Ann. Limnol. - Int. J. Lim. 52 (2016) 123–136
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DOI: 10.1051/limn/2015038

Available online at:
www.limnology-journal.org

Limnological assessment of the meteo-hydrological and physicochemical factors for summer cyanobacterial blooms in a regulated river system

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Received 4 May 2015; Accepted 9 December 2015

Abstract – This study aimed to explain how the changes in certain hydrological, meteorological and physicochemical factors influence the cell density of the cyanobacteria *Microcystis aeruginosa* in the Nakdong River. Occurrence patterns of *M. aeruginosa* were analyzed between 1993 and 2010 ($N = 96$) using a self-organizing map. The cell density of *M. aeruginosa* was sensitive to certain meteorological, hydrological and physicochemical factors. In addition, our clustering analysis results identified specific limnological features under different environmental conditions. Cluster 1 suggested that high rainfall and increased river flow, dam discharge, total phosphorous and phosphate concentrations were associated with low *M. aeruginosa* cell density (June–July; monsoon season). However, cluster 2 suggested low irradiance since water temperature decreases with irradiation time, and thus low *M. aeruginosa* cell density (April–June and after November). Finally, cluster 3 was indicative of high water temperature and irradiance, increased irradiation time, low phosphate and nitrate concentrations, and high *M. aeruginosa* cell density (August, after the monsoon season). Taken together, these results suggest that rainfall, river flow, water temperature and nutrient concentration (*i.e.*, phosphates and nitrates) were the primary factors that affected cyanobacterial bloom occurrence in the Nakdong River. *M. aeruginosa* blooms can be suppressed by employing an integrated water resource management program that accommodates meteo-hydrological factors along with the effective control of exogenous nutrient sources.

Key words: Cyanobacterial bloom / *Microcystis aeruginosa* / rainfall / regulated river / self-organizing map

Introduction

Cyanobacterial blooms are a type of severe harmful algal bloom that are associated with global environmental problems, including water toxicity, odor, and excessive cell degradation. These blooms result in hypoxic conditions and toxicity, leading to the death of fish, birds and animals, thereby adversely affecting natural ecosystems and human society (Prescott, 1948; Tencalla *et al.*, 1994; de Figueiredo *et al.*, 2006; Graham *et al.*, 2010). The freshwater systems in Northeast Asia also experience similar problems. The summer monsoon is a major climate phenomenon in Northeast Asia that brings abundant rainfall to East China, Japan and Korea (Yihui and Chan, 2005). Summer cyanobacterial blooms in this region frequently occur when the water levels are stable and nutrient input is high (Ha *et al.*, 2002; Hong *et al.*, 2002; Joung *et al.*, 2011). Lake Taihu in China (Duan *et al.*, 2012; Zhang *et al.*, 2012), Lakes Suwa (Yokoyama and Park, 2002) and Kasumigaura (Islam *et al.*, 2012) in Japan, and Han and Nakdong Rivers and Daechung Reservoir in South Korea are representatives of cyanobacterial bloom ecosystems. The Nakdong River is a regulated river system with dams and an estuarine barrage for water resource management during the monsoon season (Jeong *et al.*, 2011; Kim *et al.*, 2012; Hong *et al.*, 2014). This river had a severe cyanobacterial bloom problem in the 1990s (Ha *et al.*, 1998, 1999).

Most rainfall in the Nakdong River basin falls during the monsoon period (the monsoon is called “Jangma” in

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Korean) and varies between 783 and 1829 mm [approximately 60–65% of the total annual rainfall; data from the Korean Meteorological Administration (KMA) obtained between 1961 and 2014], thereby affecting river flow and total dam discharge. After the summer monsoon, the physicochemical environment (*i.e.*, high water temperature, pH and nutrient enrichment) of the Nakdong River becomes favorable for cyanobacterial bloom development (Ha *et al.*, 1998, 1999). Previous studies have shown significant relationships between cyanobacterial blooms and monsoon rainfall (Jeong *et al.*, 2003a, 2003b; Kim *et al.*, 2007). Most studies on cyanobacterial blooms in the Nakdong River have focused on the severe cyanobacterial bloom of the 1990s (Jeong *et al.*, 2003a; Kim *et al.*, 2007). Owing to adequate rainfall and water quality improvements, these blooms diminished in the 2000s (Chun *et al.*, 1999; Lee *et al.*, 2010), but have reappeared in the last 5 years. The hydrological changes and rainfall variability in the Nakdong River due to global climate change have been hypothesized to promote cyanobacterial bloom outbreaks (Seo *et al.*, 2012; Hur *et al.*, 2013). For almost 20 years, long-term ecological research (LTER) data have provided considerably more complex and variable information about the Nakdong River (Jeong *et al.*, 2011; Kim *et al.*, 2012; Hong *et al.*, 2014), and comparison of cyanobacterial bloom trends based on LTER data combined with monsoon climate data (*e.g.*, summer monsoon rainfall) might lead to the identification of more complex inter-annual variability of bloom formation.

In the Nakdong River, cyanobacteria dominate the phytoplankton assemblage in summer (*i.e.*, June to early September). In this study, we (i) analyzed the causal relationship patterns between *Microcystis aeruginosa* Kützing and various meteorological, hydrological and physicochemical factors using a self-organizing map (SOM); (ii) investigated the major factors that characterize cyanobacterial blooms; and (iii) discussed potential strategies to control *M. aeruginosa*.

Material and methods

Study site

The Nakdong River is the second largest river in South Korea (approximately 525 km). The basin has an average annual rainfall of approximately 1200 mm, of which 60% occurs in the summer (June–September) (Kim *et al.*, 2002). Ten million people use the Nakdong River for industrial and agricultural purposes and for drinking water. Thus, it is of considerable importance to the regional community. The Nakdong River is a regulated river controlled by four dams (Andong, Imha, Hapcheon and Namgang) and an estuarine barrage. Since the 1990s, cyanobacterial blooms have occurred frequently at the study site. The dominant cyanobacterial species is *M. aeruginosa*, but other genera such as *Oscillatoria* and *Anabaena* have also been detected.

The study site, located at Mulgeum, is 28 km north of the mouth of the Nakdong River and is also the primary water source for nearly 5 million inhabitants of Busan in South Korea (Fig. 1). Eutrophication at Mulgeum has accelerated due to nutrient input from upstream tributaries, and the estuarine barrage has increased water retention times for the lower river. Therefore, cyanobacterial blooms were observed at the lower Nakdong River at Mulgeum when summer rainfall is below the average (Kim *et al.*, 2011).

Data collection

The study site was monitored weekly or biweekly from 1993 to 2010, during which time 96 cases of *M. aeruginosa* occurrence were recorded. The hydrological factors investigated were river flow and total dam discharge; these data were obtained from the Korean Water Management Information System (http://www.wamis.go.kr). The total dam discharge was the sum of the discharge from the four large dams; river flow was measured at Jindong station, located approximately 50 km upstream from the study site.

Meteorological factors (*i.e.*, number of days without rainfall, irradiation time and rainfall amount) were obtained from the KMA (http://www.kma.go.kr). Data for the specific factors were summed at different time intervals – 2 weeks (*i.e.*, total rainfall, irradiation and irradiation time), 1 week (*i.e.*, number of days without rainfall) and per day (*i.e.*, dam discharge and river flow) – in association with the limnological sampling dates.

Physicochemical characteristics were assessed by measuring water temperature, dissolved oxygen (YSI 85; YSI Inc., Yellow Springs, OH, USA), pH (Orion 3-Star pH meter; Thermo Fisher Scientific Inc., Beverly, MA, USA) and conductivity (YSI 30; YSI, Yellow Springs, OH, USA). Turbidity (Micro100 Laboratory Turbidimeter; HF Scientific, Fort Myers, FL, USA), alkalinity, chlorophyll-*a* content and nutrient concentration (*i.e.*, total nitrogen [TN], total phosphorous [TP], nitrate, phosphate and silica) were calculated according to Wetzel and Likens (1991). Samples of *M. aeruginosa* were collected and immediately preserved in Lugol's solution. The number of *M. aeruginosa* cells were counted using an inverted microscope (Zeiss, Telaval 31, Jena, Germany) at 400 × magnification using the sedimentation method (Utermöhl, 1958).

