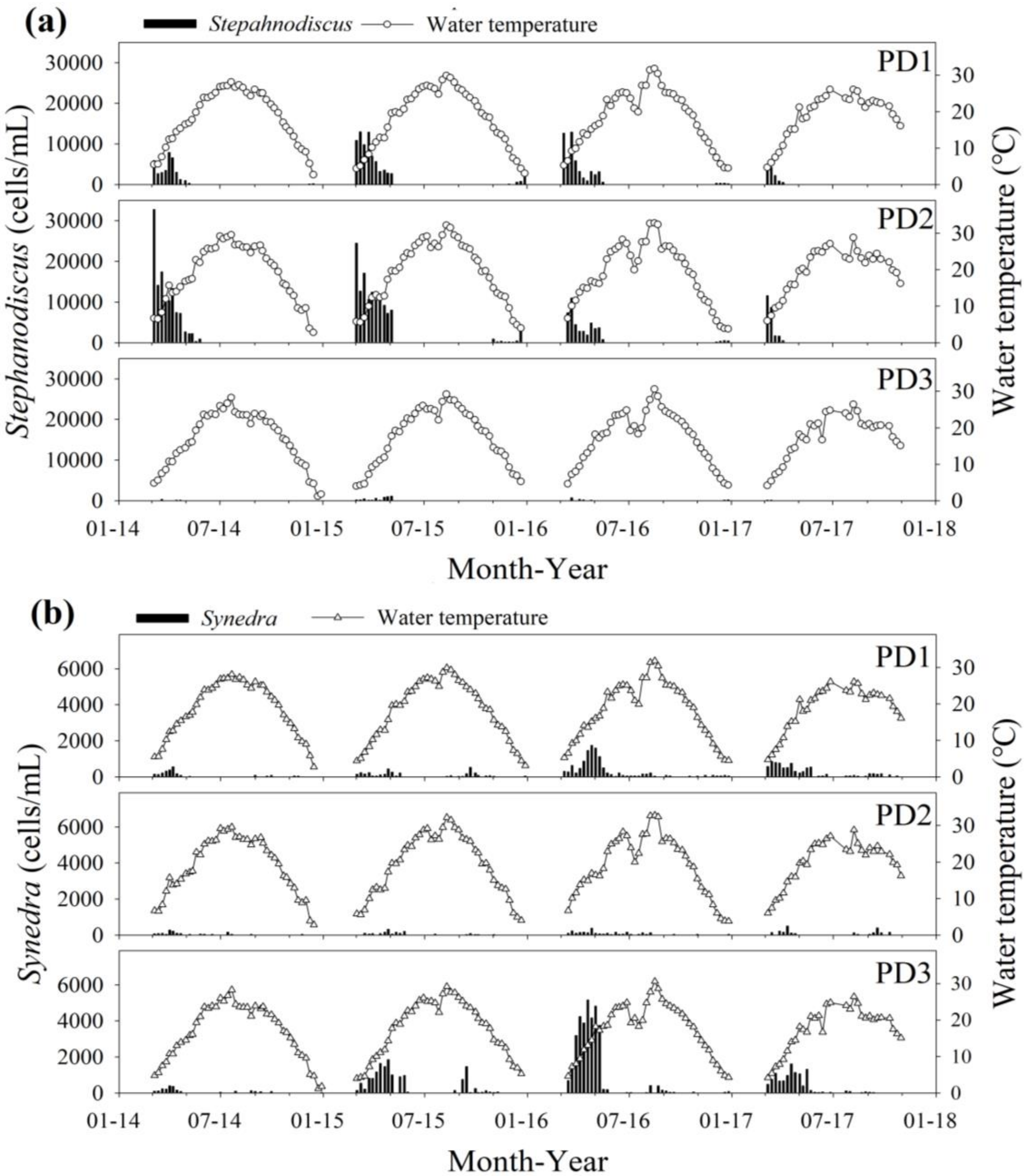

Figure 2. *Weekly variations in water temperature and abundance of Stephanodiscus (a) and Synedra (b) at Lake Paldang from March 2014 to October 2017 (except frost period)*

The concentration ranges of TP and TN in Lake Paldang were 0.006–0.279 mg/L and 1.002–3.466 mg/L, respectively. The maximum measured Si concentration in Lake Paldang was 4.107 mg/L (*Fig. 3*). TP, TN, and Si significantly increased during the summer season because of high rainfall. In fact, the values of all three parameters substantially increased in response to every rainfall event. TN concentrations were high in March at every site and steadily decreased until early June. In early March, Si was ≥1.5 mg/L at PD3, but it was ≤1.0 mg/L at PD1 and PD2. In 2016 and 2017, continuous rainfall between July and November increased Si to ≥1.5 mg/L (*Fig. 3*).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

