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Influence of Rainfall on Cyanobacterial Bloom in Daechung Reservoir

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The water quality and algal communities in the Daechung Reservoir, Korea, were monitored from summer to autumn in 1999 and 2001. Although the average weekly precipitations during June and July were very similar in 1999 and 2001, they were much different during August and September, the so-called blooming season. The rainfall in 1999 increased about 70% after late August, whereas it decreased to the one-fifth level in 2001. The higher concentrations of chlorophyll-*a*, phycocyanin, and cyanobacteria were observed in 2001, which resulted in the dense algal bloom. In addition, in 2001, the cyanobacterial percentage remained above 80% during the investigation period, and the cyanobacteria were exclusively composed of *Microcystis* spp. Conversely, there was no report on the algal bloom in 1999. However, the peak bloom seasons were the same for both years, from late August to early September, irrespective of the amount of precipitation. These results suggest that the magnitude and duration of rainfall before bloom season are important factors determining the extent of cyanobacterial bloom in this system.

Key words : Asian monsoon, bloom, cyanobacteria, Daechung Reservoir, rainfall

INTRODUCTION

Algal blooms, particularly from cyanobacteria, are common phenomena in eutrophic lakes and ponds all over the world. Accordingly, the physiology and ecology of cyanobacteria have been extensively investigated due to their induction of serious environmental problems, such as a decreased recreational value, increased cost of water treatment, and the production of toxic and malodorous compounds (Falconer, 1994). The predominance of cyanobacteria over other algal species is attributed to their competitively advantageous characteristics: vertical migration (Reynolds, 1987), excessive accumulation of nutrients (Watson *et al*., 1997), and defiance against zooplankton grazing (Porter, 1977).

Environmental factors also influence the period and severity of cyanobacterial blooms. In particular, large and small-scale meteorological conditions both determine the composition and succession of the plankton community. For example, the North Atlantic Oscillation (NAO) was recently found to drive the changes of weather patterns and plankton dynamics in Europe (Straile and Adrian, 2000). The NAO is a global oscillation of the atmospheric mass between the North Atlantic regions of subtropical high surface pressure and subpolar low surface pressure. A strong connection between water temperature, the aquatic food-web, and the NAO has already been established (Straile, 2000). In a small-scale meteorology, previous studies have demonstrated that the phytoplankton composition varied depending on the amount of summer precipitation in the Daechung Reservoir, which is under the influence of the Asian monsoon (An and Jones,

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2000). In 1993, diatoms dominated the Daechung Reservoir as a result of a strong monsoon, whereas cyanobacteria comprised over 80% of the total algal numbers with a weak monsoon in 1994.

Therefore, the current study compared the algal compositions in 1999 and 2001, as the rainfall patterns were quite different between the two years. In 1999, the total precipitation was within the average range, yet in 2001, it was lowest since the dam construction in 1980. Since the Korean government established "the alert system for algal bloom" in 1997, "outbreak", the highest state of the alert system, was first and uniquely declared in the Hoenam region of the Daechung Reservoir for 7 days in 2001, the year with the lowest precipitation. Meanwhile, even the lowest phase of the algal alert system was never declared in 1999. Thus, the current study was to evaluate the influence of rainfall on algal composition and water quality.

MATERIALS AND METHODS

Sampling

The Daechung Reservoir, located in the middle stream of the Geum River (36° 50′N, 127° 50′E), is a large branch-type lake that is influenced by the Asian monsoon. From June to October in 1999 and 2001, water samples were collected at weekly intervals from the surface water within 1 m. The sampling was performed from a floating wharf, 30 m offshore, near the Daechung Dam. The water temperature, pH, conductivity, and dissolved oxygen (DO) were also measured at the site using YSI meters (63/100 and 95/100 FT, YSI Inc., Yellow Springs, OH). All other chemical and biological measurements were conducted in the laboratory, after transfer on ice.