SOM

Artificial neural networks (ANNs) are known to be powerful processors that can be used to extract information by incorporating adaptive and self-organizing properties (Haykin and Lippmann, 1994). They have been widely used to determine an optimal solution using a data-learning process. SOM, also known as unsupervised ANN, recognizes a certain pattern from multi-dimensional data and maps it onto the reduced dimensional space that commonly shapes a two-dimensional plane (Kohonen,

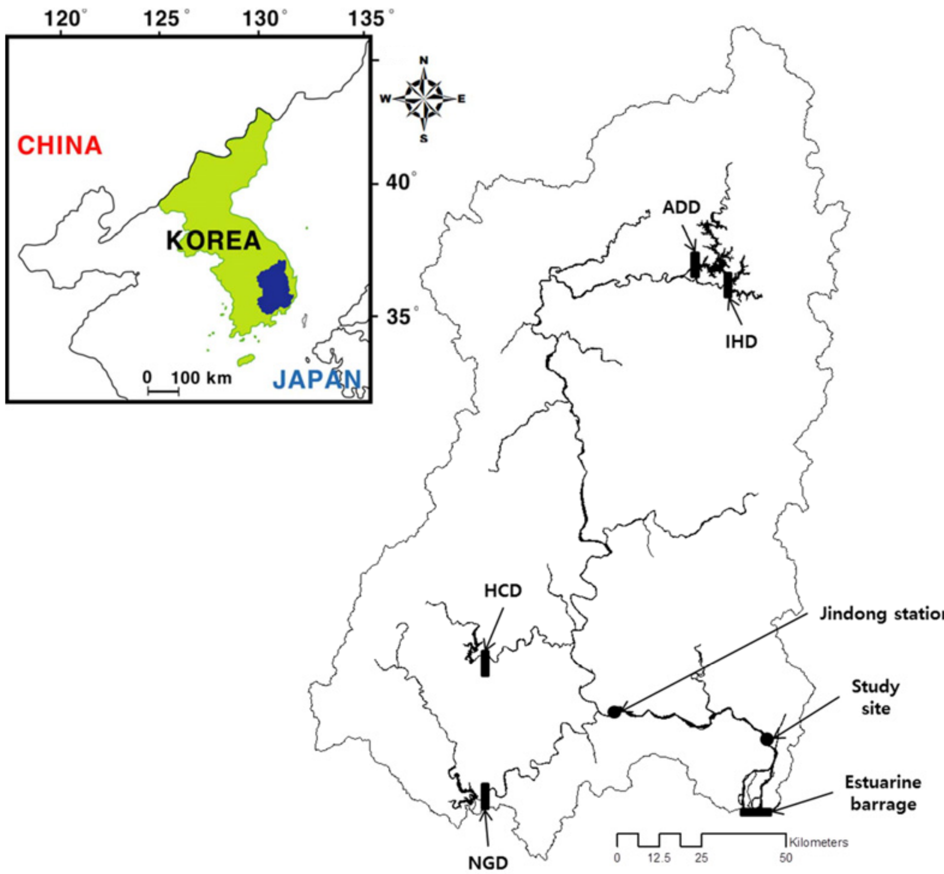

Fig. 1. Map of the Nakdong River basin (rectangles indicate dam locations; ADD, Andong dam; IHD, Imha dam; HCD, Hapcheon dam; NGD, Namgang dam; Jindong station: river flow measure station).

1997). In ecological research, SOM is often considered as a more appropriate multivariate analysis than other conventional approaches such as statistical methods under the linear assumption, since the competitive principle of the SOM network can be more feasible for dealing with the nonlinearity of ecological data (Giraudel and Lek, 2001). Therefore, SOM has been extensively used in pattern recognition in various ecological domains, including benthic macroinvertebrates in running waters (Chon *et al.*, 2000; Park *et al.*, 2003), zooplankton communities (Kim *et al.*, 2012) and biomanipulation assessments (Ha *et al.*, 2014).

SOM basically consists of two layers: (i) an input layer associated with sample units of input variables (x_1, x_2,..., x_k; where k is the number of input variables) and (ii) an output layer in which virtual units of the dataset are arranged (denoted as m_l in Fig. 2). Each virtual unit contains the corresponding weight vector w_i, connecting the input and output. Once the dataset is trained, the inputs seek the best/winning neuron, also known as the best matching unit (BMU). The mathematical equation describing this process is as follows:

$$\|x - w_c\| = \min_i \{\|x - w_i\|\} \quad (1)$$

where x denotes the input, and w_c is the BMU in the input space among i numbers of weight vectors. The w_i is initially generated at random and gradually converges over time. During the training process, the neurons activate each other to learn something from the same input. Furthermore, each weight vector mimics a biological property of adaptation by updating itself at each iteration t. All the neurons are iteratively updated by their neighboring neurons. The process can be expressed as follows:

$$w_i^{(t+1)} = w_i^{(t)} + \alpha^{(t)} \left[x_i^{(t)} - w_i^{(t)} \right] Z_i \quad (2)$$

where α is the learning rate, and Z_i is the neighborhood function; both converge to zero over time. After training, all the weight vectors are conserved in a hexagonal-lattice map called a *U*-matrix. Data ordination is then delineated based on the correspondence between inputs and the *U*-matrix.

The SOM was trained with 20 input variables, including four meteorological, two hydrological and 13 physicochemical factors, as well as *M. aeruginosa* data collected from 1993 to 2010 ($N = 96$). Before training, all the input variables were selectively transformed using the logarithmic scale. For example, several input variables, including *M. aeruginosa* cell density, turbidity, chlorophyll-*a*, TN, TP, nitrate, phosphate and silica, were log-transformed to determine their distributional normality. The SOM size was determined