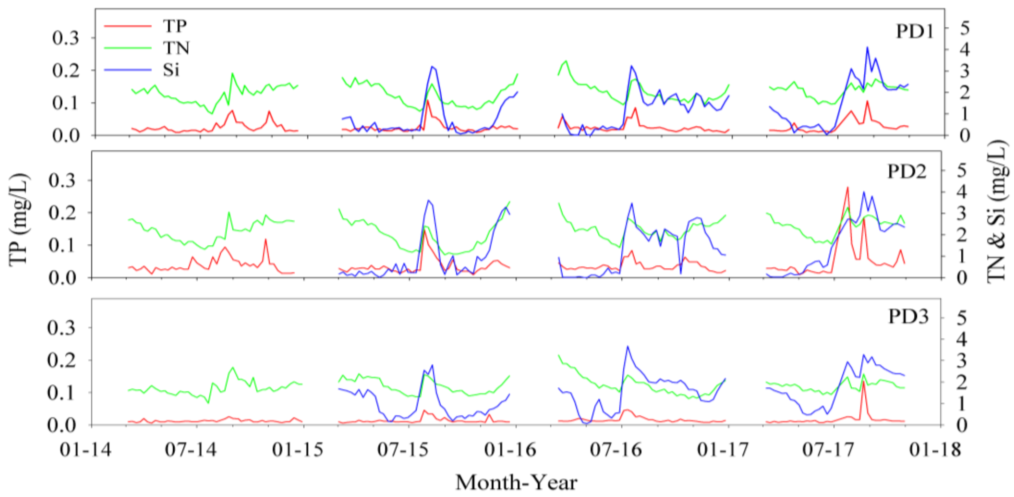

Figure 3. *Temporal variations in TP, TN, and Si from March 2014 to October 2017 (except frost period). TP: Total phosphorus, TN: Total nitrogen, Si: Silicon*

Stephanodiscus and Synedra in relation to water temperature

Stephanodiscus exhibited increased growth during spring and low growth during summer every year. Its cell counts were the highest in early March when the water temperature was <10°C, and it gradually decreased thereafter, until *Stephanodiscus* disappeared almost completely after May. As the water temperature fell once again in November, *Stephanodiscus* began to reappear. In March, PD1 had the highest cell count (12,950 cells/mL). In March 2014, PD2 had a record *Stephanodiscus* count of 32,570 cells/mL, but the cell counts decreased thereafter until May. In 2015, 2016, and 2017, the cell counts peaked in early March, followed by a steady decline (*Fig. 2a*). From PD3, *Stephanodiscus* cell counts were 1,150 cells/mL maximum, which was less than the other two points.

Stephanodiscus was detected within the temperature range of 1.2–22.7°C and had the highest biomass at 6.7°C. At PD1, the cell counts were >10,000 cells/mL within the temperature range of 4.4–9.2°C. At PD2, it was at 5.6–15.7°C that the cell counts reached >10,000 cells/mL. At PD3, the cell counts never exceeded 10,000 cells/mL (*Fig. 4a*).

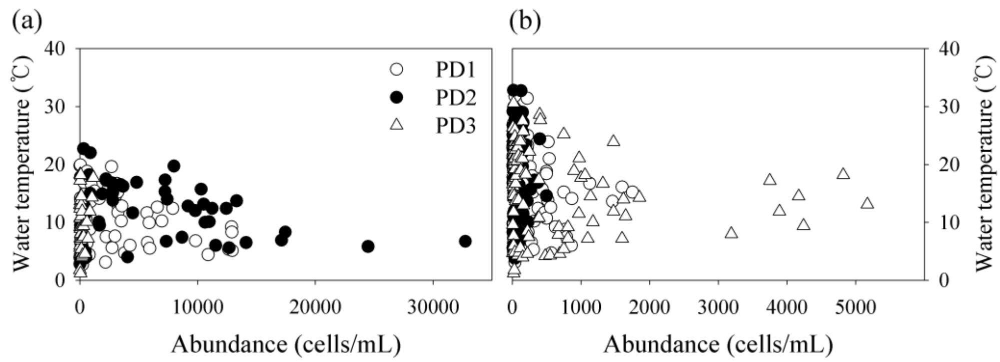

Figure 4. *Abundance of Stephanodiscus (a) and Synedra (b) relative to water temperature at the three sites at Lake Paldang. Note that cyanobacteria cell count scales are different*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