Water analyses

The chlorophyll-*a* (Chl-*a*) was extracted using a chloroform-methanol mixture (2 : 1, v/v) and measured with a fluorometer (Turner 450, Barnstead/Thermolyne, Dubuque, IA) (Wood, 1985). The phycocyanin was measured using a spectrophotometer (UV-160A, Shimadzu, Kyoto, Japan) after extraction with 80% acetone and resuspension in a 0.2 M sodium acetate buffer (Myers *et al.*, 1978).

The algal cell numbers were counted using a Fuchs-Rosenthal counting chamber (Paul Marienfeld GmbH & Co., Lauda-Königshofen, Germany) under an optical microscope (Microphot-FXA, Nikon Corp., Tokyo, Japan). The data for precipitation and daily sunshine duration were obtained from the Korea Meteorological Administration.

RESULTS

The most striking difference among the environmental conditions was the rainfall between 1999 and 2001. The total precipitation in 1999 was 1,455 mm, which was within the annual average range for the Daechung Reservoir. However, the total precipitation in 2001 was only 835 mm, the lowest value since the construction of the Daechung Dam in 1980. In particular, the difference was more critical during the investigation period (Fig. 1). Before August 20, the weekly average precipitation for 1999 and 2001 was similar (P = 0.879), yet after August 21 it became quite different (P = 0.00046). In 1999, the rainfall increased after August 21, whereas in 2001, it decreased significantly. In September of 1999, the precipitation was 2.3 times greater than the September average for the previous 22 years. In contrast, the precipitation in September of 2001 was only 1/6 of the average.

These contrasting patterns of precipitation were also reflected in the daily sunshine duration

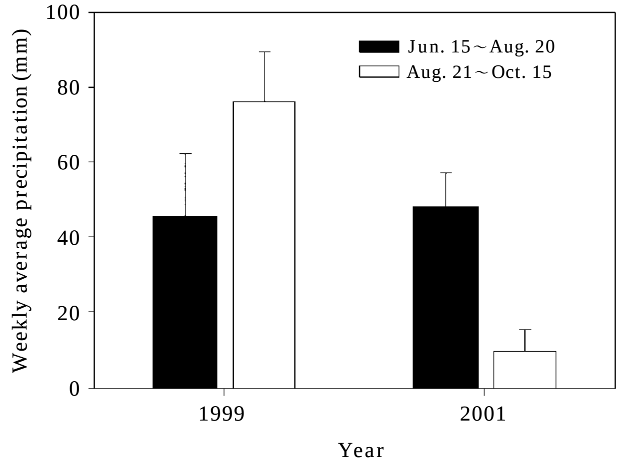

Fig. 1. Weekly precipitation patterns for 1999 and 2001. The period before and after August 21 indicate pre-bloom and post-bloom seasons, respectively. Error bars represent standard errors.

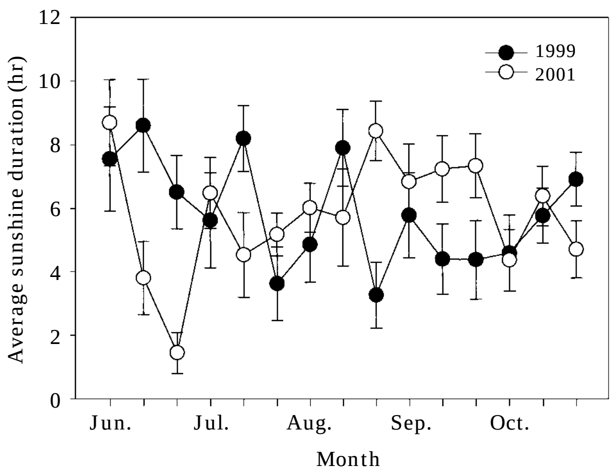

Fig. 2. Sunshine duration for 1999 and 2001. The averages of ten days for the daily duration are presented. Error bars represent standard errors.