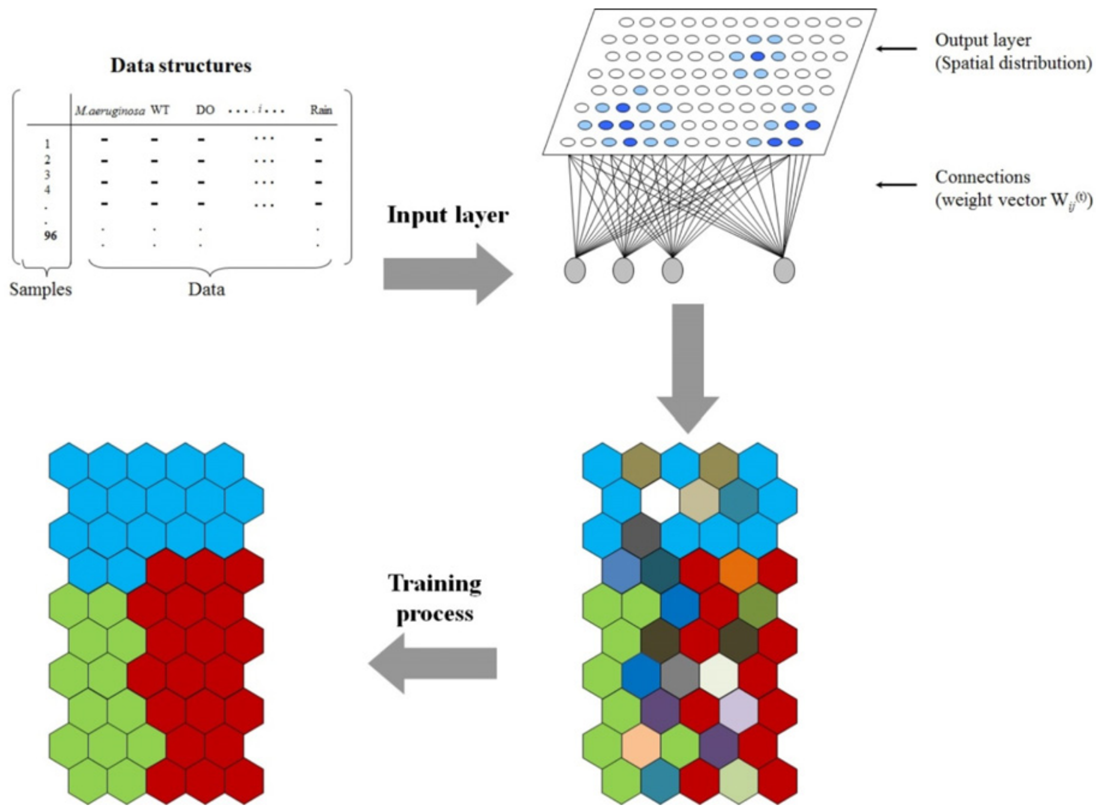

Fig. 2. Basic concept of the self-organizing map.

on the basis of the number adjacent to $5 \times \sqrt{n}$ (Vesanto and Alhoniemi, 2000). The final SOM was selected based on the minimum quantization and topographic errors as previously used by Uriarte and Diaz (2006) and Céréghino and Park (2009). To cluster the SOM map, the SOM units were classified into groups based on the dendrogram of a hierarchical cluster analysis performed using Ward's linkage method by using the Euclidian distance (Park *et al.*, 2014). The SOM model was developed using MATLAB 6.1 (The MathWorks Inc., Natick, MA, USA) and the SOM Toolbox (Helsinki University of Technology, Helsinki).

Statistical analysis

The effect of the different variables on the SOM results was compared using analysis of variance and Scheffe's test for mean separation. Pearson's correlation was used to compare the relationship between the cell density of *M. aeruginosa* and each variable in each cluster. Before correlation analysis was performed, data for cell density, turbidity, chlorophyll-*a*, TN, TP, nitrate, phosphate and silica were log-transformed (Zar, 1996), whereas the remaining variables were not transformed and represented the primary data values. The analyses were conducted using SPSS Version 21 (IBM Corporation, Armonk, NY, USA).

Results

Temporal trends of phytoplankton along with precipitation

Distinct inter-annual variations in *M. aeruginosa*, chlorophyll-*a* and rainfall were observed (Fig. 3). *M. aeruginosa* appeared every year from 1993 to 2001, and a large peak in *M. aeruginosa* cell density was recorded from 1994 to 1997. Subsequently, *M. aeruginosa* was not observed between 2002 and 2008, but appeared again from 2008 to 2010. The average chlorophyll-*a* concentration was generally stable, but increased from 1993 to 2001. During the study period (from April to November), the average annual rainfall was 1131 mm. In the years with limited rainfall, the density of *M. aeruginosa* cells was often above 50 000 cells mL^{-1}. In general, rainfall affected the density of *M. aeruginosa* cells and chlorophyll-*a* concentration (Fig. 3).

Pattern of variables on the SOM

The SOM plane was optimized on a 10×5 size map and the topology was more smoothly trained (quantization error: 0.557, topographic error: 0.000) (Fig. 4). The relationship between different environmental variables and *M. aeruginosa* cell density was investigated (Fig. 5).

In the component plane, higher water temperature was associated with higher *M. aeruginosa* cell density, whereas

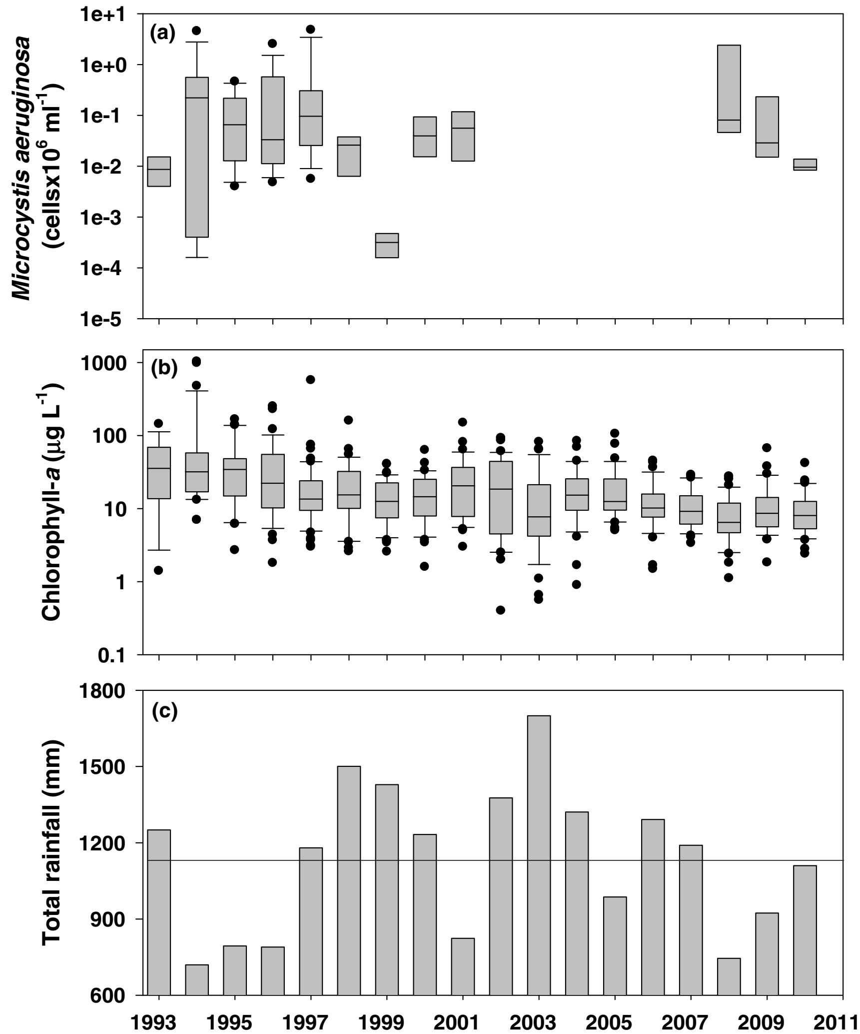

Fig. 3. Annual patterns of *Microcystis aeruginosa*, chlorophyll-*a*, and rainfall between April and November 1993–2010: (a) *M. aeruginosa* cell density, (b) chlorophyll-*a* concentration. Boxes indicate the data range; lines within boxes indicate the mean; whiskers indicate the standard deviation; dots represent outliers; (c) total rainfall; the solid line indicates an annual average of 1131 mm.

lower water temperature and *M. aeruginosa* cell density occupied the left-bottom area. Dissolved oxygen was associated with phytoplankton biomass and water temperature. Higher concentrations of dissolved oxygen were found in two sections of the component plane. In the right-bottom corner of the plane, a higher concentration of dissolved oxygen was associated with higher *M. aeruginosa* cell density, indicating that oxygen increased with an increase in *M. aeruginosa* photosynthetic output.

In the left-bottom corner of the plane, the increase in dissolved oxygen appeared to have a stronger correlation with lower water temperature than with phytoplankton-associated photosynthesis, whereas lower water temperature was indicative of a higher dissolved oxygen concentration. The highest (*i.e.*, most basic) pH was found in the right-bottom section of the plane.