The temperature-dependent growth pattern of *Synedra* was essentially the same every year. *Synedra* cell counts began to increase from March and reached their maxima by mid-April when the water temperature was ~14 ± 2°C. Thereafter, the cell counts significantly decreased and remained low. PD1 had the highest *Synedra* cell counts of all three sites (1,750 cells/mL) between March and May 2016. In contrast, the *Synedra* cell counts at PD2 never surpassed 500 cells/mL and were significantly lower than those at the other two sites. The highest *Synedra* counts were obtained at PD3 (5,170 cells/mL) (*Figure 2b*). *Synedra* appeared from March to May and proliferated at 13–15°C, except in 2014, when the mean water temperature was only 11°C at that time of year.

At all three sites, *Synedra* grew under a very wide water temperature range of 1.2-32.8°C. However, cell counts ≥1,000 cells/mL were measured only at 7.2–23.9°C. At PD2, the *Synedra* cell counts never exceeded 1,000 cells/mL (*Fig. 4b*).

Effect of nutrients on the growth of Stephanodiscus and Synedra during springtime

Correlations between nutrient concentration and cell count were determined for *Stephanodiscus* and *Synedra* in springtime (March to May) when their cell counts were >85% of their annual totals. The average springtime TP concentration was the lowest at PD3 (0.011 mg/L). At the same time, PD2 had an average TP concentration of 0.027 mg/L (>2 times that of PD3). PD1 recorded a TP concentration of 0.019 mg/L, which was intermediate between those of PD2 and PD3. PD2 presented with a wider TN concentration range than PD3 (*Fig. 5*). However, the average springtime Si concentration at PD3 was 1.116 mg/L, which substantially exceeded that at PD2 (0.181 mg/L). The Si concentration at PD1 was higher than that at PD2, but lower than that at PD3 (*Fig. 5*). The cell counts of *Stephanodiscus* and *Synedra* of Lake Paldang varied with site during the springtime. The *Stephanodiscus* cell count was high at PD2 (average 6,108 ± 6,954 cells/mL) but significantly lower at PD3 (average 150 ± 264 cells/mL). In contrast, *Synedra* had a relatively lower cell count at PD2 (average 101 ± 103 cells/mL) and a comparatively high cell count at PD3 (average 1,089 ± 1,362 cells/mL).

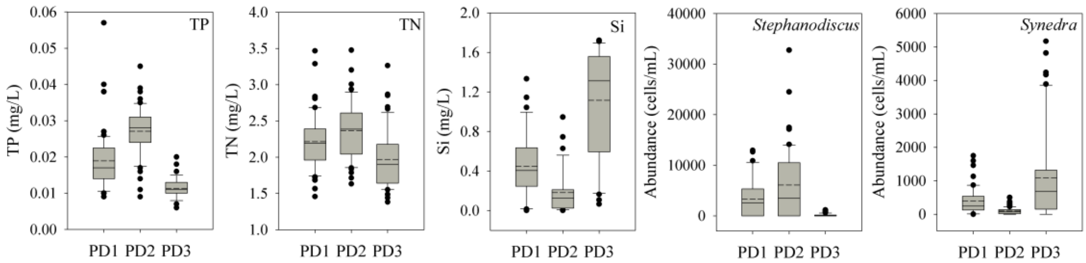

Figure 5. *Range of nutrients (TP, TN, and Si) and diatoms (Stephanodiscus and Synedra) densities during springtime (2014–2017) at Lake Paldang (Median values: horizontal dashed line; mean values: solid line; boxes: 25th and 75th percentiles; error bars: 10thth and 90th percentiles; circles; outliers). TP: Total phosphorus, TN: Total nitrogen, Si: Silicon*

The growth rates of *Stephanodiscus* and *Synedra* in the springtime varied differentially in response to nutrient concentration. *Stephanodiscus* had the highest cell counts when the concentrations of TP, TN, and Si were 0.030 mg/L, 2.688 mg/L, and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

0.161 mg/L, respectively. The cell counts of *Synedra* were the highest when the TP, TN, and Si concentrations were 0.020 mg/L, 2.412 mg/L, and 0.473 mg/L, respectively (*Fig. 6*). High TP and TN concentrations increased *Stephanodiscus* cell counts more than they did those of *Synedra*. When TP was ≥0.020 mg/L, *Stephanodiscus* cell counts substantially increased. On the contrary, the cell counts of *Synedra* were the highest when TP was ≤0.020 mg/L. At springtime, Si concentrations were ≤0.4 mg/L, and >70% of the total annual *Stephanodiscus* cells appeared then. In contrast, the *Synedra* cell counts were high even when Si was ≥0.4 mg/L. When TP was ≥0.020 mg/L, and Si was ≤0.4 mg/L, (Si:P ratio <20), the cell count of *Stephanodiscus* increased significantly. Contrarily, there were large numbers of *Synedra* cells when TP was ≤0.020 mg/L and Si was ≥0.4 mg/L (Si:P ratio > 20) (*Fig. 7*).