(Fig. 2). From June to September in 1999, the sunshine duration decreased continuously with minor fluctuations. However, during the same period in 2001, the duration increased and remained relatively high for about 40 days from late August to September. As such, the low precipitation and high sunshine duration in the late summer of 2001 provided one of the most favorable environmental conditions for cyanobacterial growth. Conversely, the environmental conditions were more unfavorable for cyanobacterial growth in 1999, with the passage of the bloom season in late August.

Meanwhile, the changes in the water temperature were not so different, in spite of the completely different rainfall patterns (Fig. 3). The water temperature peaked in mid-August in both years. In addition, the pH, dissolved oxy-

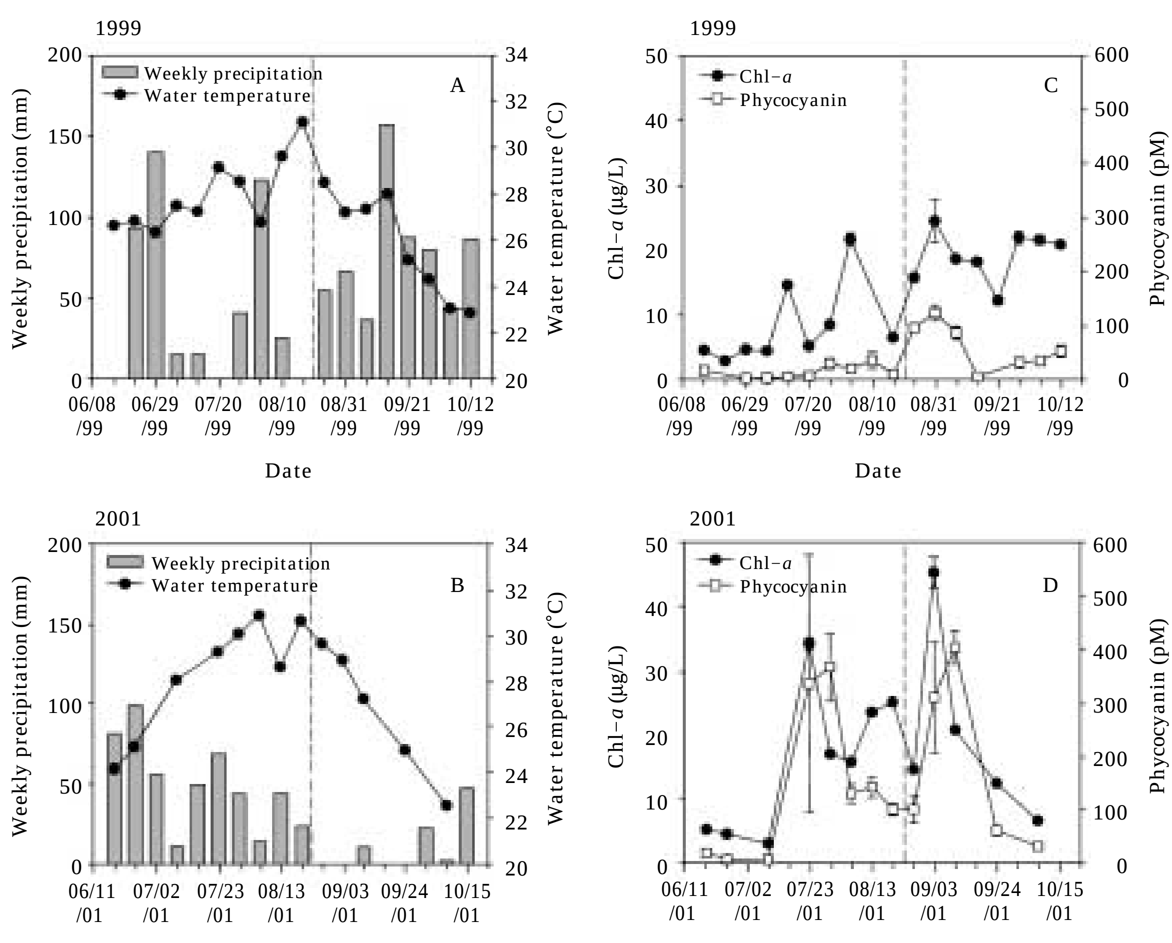

Fig. 3. Weekly precipitation and water temperature in 1999 (A) and 2001 (B), and concentrations of chlorophyll-*a* and phycocyanin in 1999 (C) and 2001 (D). The vertical dashed lines indicate the boundary between pre-bloom and post-bloom.