Conductivity and alkalinity patterns were homogenous but not strongly correlated with *M. aeruginosa* cell density. Higher turbidity was located in two zones of the component plane. The right-top area largely coincided with increasing rainfall, which caused an increase in suspended solids. The right-bottom area mostly coincided with increasing *M. aeruginosa* cell density. The area of increased chlorophyll-*a* concentration overlapped with the increased density of *M. aeruginosa* cells. The left-bottom area was occupied by higher chlorophyll-*a* concentration but a lower density of *M. aeruginosa* cells.

Concentrations of TN and nitrate had similar distributions on the component map, except in the area of maximum cell density. The left-bottom area had significantly lower TN and nitrate concentrations. The input of TP and phosphate into the river matched with the rainfall pattern; therefore, these factors increased during the rainy season (Ha *et al.*, 2002). Different correlation patterns were confirmed between the maximum cell density of *M. aeruginosa* and TP and phosphate in the right and left-bottom zones, respectively. No difference occurred in the concentration of TP between the left-bottom and right-bottom areas, whereas the concentration of

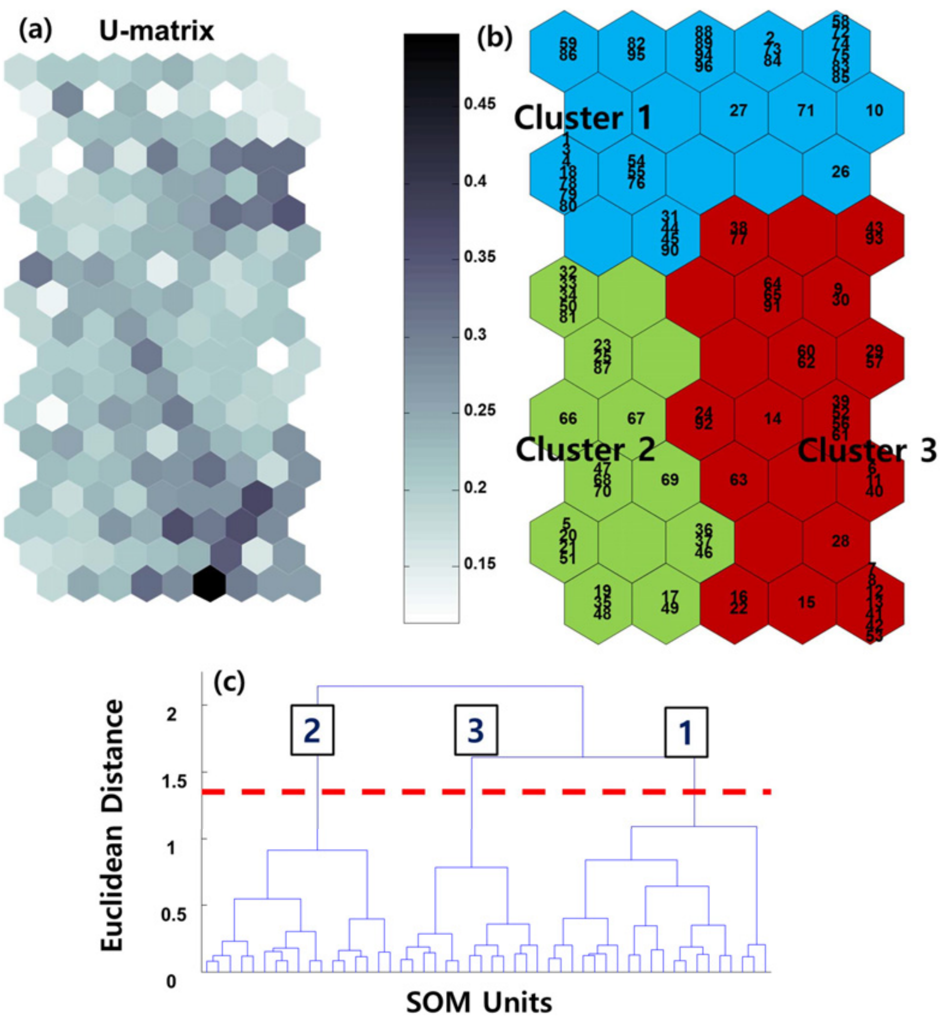

Fig. 4. Clustering results of the self-organizing map (SOM): (a) *U*-matrix (gray scale bar: distance between neurons); (b) data ordination; and (c) dendrogram. Numbers within cells indicate data samples used for modeling.

phosphate was lower in the right-bottom area than in the left-bottom area.

The concentration pattern of silica coincided with the rainfall pattern, but not with *M. aeruginosa* cell density. The area of low water temperature and silica concentration overlapped with low *M. aeruginosa* cell density, whereas chlorophyll-*a* concentration was slightly higher than that at the same level in the other areas.

M. aeruginosa cell density was lower on the top section of the component map, where rainfall, dam discharge, and river flow were significantly higher. During the summer rainy season, rainfall, dam discharge, and river flow increased. The irradiance level and irradiating time showed similar patterns to *M. aeruginosa* cell density, although cell density was more strongly correlated with irradiating time than irradiance in the area with highest cell density.

SOM clustering and its characteristics

As explained by the Euclidean distance, cluster 2 was divided first, and then was subdivided by clusters 1 and 3 (Fig. 4 (c)). Statistically significant differences among cluster variables were shown in Table 1. The densities of *M. aeruginosa* cells were significantly similar for clusters 1 and 2, but not for cluster 3. Water temperature, conductivity, silica, irradiating time and total dam discharge were significantly different among the clusters. The number of *M. aeruginosa* occurrence was different between each cluster (Table 2).

The results of correlation analysis for each cluster showed clear differences in the effect of variables on *M. aeruginosa* cell density. Water temperature had the largest positive correlation with *M. aeruginosa* cell density in clusters 1 and 3, whereas the concentration of TP had the largest negative correlation with *M. aeruginosa* cell density in cluster 2 (Table 3 and Appendices 1–4).

In cluster 1, the density of *M. aeruginosa* cells was only 3.5% lower than that in cluster 3. River flow, total dam discharge, and rainfall were higher in cluster 1 than in the other clusters (Table 1). *M. aeruginosa* appeared in all years in cluster 1, with the highest incidence in summer from July to August (Table 3). *M. aeruginosa* cell density increased with increasing water temperature.

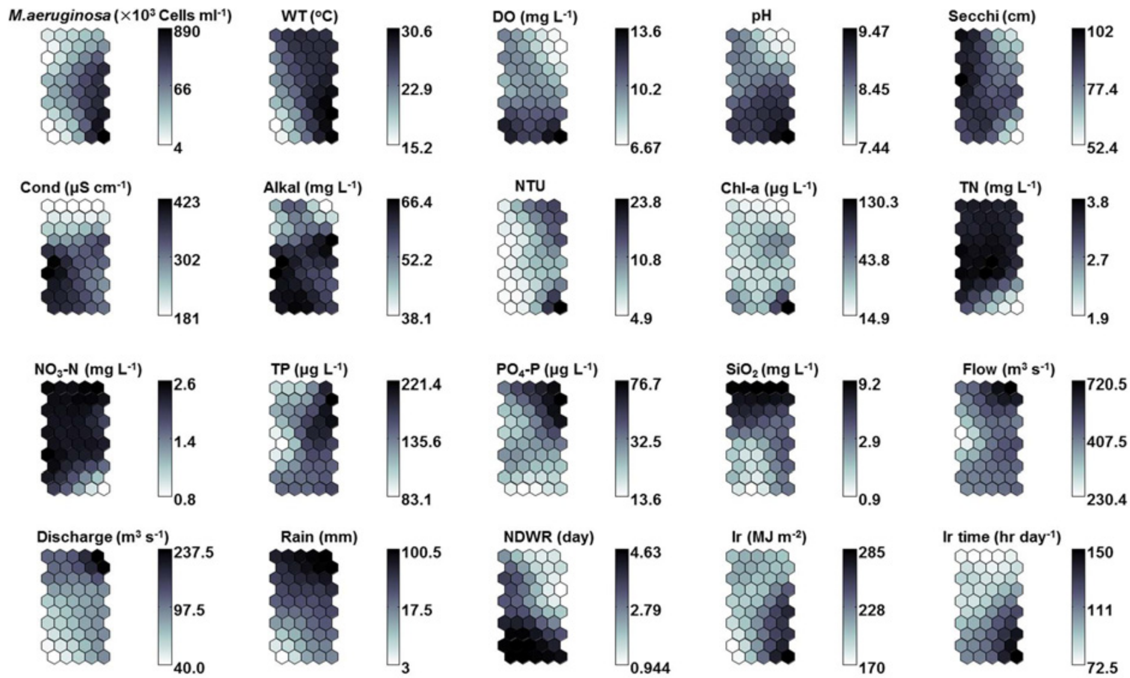

Fig. 5. Component maps of *Microcystis aeruginosa* and the corresponding meteorological, hydrological and physicochemical variables. The three numbers next to each band indicate the range of the variables. All acronyms are defined in Table 1.