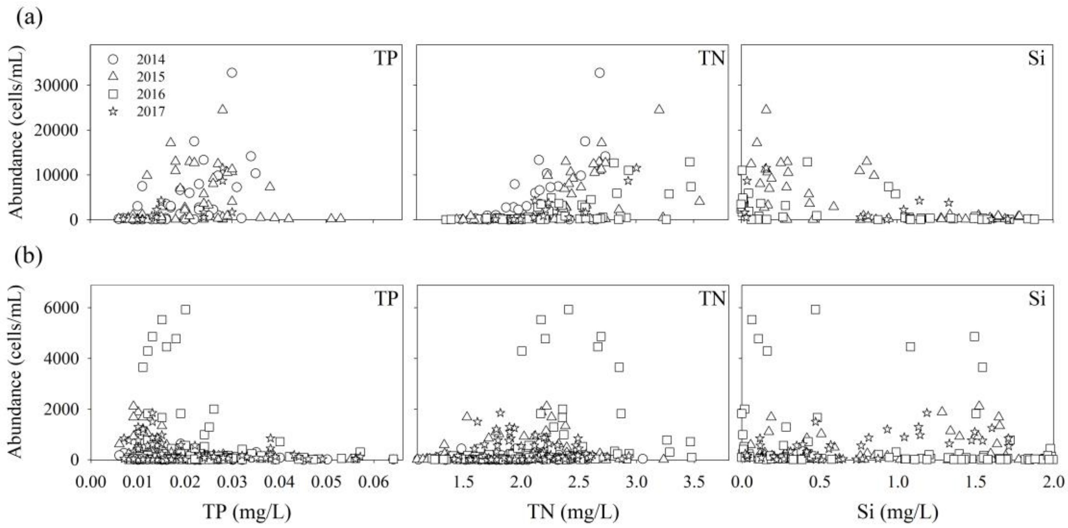

Figure 6. *Comparison of cell counts of Stephanodiscus (a) and Synedra (b) as functions of nutrient (TP, TN, and Si) concentrations in springtime from 2014 to 2017. TP: Total phosphorus, TN: Total nitrogen, Si: Silicon*

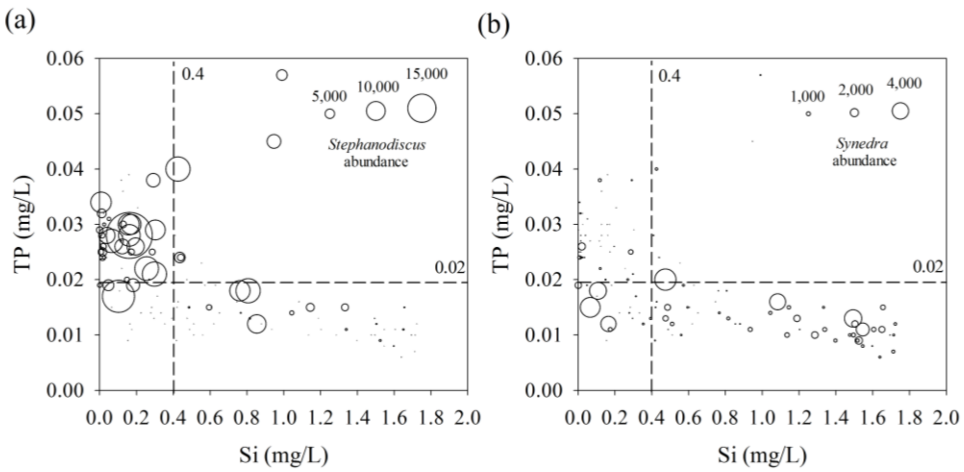

Figure 7. *Distribution of Stephanodiscus (a) and Synedra (b) abundance as functions of nutrient (TP and Si) concentrations during springtime (2015–2017). TP: Total phosphorus, Si: Silicon. Legend unit is 'cells/mL'*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

The cell count of *Stephanodiscus* had weak positive correlations with DO, conductivity, and TN, and weak negative correlations with water temperature, Si, and Si:P ratio. The *Synedra* cell counts had weak positive correlations with DO, TN, and N:P ratio, and weak negative correlations with water temperature, conductivity, TP, and Si (*Table 2*). In springtime, the cell count of *Stephanodiscus* had weak negative correlations with water temperature, Si, N:P ratio, and Si:P ratio. In contrast, the *Synedra* cell counts had weak positive correlations with Si, N:P ratio, and Si:P ratio during that period.