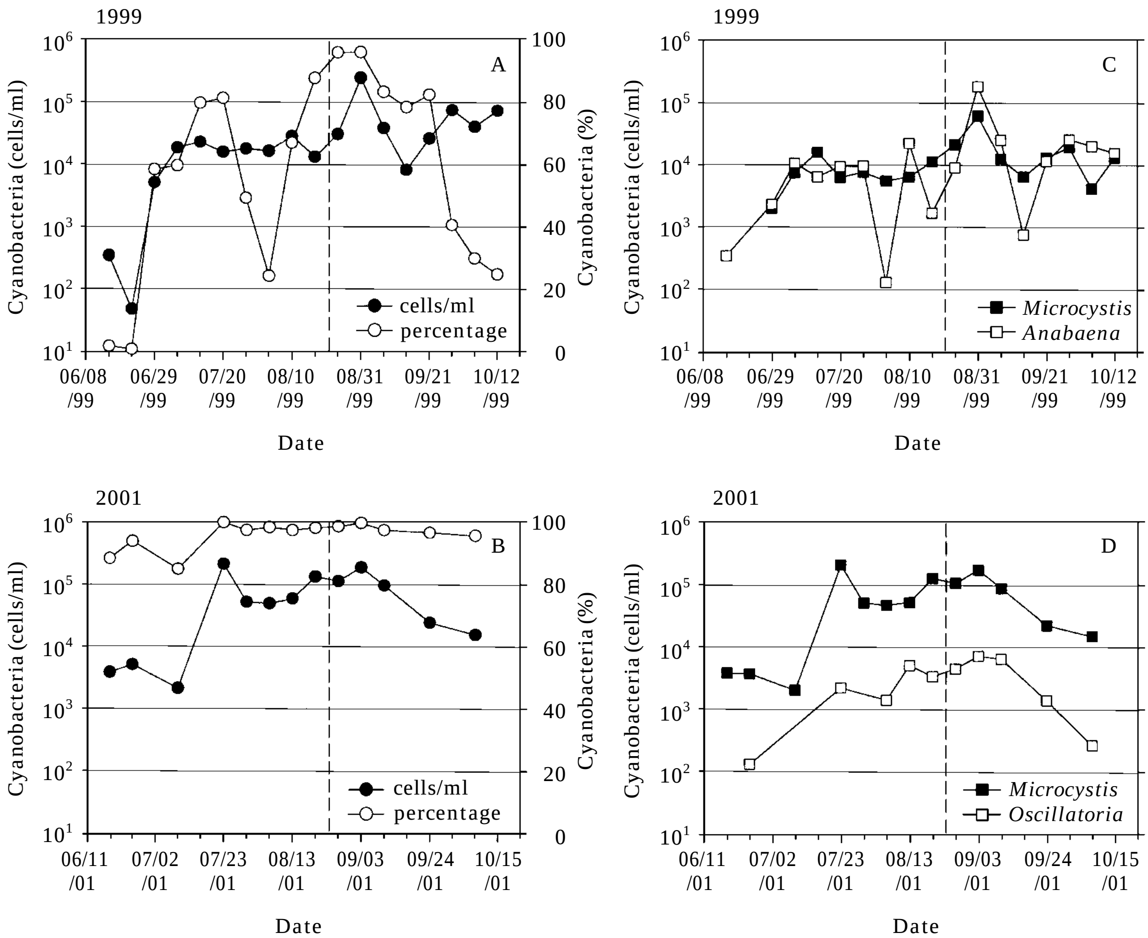

Fig. 4. Cyanobacterial cell number and percentage in 1999 (A) and 2001 (B), with two most dominant species in 1999 and 2001 shown in (C) and (D), respectively. The vertical dashed lines indicate the boundary between pre-bloom and post-bloom.