Table 1. Comparison of variables (mean ± SE) for different clusters defined in the self-organizing map (SOM).

Variable	Acronym	Unit	Clusters 1 ($n = 35$)	2 ($n = 26$)	3 ($n = 35$)	Total ($n = 96$)
M. aeruginosa	*M. aeruginosa*	Cells.mL^{-1}	32 106 ± 4634^{a}	31 159 ± 3325^{a}	**897 423 ± 138 365^{b}**	347 330 ± 93 805
Water temperature	WT	°C	25.9 ± 0.4^{b}	18.8 ± 0.5^{a}	**28.8 ± 0.3^{c}**	25.0 ± 0.6
Dissolved oxygen	DO	mg.L^{-1}	8.8 ± 0.2^{a}	10.7 ± 0.3^{b}	10.7 ± 0.3^{b}	10.0 ± 0.3
pH	pH	–	8.0 ± 0.1^{a}	8.7 ± 0.1^{b}	**9.0 ± 0.1^{b}**	8.5 ± 0.1
Secchi depth	Secchi	cm	81.0 ± 2.9^{ab}	**95.8 ± 3.3^{b}**	72.7 ± 2.3^{a}	82.0 ± 3.0
Conductivity	Cond	µS.cm^{-1}	199.3 ± 3.8^{a}	**401.5 ± 8.4^{c}**	322.5 ± 7.2^{b}	299.0 ± 10.6
Alkalinity	Alkal	mg.L^{-1}	45.5 ± 1.7^{a}	**66.4 ± 1.0^{b}**	59.9 ± 1.3^{b}	56.4 ± 1.6
Turbidity	NTU	NTU	10.7 ± 0.9^{ab}	5.1 ± 0.2^{a}	**16.3 ± 1.6^{b}**	11.2 ± 1.2
Chlorophyll-*a*	Chl-*a*	µg.L^{-1}	22.6 ± 1.4^{a}	33.3 ± 2.7^{ab}	**111.1 ± 20.5^{b}**	57.8 ± 13.2
Total nitrogen	TN	mg.L^{-1}	3.4 ± 0.1^{a}	3.4 ± 0.1^{a}	3.1 ± 0.1^{a}	3.3 ± 0.1
Nitrate	NO_3-N	mg.L^{-1}	**2.5 ± 0.1^{b}**	2.4 ± 0.1^{ab}	1.9 ± 0.1^{a}	2.2 ± 0.1
Total phosphorus	TP	µg.L^{-1}	166.9 ± 13.1^{ab}	122.3 ± 5.4^{a}	**186.0 ± 9.3^{b}**	161.8 ± 10.4
Phosphate	PO_4-P	µg.L^{-1}	**50.4 ± 3.5^{a}**	28.4 ± 2.3^{a}	39.0 ± 5.0^{a}	40.3 ± 4.0
Silica	SiO_2	mg.L^{-1}	**8.5 ± 0.3^{b}**	2.5 ± 0.2^{a}	3.9 ± 0.3^{a}	5.2 ± 0.4
Irradiance	Ir	MJ.m^{-2}	203.4 ± 3.3^{a}	186.8 ± 4.6^{a}	**254.8 ± 4.7^{b}**	217.6 ± 5.2
Irradiating time	Ir time	h.day^{-1}	79.6 ± 2.2^{a}	99.0 ± 2.1^{b}	**124.4 ± 2.7^{c}**	101.2 ± 3.1
River flow	Flow	m^{3}.s^{-1}	**561.4 ± 29.7^{b}**	347.1 ± 12.8^{a}	480.4 ± 30.5^{ab}	473.8 ± 28.0
Dam discharge	Discharge	m^{3}.s^{-1}	**179.6 ± 21.2^{b}**	51.9 ± 1.9^{a}	86.3 ± 3.9^{a}	111.0 ± 14.1
Rainfall	Rain	mm	**82.5 ± 4.2^{b}**	16.0 ± 1.5^{a}	31.0 ± 2.5^{a}	45.7 ± 4.2
Number of days without rainfall	NDWR	Day	2.3 ± 0.2^{a}	**4.1 ± 0.1^{b}**	2.9 ± 0.2^{a}	3.0 ± 0.2

Values in bold are the greatest among the clusters within each variable. Mean ± SE values within columns followed by different lowercase letters are significantly different (Scheffe's test; $P < 0.05$).

However, this increase was accompanied by a decrease in dissolved oxygen and pH. An average pH of 8.0 is optimal for *M. aeruginosa* growth (Shapiro, 1984). The density of *M. aeruginosa* cells increased with an increase in river flow. Therefore, increases in water temperature can be associated with increases in *M. aeruginosa* cell density following the rainy season (Table 3, Appendix 2).

In cluster 2, the cell density of *M. aeruginosa* was similar to that in cluster 1. Total dam discharge and river flow were lower than those in the other clusters. The mean number of days ± SE without rainfall in cluster 2 was 4.1 ± 0.1 days, which was higher than those in other clusters. Water temperature in cluster 2 was 18.8 ± 0.5 °C, which was the lowest among the three clusters (Table 1).

Table 2. Number of *Microcystis aeruginosa* outbreaks observed in each cluster by year and month.

		Clusters			
		1	2	3	Total
Year	1993	4	1		5
	1994	2	4	10	16
	1995	3	6	5	14
	1996	2	8	6	16
	1997	4	5	10	19
	1998	6		1	7
	1999	3			3
	2000	5	1		6
	2001	3	1	2	6
	2008			1	1
	2009	2			2
	2010	1			1
Month	4	3			3
	5		3	1	4
	6	1	2	3	6
	7	11	1	6	18
	8	12		16	28
	9	7	5	9	21
	10	1	9		10
	11		6		6

Table 3. Pearson's correlation coefficients between *Microcystis aeruginosa* and the 19 meteo-hydrological and physicochemical variables.