Table 2. *Pearson's correlation coefficients between the abundance of two diatoms and environmental parameters during all time periods investigated and during springtime at Lake Paldang*

Parameter	All period		Spring	
	Stephanodiscus	***Synedra***	***Stephanodiscus***	***Synedra***
W.T	-0.368**	-0.187**	-0.416**	-
DO	0.431**	0.120**	0.530**	-0.172*
Cond.	0.221**	-0.206**	0.396**	-0.372*
TP	-	-0.130**	0.442**	-0.203*
TN	0.405**	0.163**	0.584**	-
Si	-0.274**	-0.145**	-0.283**	0.233*
N:P	-	0.278**	-0.286**	0.258**
Si:P	-0.250**	-	-0.320**	0.196*

W.T: Water temperature, Cond.: Conductivity, * $P < 0.05$, ** $P < 0.01$

Discussion

In Lake Paldang, the variations in phytoplankton biomass and the spatial distributions of the dominant species comprising it were greatly affected by environmental factors. Water temperature plays an important role in modifying phytoplankton dynamics (Lee et al., 2013). The present study also showed that the growth of *Stephanodiscus* and *Synedra* were significantly affected by the water temperature of Lake Paldang. Both diatom species had the highest cell counts during spring. This pattern recurred at about the same time each year. Both species preferred low water temperatures, but their cell counts peaked at different ranges of water temperature. It was reported that *Stephanodiscus* adapted to low water temperatures and proliferated at <7°C (Ha et al., 2003). *Synedra* has a similar preference for low water temperatures. Bondarenko and Geuselnikova (2002) reported that the optimal water temperature range for the proliferation of *Synedra acus* var. *radians* was 12–14°C in vitro. The growth rates of both diatom species were negatively correlated with water temperature throughout the survey period, and they were found to prefer low water temperatures to high ones. However, *Stephanodiscus* grew at the range of 1.2–22.7°C whereas *Synedra* proliferated at 1.2–32.8°C. Accordingly, *Synedra* was detected at higher temperatures than *Stephanodiscus*. In addition, *Stephanodiscus* was dominant and had the highest cell count at ≤10°C whereas *Synedra* prevailed at the range of 10.8-15.7°C. In Lake Paldang, *Stephanodiscus* flourished at low water temperatures, and, therefore, occurred earlier than *Synedra*. Both species contributed to the spring bloom at relatively low water temperatures. However, since they have different

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

temperature optima, they would not proliferate or compete for resources simultaneously.