gen, and conductivity also reached their peaks about the middle of August and decreased thereafter (data not shown). The peaks for Chl-*a*, phycocyanin, and the cyanobacterial cell density overlapped on August 31, 1999 (Figs. 3 and 4), while in 2001 their peaks were on September 3, except for phycocyanin (September 10). Although the amounts of precipitation after August 21 were totally different between the two years, the general pattern of cyanobacterial blooms from late August to early September was common for both years.

Since the establishment of "the alert system for algal bloom" in 1997 in Korea, which can declare 3 levels of alert according to predetermined criteria (Table 1), the Chl-*a* and cyanobacterial cell numbers have never exceeded the alert criteria in 1999, yet an "outbreak" level of cyanobacterial bloom was declared in 2001 (Table 2). However, due to the use of different sampling sites, there are discrepancies in the measured concentrations of Chl-*a* and cyanobacteria between the current study and the alert system.

Table 1. Three levels of "the alert system for algal bloom" in Korea

Level	Chlorophyll-*a* (μg/L)	Cyanobacteria (cells/ml)	Monitoring interval (/week)
I. Caution	≥15	≥500	1
II. Warning	≥25	≥5,000	2
III. Outbreak	≥100	≥1,000,000	2

The concentrations of Chl-*a* and phycocyanin were much higher in 2001 and their peaks more outstanding compared to those in 1999. However, the Chl-*a* concentration in 1999 remained

Table 2. Long-term report of "the alert system for algal bloom"

Year	Level			Region
	Caution	Warning	Outbreak	
1997	Aug. 26-Nov. 29 (96 days)	–	–	–
1998	Sep. 9-Oct. 9 (31 days)	–	–	–
1999	–	–	–	–
2000	Oct. 4-Oct. 31 (28 days)	Aug. 10-Aug. 27 (18 days)	–	–
2001	Sep. 1-Oct. 5 (35 days)	Jul. 14-Aug. 3 (21 days) Aug. 11-Aug. 31 (21 days)	Aug. 4-Aug. 10 (7 days)	Hoenam
2002	Sep. 19-Oct. 4 (16 days)	–	–	Munui

*The bloom in the Daechung Reservoir was discriminated into 3 regions, Hoenam, Chudong, and Munui, since 2001.

relatively high even after late September, plus the phycocyanin concentration also increased during the same period, even though it was low. In contrast, these concentrations decreased abruptly in September of 2001.

The cyanobacterial cell density and percentage were greater in 2001 (Fig. 4). In particular, the cyanobacterial percentage remained above 80% throughout the entire period of sampling in 2001. However, greater fluctuation was observed in 1999 with a peak on August 31. In 1999, *Anabaena spiroides* and *Microcystis incerta* comprised about 74% and 20% of the cyanobacteria at the bloom peak, respectively. Meanwhile, *Microcystis aeruginosa* preeminently dominated in 2001, with *Oscillatoria* spp. occupying a minor proportion. Therefore, although there was no difference in the cyanobacterial dominance, the major species and relative abundance did vary, depending on the climatic conditions.

DISCUSSION

In 1997, Korea adopted "the alert system for algal bloom" to ensure the safety of drinking water. As such, if the Chl-*a* concentration and cyanobacterial cell number exceed certain predetermined criteria, three levels of alert can be declared according to the extent of cyanobacterial growth (Table 1). In the case of an alert, sampling frequency is increased for water quality conservation. Moreover, a variety of countermeasures are also executed to remove overgrown algae and prevent further bloom formation.