	Clusters			
Variable	1	2	3	Total
Water temperature	**0.727****	0.417*	**0.620****	0.646**
Dissolved oxygen	– 0.437**	– 0.350	0.225	0.025
pH	– 0.443**	– 0.382	0.182	0.164
Secchi depth	– 0.047	0.305	– 0.205	– 0.145
Conductivity	0.118	0.335	– 0.068	0.171
Alkalinity	0.219	– 0.094	0.199	0.199
Turbidity[a]	0.028	– 0.174	0.420*	0.368**
Chlorophyll-*a*[a]	– 0.089	– 0.422*	0.278	0.245*
Total nitrogen[a]	– 0.290	0.301	– 0.153	– 0.191
Nitrate[a]	– 0.284	0.172	– 0.060	– 0.289**
Total phosphorus[a]	0.136	– **0.601****	0.244	0.160
Phosphate[a]	0.189	– 0.011	0.136	0.047
Silica[a]	– 0.001	0.107	0.145	– 0.040
Irradiance	– 0.087	0.249	0.416*	0.509**
Irradiating time	– 0.012	– 0.121	0.473**	0.483**
River flow[a]	0.439**	– 0.373	0.018	0.073
Dam discharge[a]	0.161	0.373	0.412*	0.120
Rainfall[a]	0.115	0.223	– 0.115	0.016
Number of days without rainfall	– 0.201	– 0.072	0.069	– 0.080

Values in bold are the greatest among the variables within each cluster ([a]: natural log-transformed variable, $*P < 0.05$, $**P < 0.01$)

M. aeruginosa appeared from 1994 to 1998 and in 2000 to 2001, which coincided with periods of low rainfall. During the years with low rainfall, *M. aeruginosa* appeared in early summer from May to July, and in fall from September to November (Table 2). In cluster 2, the TP concentration decreased with an increase in *M. aeruginosa* cell density; however, in the other clusters, increases in TP concentration were followed by an increase in *M. aeruginosa* cell density (Table 3, Appendix 3).

In cluster 3, *M. aeruginosa* cell density ($897\,423 \pm 138\,365$ cells mL^{-1}) and water temperature ($28.8 \pm 0.3\,°C$) and pH (9.0 ± 0.1) were the highest among the three clusters. Irradiance, irradiating time, turbidity, chlorophyll-*a* and TP concentration were higher in cluster 3 than in the other clusters (Table 1). In cluster 3, *M. aeruginosa* appeared between 1994 and 1998, in 2001, and in 2008. Further, *M. aeruginosa* blooms were found in summer (*i.e.,* August from 1994 to 1998; Table 2). Irradiance had a stronger correlation with cell density than with irradiating time in all the clusters, whereas irradiating time showed a stronger correlation with cell density than with irradiance in cluster 3 (Table 3, Appendix 4).

Discussion

What causes the *M. aeruginosa* bloom?

Increased river flow suppressed *M. aeruginosa* cell density in the Nakdong River, because most cyanobacteria do not bloom in areas with short water retention times (Jeong *et al.*, 2011, 2003a). Alternatively, low rainfall was responsible for an increase in the water retention time, thereby increasing *M. aeruginosa* cell density by establishing environmental conditions optimal for its growth (Joo and Jeong, 2005).

Our SOM results corroborated Shapiro's hypothesis (1990) that cyanobacteria dominate in rivers and lakes because of their adaptability to water temperatures, light, the N:P ratio, CO_2 concentrations and pH. *M. aeruginosa* have gas vacuoles that enable them to remain at the water surface layer, which is advantageous in utilizing CO_2. This typically occurs when the pH increases after extensive photosynthesis occurs (Shapiro, 1984). In cluster 3, high water temperatures caused by strong irradiance (which is proportional to irradiating time) and a high pH might have provided a competitive advantage to the cyanobacterial bloom. The buoyancy of *M. aeruginosa* colonies creates scum, resulting in increased turbidity and low light penetration (*i.e.*, Secchi depth).

With an increase in *M. aeruginosa* cell density (*i.e.*, comparing cluster 3 with clusters 1 and 2), the concentrations of TP and phosphate increased, but TN and nitrate concentrations decreased. *M. aeruginosa* cannot fix nitrogen (Moisander *et al.*, 2009) and obtains it from the surrounding water. The high level of nitrogen in the river promotes the growth of *M. aeruginosa* and increases the probability of blooms (McCarthy *et al.*, 2009). In cluster 2, the TP concentration decreased as *M. aeruginosa* cell density increased; however, in the other clusters, increases in the TP concentration were followed by an increase in *M. aeruginosa* cell density. Because *M. aeruginosa* absorbs and stores phosphorous in the cells from water, its concentration decreases as rainfall decreases (*e.g.*, cluster 2). *M. aeruginosa* cell density increased with an increase in water temperature, a pattern similar to that observed in the other clusters. Relatively low concentrations of phosphate in cluster 3 were associated with a higher phosphate uptake, which increases the growth rate of *M. aeruginosa* (Xie *et al.*, 2003; Reynolds, 2006; Chuai *et al.*, 2011).

Interaction between *M. aeruginosa* and meteo-hydrological factors in the Nakdong River

In contrast to previous *M. aeruginosa* studies at the Nakdong River, a clear inter-annual variation of species proliferation was observed in this study. During a prolonged period of low rainfall during the mid-1990s, *M. aeruginosa* bloomed intensely in the Nakdong basin (Ha *et al.*, 2002; Park *et al.*, 2002; Jeong *et al.*, 2003a). However, *M. aeruginosa* failed to bloom at the study site in the early 2000s, although several studies reported a very low abundance in the Nakdong River (Son, 2013a, 2013b). In 2008, the number of *M. aeruginosa* cells exceeded 4 000 000 mL^{-1}. Although the amount of rainfall in 2001 and 2005 was below the 18-year average, *M. aeruginosa* blooms were not detected. Short-term studies revealed seasonality in cyanobacterial blooms (*i.e.,* based on water temperature and irradiance), although LTER recognized that inter-annual rainfall variability by global climate change is an important cause of *M. aeruginosa* blooms (Paerl and Huisman, 2009; Paerl and Paul, 2012). If the amount of rainfall across two or three consecutive years is large enough to raise the water level at the study site, then *M. aeruginosa* blooms can be suppressed (Jeong *et al.*, 2007).

The hydrological changes at Nakdong River (*i.e.*, drought and flooding) are important factors in temperate river-floodplain ecosystems, especially for phytoplankton (Mihaljević and Stević, 2011). This is true in Northeast Asia where summer rainfall is the major water source for residents. Our findings suggested that *M. aeruginosa* blooms were strongly associated with water temperature and nutrient concentration, but the distribution of annual rainfall patterns governs the inter-annual variation of *M. aeruginosa* populations. Pollution control in the Nakdong River's basin is known to be a key factor for suppressing cyanobacterial blooms. In contrast, understanding the inter-annual variability of cyanobacterial blooms, with respect to long-term rainfall patterns, might help in the management of water quality. The relationship between cyanobacterial blooms and hydrological characteristics was successfully identified in our study by application of SOM to a long-term *M. aeruginosa* database.

Water quality management strategies in a regulated river

Since the 1990s, the Korean government has implemented strategies to reduce cyanobacterial blooms in order to improve the water quality of the Nakdong River. These methods include installment of wastewater treatment facilities and pollution management (Chun *et al.*, 1999; Jung *et al.*, 2008; Lee *et al.*, 2010). These efforts were then applied to other major rivers in Korea, and eventually, the Korean government initiated the Total Maximum Daily Load program. As a result, biochemical oxygen demand and TP concentration have decreased in the major rivers. Reduced TP concentrations are related to decreased cyanobacterial blooms (Stumpf *et al.*, 2012). However, unlike in other countries, effluent standards in Korea remain high. The TP effluent standard for wastewater treatment in Korea is 2.0–8.0 $mg.L^{-1}$ and, in the US, it is 0.3–1.0 $mg.L^{-1}$ (according to the US Environmental Protection Agency). In addition, the newly established TP effluent standard in Japan is 1.0–3.0 $mg.L^{-1}$. Therefore, further reduction of the occurrence of cyanobacterial blooms requires the use of two-fold lower TP effluent standard because the present

TP effluence determines the main influx of P in the rivers of Korea.