The types of predominant diatoms and their population densities depend on nutrient concentrations. In the Behler See, centric diatoms increased their relative biovolumes by >60% at low Si:P ratio (<15). Contrarily, Fragilariaceae species, which are linear, had comparatively low biomasses at low Si:P ratio (Makulla and Sommer, 1993). *Stephanodiscus minutulus*, a centric diatom, required significantly more phosphorus than silicon. Its optimal Si:P (molar) ratio was ~1.0. In contrast, *Synedra* grew well despite the lack of phosphorus, but did not flourish at low silicon concentrations (Kilham et al., 1986). According to Tilman et al. (1982), *Synedra* was more competitive than *Stephanodiscus* when phosphorus was limited. In a culture with limited phosphorus (Si:P ratio> 75), *Asterionella* and *Fragilaria* predominated but *Stephanodiscus* failed to thrive (Van Donk and Kilham, 1990). In the present study, PD2 presented with *Stephanodiscus* blooms but *Synedra* was nearly absent there. Contrarily, PD3 had a low *Stephanodiscus* biomass but substantial quantities of *Synedra* (*Figure 5*). The two watershed influencing Lake Paldang (Namhan River and Bukhan River) have very different water quality properties. The Namhan River has a high nutrient concentration because it receives pollution inputs from widely dispersed point- and nonpoint sources. In contrast, the upper part of the Bukhan River is adjacent to mountains and is mesotrophic or oligotrophic (Park et al., 2004; Kim et al., 2014). In addition, the watershed of the Bukhan River is more prone to silicate weathering than that of the Namhan River. Therefore, the silicic acid concentration is higher in the Bukhan River than in the Namhan River (Ryu et al., 2008). PD2 had low silicon and high phosphorus levels; so, its average springtime Si:P ratio was as low as 8. For this reason, *Stephanodiscus* could bloom at PD2, since it prefers low Si:P ratio. As the *Stephanodiscus* population decreased at PD2, the Si:P ratio remained low there and the growth of *Synedra* was restricted, even when its optimal water temperature was attained. PD3 showed high silicon and relatively low phosphorus levels. At this site, the average springtime Si:P ratio was 109. Since *Synedra* prefers high Si:P ratio, its population density at PD3 was very high. However, *Stephanodiscus* populations were very sparse because they fail to thrive under phosphorus restriction. Consequently, *Stephanodiscus* can flourish at water temperatures <10°C, since its growth is positively correlated with phosphorus and nitrogen concentrations and the levels of this nutrient are relatively high in springtime (r = 0.442, $P < 0.01$, r = 0.584, $P < 0.01$, respectively). Therefore, its population density would be high at elevated phosphorus concentrations (>0.02 mg/L) and low Si:P ratio. Contrarily, *Synedra* prefers higher water temperatures (10.8–15.7°C) than *Stephanodiscus*. Moreover, *Synedra* tends to flourish at high silicon levels (>0.4 mg/L). *Synedra* showed weak negative correlations with silicon concentration during springtime. However, throughout the study period, there were negative correlations as silicon concentration increased during summer due to heavy rain. *Synedra* did not appear during summer because of high water temperatures. From our analysis, it can be inferred that both diatoms can grow at low water temperatures, but they have different temperature range preferences. In addition, *Stephanodiscus* and *Synedra* flourish at low Si:P ratio and high Si:P ratio, respectively.

Both *Stephanodiscus* and *Synedra* were detected at PD1. Since PD1 was located at the boundary or interface of PD2 and PD3, its nutrient levels were the combination of those for the other two sites. In springtime, the average cell count of *Stephanodiscus* was 3,291 cells/mL, which was only ~54% that of PD2. During the same period, the

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

average cell count of *Synedra* was 391 cells/mL, which corresponded to ~36% of that of PD3. At PD1, the highest cell counts for *Stephanodiscus* were recorded in early March. The same phenomenon was observed at PD2. *Synedra* cell counts peaked in mid-April. The same trend was found at PD3 (*Figure 3*). The growth rates and patterns of both diatoms at PD1 resembled those observed at the Namhan (PD2) and Bukhan (PD3) Rivers. Relative to the inflow into Lake Paldang, the cell counts at PD1 were lower than those at the other sites. Therefore, the inflow of the Bukhan and Namhan Rivers diluted the diatoms. At PD1, then, the growth rates of *Stephanodiscus* and *Synedra* were affected mainly by the inflow from the upper regions rather than their own population densities. However, more detailed investigation is necessary in future to estimate the effects of rainfall, flow rate, and zooplankton predation on diatom growth.

Conclusions

Through this study, it was demonstrated that the timing and magnitude of spring diatom bloom are affected by physicochemical factors like water temperature, and nutrient levels and their ratios. (1) Both *Stephanodiscus* and *Synedra* prefer low water temperatures, but *Synedra* biomass reaches it maxima at higher temperatures. (2) The two diatoms have different optima for available nutrient concentrations. Low levels of phosphorus and silicon limit the growth of *Stephanodiscus* and *Synedra*, respectively. (3) Growth of these diatoms is affected both by nutrient concentrations (especially phosphorus and silicon) and water temperature. The growth rates of *Stephanodiscus* and *Synedra* are controlled by multiple factors. Optimal water temperature, and phosphorus and silicon concentrations and their ratios can promote diatom growth. These factors must be considered in the prediction of the growth trends and population densities of *Stephanodiscus* and *Synedra* in Lake Paldang. However, in order to clearly identify the effects of environmental factors on the appearances of *Stephanodiscus* and *Synedra*, future research should be conducted using various types of statistical analyses for factors such as hydraulic and hydrologic factors, competition with other species, and predation.

Acknowledgements. This research was supported by a grant from the National Institute of Environmental Research (NIER), funded by the Ministry of Environment (ME) of the Republic of Korea (NIER-2020-01-01-022).