No algal bloom alert was announced in 1999. However, an "outbreak", the highest level of alert, was announced for the first time in 2001 (Table 2). Even though the cyanobacterial bloom was intense, the outbreak of severe cyanobacterial bloom was confined to the Hoenam region, the central part of the Reservoir, and not widely spread. However, in the current study, the measured Chl-*a* concentration and cyanobacterial cell number remained below the "outbreak" criteria (Figs. 3 and 4), as the sampling site was about 20 km downstream of the Hoenam region. The extreme difference in cyanobacterial blooms for 1999 and 2001 has mainly been attributed to the amount and time of precipitation.

An and Jones (2000) suggested that the intensity of the Asian monsoon could determine the magnitude, frequency, and composition of algal blooms. They compared seasonal patterns of taxonomic composition and size structure in algal communities between 1993 and 1994. The major differences in precipitation and sunshine duration between 1993 and 1994 were from June to August, when the mean monthly precipitation was 294.1 and 122.1 mm, respectively, and the mean sunshine duration was 4.6 and 8.1 hr, respectively. These differences in the intensities of the Asian monsoon resulted in contrasting algal compositions for the two years.

Oh and Kim (1995) reported the importance of precipitation in the formation of cyanobacterial bloom in the Daechung Reservoir. The Chl-*a* content was affected by the time of precipitation that might bring a lot of phosphorus from the catchment area (An, 2000). The cyanobacterial bloom appeared about 5 days after a heavy rain at Dam site.

The primary differences in precipitation and sunshine duration between 1999 and 2001 lasted from August to September. The difference in precipitation during this period was more critical, as the mean monthly rainfall in 1999 was 281.3 mm, whereas in 2001 it was only 51.7 mm. The sunshine duration for 1999 and 2001 was 5.1 and 7.0 hr, respectively. The climatic pattern in 1993 was very similar to that in 1999. The weak monsoon in 1994 was also similar to that in 2001. Yet, despite such similarities, there were also important dissimilarities. The interannual differences in the environmental factors in 1993 and

1994 corresponded to the pre-bloom period, while in 1999 and 2001 these differences corresponded to the post-bloom period. Whereas the disparities in the environmental conditions before bloom formation resulted in the dominance of entirely different taxa in 1993 and 1994 (An and Jones, 2000), the different environmental conditions in late summer led to a relatively similar algal composition, although only in the different degrees of cyanobacterial growth.

Accordingly, from the results of the above 4 years, it can be concluded that the peaks of algal bloom generally occur from late August to early September, regardless of the amount of precipitation. Although a large difference in precipitation before the bloom season brought about the dominance of quite different taxa, a difference just after the bloom season did not lead to a totally different taxonomic composition. Furthermore, a greater rainfall during the blooming season also decreased the cyanobacterial abundance by disturbing favorable environmental conditions for cyanobacterial growth.

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<국문적요>

대청호에서 남조류 수화 현상에 대한 강우의 영향

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1999년과 2001년, 여름부터 가을까지 대청호의 남조류 수화현상에 대한 강우영향을 조사하였다. 두 해의 6, 7월 강수량은 매우 유사하였으나, 수화발생 시기인 8, 9월의 강수량은 현저한 차이를 보였다. 1999년에는 8월 하순 이후 그전 2개월에 비해 약 70%의 강수량 증가가 있었으나, 2001년에는 같은 기간 동안 5분의 1 수준으로 감소하였다. 더 높은 엽록소-*a*, 파이코시아닌, 남조류 농도가 2001년 측정되었으며, 이것은 극심한 수화의 발생으로 이어졌다. 또한 2001년에는 조사기간동안 남조류의 비율이 항상 80%를 상회하였으며, 남조류는 *Microcystis* spp.가 대부분을 차지하였다. 이와는 반대로 1999년에는 수화의 발생이 보고되지 않았다. 이러한 차이에도 불구하고 수화가 절정을 이루는 시기는 두 해 모두 8월 하순에서 9월 초순으로, 강수량에 관계없이 일정하였다. 수화 이전 시기의 적당한 강수와 이후의 충분한 일조 시기가 남조류의 수화 형성에 영향을 끼치는 중요인자들 중의 하나로 판단되었다.