In this study, cyanobacterial blooms were confirmed to be associated with the summer monsoon in Korea: they were suppressed during the summer monsoon period (from July to August) and recurred after the monsoon (from August to September). In regulated river systems, dams and estuarine barrages control river flow. Therefore, a regulated river system can control cyanobacterial blooms by regulating river flow via hydrological control devices. In particular, summer cyanobacterial blooms could be reduced or eliminated by increasing the total dam discharge, which in turn, decreases water retention time and increases water velocity. This scenario has been achieved in the Australian Darling River, where cyanobacterial cell density decreased from 100 000 to 1000 cells.mL^{-1} in a week when 3000 mL.day^{-1} of water was discharged (Mitrovic *et al.*, 2011). In the Nakdong River, if the total dam discharge increases over 129 CMS (a 50% increase in dam discharge from cluster 3), cyanobacterial blooms would be suppressed after the monsoon and the hot summer period (from August to September). The dam-weir-estuarine barrage system needs to be considered in order to create an integrated, regulated river plan, which has been defined by previous smart-flow strategies applied in other countries and in Korea.

As mentioned above, cyanobacterial blooms were found to be associated with the summer monsoon in Korea: they were suppressed during the summer monsoon period (from July to August) and recurred after the monsoon (from August to November). In a regulated river system, successful water resource management requires the simultaneous control of pollution levels and river flow. Pollution control is focused on point pollution; however, measures to reduce non-point pollution, such as the control of farming and livestock, are also important. In regulated river flow, water source security for reducing cyanobacterial blooms is a major factor during the summer monsoon. Hence, the control of cyanobacterial blooms involves many factors and the integration of watershed management and meteo-hydrological and physicochemical factors of regulated river systems. Reducing dam and weir discharge can reduce cyanobacterial blooms in the middle of rivers, but might result in the transport of cyanobacterial colonies from the middle to the shoreline or further downstream (Qin *et al.*, 2010). Thus, an optimal flow rate, with respect to efficient cyanobacterial bloom regulation, needs to be determined.

The Four Major Rivers Restoration Project (FMRRP) was initiated in 2009 to prevent drought and flooding, increase water quality, provide leisure and enhance regional culture. It targeted the major rivers (*i.e.*, the Han, Geum, Young san-Seomjin and Nakdong) in South Korea. The project required weir installation, dredging, widening portions of the river and maintaining the optimal water level, which were the major objectives of the $19 billion project (Normile, 2010; Shin and Chung, 2011). The completion of the FMRRP led to a decrease in water velocity and increase in water retention times in the Nakdong River system. These hydrological changes led to cyanobacterial blooms in the river (Domingues *et al.*, 2013). Previous management studies focused on the lower Nakdong River (from the river mouth to 30–40 km upstream); however, water management and models of cyanobacterial bloom prediction studies are presently needed for the mid-lower Nakdong River basin (Seo *et al.*, 2012; Hur *et al.*, 2013; Srivastava *et al.*, 2015).

Conclusion

Meteorological, hydrological and physicochemical factors explained the presence of *M. aeruginosa* blooms based on SOM results for the regulated Nakdong River system. An increase in rainfall, river flow and dam discharge decreased cell density of *M. aeruginosa*. In contrast, low summer rainfall and increased water temperature, irradiance and irradiating time resulted in higher *M. aeruginosa* cell densities. In a regulated river system, increases in water retention time would increase the frequency of cyanobacterial blooms due to increases in water temperature and nutrient concentrations. Therefore, the successful control of cyanobacterial blooms requires integrated watershed management that accommodates the control and management of meteo-hydrological and physicochemical factors.

Acknowledgements. This work was supported by National Research Foundation of Korea (NRF) Grants funded by the Korea government (Grant No., NRF-2014M3C8A4030721).

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Appendix 1. Pearson correlation values between *Microcystis aeruginosa* and the 19 meteo-hydrological and physicochemical variables.

	M. aeruginosa	WT	DO	pH	Secchi	Cond	Alkal	NTU	Chl-*a*	TN	NO_3-N	TP	PO_4-P	SiO_2	Ir	Ir time	Flow	Discharge	Rain	NDWR
M. aeruginosa	1.000																			
WT	0.646	1.000																		
DO	0.025	−0.215	1.000																	
pH	0.164	−0.043	0.719	1.000																
Secchi	−0.145	−0.175	−0.129	−0.046	1.000															
Cond	0.171	−0.365	0.153	0.242	0.138	1.000														
Alkal	0.199	−0.076	0.046	0.154	0.115	0.659	1.000													
NTU	0.368	0.382	0.038	0.012	−0.556	−0.137	−0.047	1.000												
Chl-*a*	0.245	0.001	0.348	0.348	−0.339	0.209	0.120	0.326	1.000											
TN	−0.191	−0.202	−0.221	−0.209	0.206	0.008	−0.055	−0.255	−0.297	1.000										
NO_3-N	−0.289	−0.183	−0.344	−0.268	0.260	−0.109	−0.175	−0.397	−0.320	0.726	1.000									
TP	0.160	0.172	0.017	0.049	−0.141	−0.098	−0.029	0.255	0.088	0.050	−0.051	1.000								
PO_4-P	0.047	0.209	−0.418	−0.348	0.074	−0.252	−0.094	0.149	−0.219	0.174	0.226	0.151	1.000							
SiO_2	−0.040	0.228	−0.071	−0.182	−0.052	−0.609	−0.424	0.038	−0.152	0.082	0.144	0.020	0.370	1.000						
Ir	0.509	0.576	0.032	0.258	−0.130	0.027	0.090	0.417	0.213	−0.301	−0.373	0.017	−0.003	0.004	1.000					
Ir time	0.483	0.302	0.396	0.580	−0.146	0.212	0.104	0.161	0.337	−0.386	−0.376	0.113	−0.175	−0.140	0.622	1.000				
Flow	0.073	0.242	−0.131	−0.172	−0.412	−0.306	−0.256	0.236	0.042	0.017	0.094	0.317	0.061	0.183	0.012	−0.026	1.000			
Discharge	0.120	0.418	−0.344	−0.356	−0.134	−0.475	−0.430	0.264	−0.105	−0.008	0.138	0.211	0.427	0.442	0.168	−0.024	0.303	1.000		
Rain	0.016	0.403	−0.481	−0.463	−0.032	−0.402	−0.179	0.179	−0.248	0.149	0.100	0.033	0.334	0.374	0.092	−0.397	0.248	0.477	1.000	
NDWR	−0.080	−0.275	0.456	0.468	0.079	0.203	−0.050	−0.219	0.098	−0.173	−0.135	−0.063	−0.359	−0.272	0.026	0.398	−0.180	−0.214	−0.494	1.000

Appendix 2. Pearson correlation values between *Microcystis aeruginosa* and the 19 meteo-hydrological and physicochemical variables from cluster 1.

	M. aeruginosa	WT	DO	pH	Secchi	Cond	Alkal	NTU	Chl-*a*	TN	NO_3-N	TP	PO_4-P	SiO_2	Ir	Ir time	Flow	Discharge	Rain	NDWR
M. aeruginosa	1.000																			
WT	0.727	1.000																		
DO	−0.437	−0.356	1.000																	
pH	−0.443	−0.267	0.735	1.000																
Secchi	−0.047	0.005	0.202	0.444	1.000															
Cond	0.118	−0.057	0.093	0.091	−0.002	1.000														
Alkal	0.219	0.444	0.039	0.040	0.104	0.265	1.000													
NTU	0.028	0.042	−0.367	−0.430	−0.436	−0.299	0.006	1.000												
Chl-*a*	−0.089	−0.222	0.113	0.248	0.289	0.088	−0.241	−0.355	1.000											
TN	−0.290	−0.011	0.233	0.121	−0.304	−0.229	0.087	0.054	−0.104	1.000										
NO_3-N	−0.284	0.017	0.013	0.036	−0.147	−0.397	−0.399	−0.043	0.220	0.525	1.000									
TP	0.136	0.116	−0.270	−0.238	−0.017	0.200	−0.019	0.143	−0.278	0.097	0.035	1.000								
PO_4-P	0.189	0.399	−0.504	−0.457	0.023	−0.554	−0.037	0.432	−0.252	−0.011	0.102	0.238	1.000							
SiO_2	−0.001	0.147	0.080	0.018	0.020	−0.606	−0.232	0.049	0.052	0.054	0.520	−0.213	0.196	1.000						
Ir	−0.087	0.050	−0.096	0.143	0.003	−0.005	0.057	0.056	0.199	−0.114	0.015	−0.244	−0.109	0.121	1.000					
Ir time	−0.012	0.029	0.127	0.220	0.046	0.168	−0.161	−0.305	0.158	−0.219	0.018	−0.040	−0.098	0.050	0.543	1.000				
Flow	0.439	0.343	−0.529	−0.573	−0.444	−0.111	−0.102	0.338	−0.136	0.009	0.277	0.130	0.182	0.285	−0.094	−0.121	1.000			
Discharge	0.161	0.152	−0.325	−0.297	−0.227	−0.292	−0.321	0.130	−0.032	−0.118	0.223	0.291	0.398	0.440	0.124	0.389	0.301	1.000		
Rain	0.115	0.246	−0.393	−0.278	−0.187	−0.043	0.158	0.222	−0.379	0.092	0.276	0.272	0.328	0.228	−0.209	−0.301	0.364	0.156	1.000	
NDWR	−0.201	−0.318	0.283	0.410	0.290	0.131	−0.235	−0.410	0.116	−0.143	−0.157	−0.011	−0.294	−0.102	0.178	0.397	−0.374	0.117	−0.217	1.000