REFERENCES

[1] Bleiker, W., Schanz, F. (1989): Influence of environmental factors on the phytoplankton spring bloom in lake Zürich. – Aquatic Sciences 51(1): 47-58.

[2] Bondarenko, N. A., Geuselnikova, N. Y. (2002): Studies on *Synedra acus* Kutz. var. *radians* (*Kutz.*) Hust. (*Bacillariophyta*) in culture. – International Journal on Algae 4(1): 85-95.

[3] Clegg, M. R., Maberly, S. C., Jones, R. J. (2003): Behavioural response of freshwater phytoplanktonic flagellates to a temperature gradient. – European Journal of Phycology 38(3): 195-203.

[4] Deng, X. W., Tao, M., Zhang, L., Xie, P., Chen, J., Zhang, J. (2013): Relationships between Odors and Algae and Water Quality in Dongting Lake. – Research of Environmental Sciences 26(1): 16-21.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

[5] Ha, K., Jang, M. H., Joo, G. J. (2003): Winter *Stephanodiscus* bloom development in the Nakdong River regulated by an estuary dam and tributaries. – Hydrobiologia 506(1-3): 221-227.

[6] Hijnen, W. A. M., Dullemont, Y. J., Schijven, J. F., Hanzens-Brouwer, A. J., Rosielle, M., Medema, G. (2007): Removal and fate of *Cryptosoridium parvum*, *Closteridium perfringens* and small-sized centric diatoms (*Stephanodiscus hantzschii*) in slow sand filters. – Water Research 41(10): 2151-2162.

[7] Joh, G. (2010): Algal flora of Korea 3 (1). Chrysophyta: Bacillariophyceae: Centrales. Freshwater diatoms I. – National Institute of Biological Resources, Incheon.

[8] Joh, G., Lee, J. H., Lee, K., Yoon, S. K. (2010): Algal flora of Korea 3 (2). Chrysophyta: Bacillariophyceae: Pennales: Araphidineae: Diatomaceae. Freshwater diatoms II. – National Institute of Biological Resources, Incheon.

[9] Joh, G., Choi, Y. S., Shin, J. K., Lee, J. (2011): Problematic algae in the sedimentation and filtration process of water treatment plants. – Journal of Water Supply: Research and Technology-AQUA 60(4): 219-230.

[10] John, D. M., Whittonand, B. A., Brook, A. J. (2002): The freshwater algal flora of the British Isles. – Cambridge University Press, Cambridge.

[11] Jüttner, F. (1983): Volatile odorous excretion products of algae and their occurrence in the natural aquatic environment. – Water Sciences & Technology 15(6-7): 247-257.

[12] Kilham, P., Kilham, S. S., Hecky, R. E. (1986): Hypothesized resource relationships among African planktonic diatoms. – Limnology and Oceanography 31(6): 1169-1181.

[13] Kim, D. W., Jang, M. J., Han, I. S. (2014): Determination of focused control pollutant source by analysis of pollutant delivery characteristics in unit watershed upper Paldang Lake. – Journal of Korean Society of Environmental Engineers 36(5): 367-377.

[14] Lee, K. R., Sung, E. J., Park, H. J., Park, C. H., Park, M. H., Hwang, S. J. (2013): Phytoplankton community change of Lake Paldang by increasing CO_2 and temperature during spring cold water season. – Korean Journal of Ecology and Environment 46(4): 588-595.

[15] Lv, H., Yang, J., Liu, L., Yu, X., Yu, Z., Chiang, P. (2014): Temperature and nutrients are significant drivers of seasonal shift in phytoplankton community from a drinking water reservoir, subtropical China. – Environmental Sciences and Pollution Research 21(9): 5917-5928.

[16] Makulla, A., Sommer, U. (1993): Relationships between resource ratios and phytoplankton species composition during spring in five North German lakes. – Limnology and Oceanography 38(4): 846-856.

[17] Marshall, T. C., Peters, R. H. (1989): General patterns in the seasonal development of chlorophyll *a* for temperate lakes. – Limnology and Oceanography 34(5): 856-867.

[18] Masaki, A., Seki, H. (1984): Spring bloom in hypereutrophic lake, Lake Kasumigaura, Japan-IV: Inductive factors for phytoplankton bloom. – Water Research 18(7): 869-876.

[19] McCauley, E., Downing, J. (1991): Different effects of phosphorus and nitrogen on chlorophyll concentration in oligotrophic and eutrophic lakes. – Canadian Journal of Fisheries and Aquatic Sciences 48(12): 2552-2553.

[20] Ministry of Environment (ME). (2016): Standard method for the examination of water pollution. – Ministry of Environment, Sejong.

[21] Muylaert, K., Sabbe, K. (1999): Spring phytoplankton assemblages in and around the maximum turbidity zone of the estuaries of the Elbe (Germany), the Schelde (Belgium/The Netherlands), and the Gironde (France). – Journal of Marine Systems 22(2-3): 133-149.

[22] Park, H. K., Jheong, W. H. (2003): Long-term changes of algal growth in Lake Paldang. – Journal of Korean Society on Water Environment 19(6): 673-684.

[23] Park, H. K., Byeon, M. S., Kim, E. K., Lee, H. J., Chun, M. J., Jung, D. J. (2004): Water quality and phytoplankton distribution pattern in upper inflow rivers of Lake Paldang. – Journal of Korean Society on Water Environment 20(6): 615-624.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147

[24] Reavie, E. D., Cai, M., Twiss, M. R., Carrick, H. J., Davis, T. W., Johengen, T. H., Gossiaux, D., Smith, D. E., Palladino, D., Burtner, A., Sgro, G. V. (2016): Winter–spring diatom production in Lake Erie is an important driver of summer hypoxia. – Journal of Great Lakes Research 40(3): 608-618.
[25] Reynolds, C. S. (2006): The ecology of phytoplankton. – Cambridge University Press, Cambridge.
[26] Round, F. E., Crawford, R. M., Mann, D. G. (1990): The diatoms: biology and morphology of the genera. – Cambridge University Press, Cambridge.
[27] Ryu, J. S., Lee, K. S., Chang, H. W., Shin, H. S. (2008): Chemical weathering of carbonates and silicates in the Han River basin, South Korea. – Chemical Geology 247(1-2): 66-80.
[28] Schindler, D. W., Bayley, S. E., Parker, B. R. (1996): The effects of climatic warming on the properties of Boreal lakes and streams at the Experimental Lakes Area, Northwestern Ontario. – Limnology and Oceanography 41(5): 1004-1017.
[29] Schindler, D. W. (2006): Recent advances in the understanding and management of eutrophication. – Limnology and Oceanography 51(1): 356-363.
[30] Shatwell, T., Köhler, J., Nicklisch, A. (2013): Temperature and photoperiod interactions with silicon-limited growth and competition of two diatoms. – Journal of Plankton Research 35(5): 957-971.
[31] Sommer, U. (1985): Comparison between steady state and non-steady state competition: experiments with natural phytoplankton. – Limnology and Oceanography 30(2): 335-346.
[32] Teubner, K., Dokulil, M. T. (2002): Ecological stoichiometry of TN: TP: SRSi in freshwaters: nutrient ratios and seasonal shifts in phytoplankton assemblages. – Archiv fur Hydrobiologie 154(4): 625-646.
[33] Tilman, D., Mattson, M., Langer, S. (1981): Competition and nutrient kinetics along a temperature gradient: an experimental test of a mechanistic approach to niche theory. – Limnology and Oceanography 26(6): 1020-1033.
[34] Tilman, D., Kilham, S. S., Kilham, P. (1982): Phytoplankton community ecology: the role of limiting nutrients. – Annual Review of Ecology, Evolution, and Systematics 13(1): 349-372.
[35] Tilman, D., Kiesling, R., Sterner, R., Kilham, S. S., Johnson, F. A. (1986): Green, bluegreen and diatom algae: taxonomic differences in competitive ability for phosphorus, silicon and nitrogen. – Archiv fur Hydrobiologie 106(4): 473-485.
[36] Tsuchida, A., Hara, Y., Seki, H. (1984): Spring bloom in a ypereutrophic Lake, Lake Kasumigaura, Japan V: factors controlling natural population of phytoplankton. – Water Research 18(7): 877-883.
[37] Van Donk, E., Kilham, S. S. (1990): Temperature effects on silicon and phosphorus limited growth and competitive interactions among three diatoms. – Journal of Phycology 26(1): 46-50.
[38] Wu, Z., Cai, Y., Liu, X., Xu, C. P., Chen, Y., Zhang, L. (2013): Temporal and spatial variability of phytoplankton in Lake Poyang: the largest freshwater lake in China. – Journal of Great Lakes Research 39(3): 476-483.
[39] Ye, L., Han, X. Q., Xu, Y. Y., Cai, G. H. (2007): Spatial analysis for spring bloom and nutrient limitation in Xiangxi Bay of Three Gorges Reservoir. – Environmental Monitoring and Assessment 127(1-3): 135-145.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1804_51355147