Appendix 3. Pearson correlation values between *Microcystis aeruginosa* and the 19 meteo-hydrological and physicochemical variables from cluster 2.

	M. aeruginosa	WT	DO	pH	Secchi	Cond	Alkal	NTU	Chl-*a*	TN	NO_3-N	TP	PO_4-P	SiO_2	Ir	Ir time	Flow	Discharge	Rain	NDWR
M. aeruginosa	1.000																			
WT	0.417	1.000																		
DO	− 0.350	− 0.661	1.000																	
pH	− 0.382	− 0.392	0.528	1.000																
Secchi	0.305	0.236	− 0.259	− 0.480	1.000															
Cond	0.335	0.000	− 0.159	− 0.372	0.175	1.000														
Alkal	− 0.094	0.135	− 0.336	− 0.305	0.089	0.483	1.000													
NTU	− 0.174	0.091	0.054	0.200	− 0.284	0.101	0.074	1.000												
Chl-*a*	− 0.422	− 0.541	0.549	0.498	− 0.570	− 0.420	− 0.339	0.235	1.000											
TN	0.301	− 0.343	− 0.022	− 0.214	0.279	0.269	− 0.018	− 0.411	− 0.035	1.000										
NO_3-N	0.172	− 0.150	− 0.134	− 0.060	0.173	0.182	− 0.117	− 0.141	− 0.139	0.751	1.000									
TP	− 0.601	− 0.333	0.452	0.441	− 0.194	− 0.440	− 0.190	− 0.308	0.324	− 0.187	− 0.132	1.000								
PO_4-P	− 0.011	− 0.075	− 0.150	0.074	0.169	0.280	0.115	0.093	− 0.387	0.203	0.395	0.009	1.000							
SiO_2	0.107	− 0.298	0.086	0.120	− 0.032	− 0.076	− 0.228	− 0.309	0.090	0.415	0.191	0.030	0.361	1.000						
Ir	0.249	0.665	− 0.463	− 0.315	0.376	0.132	0.136	0.353	− 0.613	− 0.323	− 0.126	− 0.459	0.087	− 0.288	1.000					
Ir time	− 0.121	0.009	0.240	0.394	0.004	− 0.229	− 0.352	− 0.047	− 0.184	− 0.437	− 0.366	0.218	− 0.038	− 0.002	0.386	1.000				
Flow	− 0.373	− 0.215	0.324	0.393	− 0.582	− 0.157	− 0.081	− 0.139	0.274	− 0.172	− 0.140	0.570	− 0.013	− 0.089	− 0.320	0.240	1.000			
Discharge	0.373	0.416	− 0.314	− 0.124	0.392	0.402	0.100	0.110	− 0.532	0.101	0.277	− 0.224	0.426	− 0.234	0.348	− 0.024	− 0.153	1.000		
Rain	0.223	0.350	− 0.449	− 0.547	0.307	0.294	0.584	− 0.105	− 0.371	0.346	0.167	− 0.448	0.077	− 0.063	0.181	− 0.488	− 0.276	0.347	1.000	
NDWR	− 0.072	− 0.032	0.416	0.376	− 0.154	− 0.440	− 0.637	− 0.125	0.070	− 0.246	− 0.079	0.303	− 0.024	0.058	0.050	0.621	0.258	− 0.098	− 0.472	1.000

Appendix 4. Pearson correlation values between *Microcystis aeruginosa* and the 19 meteo-hydrological and physicochemical variables from cluster 3.

	M. aeruginosa	WT	DO	pH	Secchi	Cond	Alkal	NTU	Chl-*a*	TN	NO_3-N	TP	PO_4-P	SiO_2	Ir	Ir time	Flow	Discharge	Rain	NDWR
M. aeruginosa	1.000																			
WT	0.620	1.000																		
DO	0.225	0.221	1.000																	
pH	0.182	0.202	0.766	1.000																
Secchi	− 0.205	− 0.123	− 0.414	− 0.271	1.000															
Cond	− 0.068	− 0.461	− 0.278	− 0.214	− 0.077	1.000														
Alkal	0.199	− 0.236	− 0.314	− 0.315	− 0.010	0.693	1.000													
NTU	0.420	0.073	0.363	0.227	− 0.752	0.221	0.132	1.000												
Chl-*a*	0.278	0.056	0.258	0.086	− 0.620	0.378	0.281	0.604	1.000											
TN	− 0.153	− 0.099	− 0.431	− 0.270	0.397	0.069	− 0.080	− 0.293	− 0.335	1.000										
NO_3-N	− 0.060	− 0.011	− 0.458	− 0.226	0.443	− 0.023	− 0.022	− 0.479	− 0.308	0.749	1.000									
TP	0.244	0.039	− 0.011	0.026	0.032	0.063	0.147	0.285	0.091	0.321	0.129	1.000								
PO_4-P	0.136	0.059	− 0.413	− 0.344	0.226	− 0.074	0.200	− 0.187	− 0.090	0.257	0.251	0.102	1.000							
SiO_2	0.145	0.401	0.229	0.148	0.127	− 0.446	− 0.121	− 0.144	− 0.144	− 0.134	− 0.007	0.050	0.241	1.000						
Ir	0.416	0.449	0.231	0.292	− 0.280	0.030	0.114	0.326	0.265	− 0.223	− 0.343	0.056	− 0.038	0.225	1.000					
Ir time	0.473	0.720	0.418	0.532	− 0.273	− 0.288	− 0.177	0.256	0.249	− 0.360	− 0.249	− 0.123	− 0.151	0.272	0.596	1.000				
Flow	0.018	− 0.003	0.049	0.124	0.132	0.090	− 0.129	0.028	0.089	0.214	0.236	0.212	− 0.382	− 0.120	0.146	0.013	1.000			
Discharge	0.412	0.377	− 0.066	− 0.070	− 0.046	− 0.147	0.080	0.217	0.222	− 0.035	0.106	0.251	0.204	0.353	0.184	0.269	0.004	1.000		
Rain	− 0.115	− 0.064	− 0.416	− 0.334	0.093	0.115	0.056	− 0.091	− 0.052	0.095	− 0.034	0.051	0.293	0.064	0.143	− 0.279	0.257	0.013	1.000	
NDWR	0.069	0.139	0.523	0.576	− 0.266	− 0.155	− 0.305	0.165	0.067	− 0.226	− 0.196	− 0.159	− 0.426	− 0.159	0.158	0.443	0.128	− 0.083	− 0.466	1.000