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Primary Research Paper

Relationships between cyanobacterial production and the physical and chemical properties of a Midwestern Reservoir, USA

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Abstract

Drinking water reservoirs in agricultural dominated watersheds are particularly vulnerable to cyanobacterial blooms. A major byproduct of cyanobacteria is the production of objectionable taste and odor compounds such as geosmin. During May 1997 to September 1998, we studied spatial and temporal patterns of cyanobacterial abundance and composition with respect to a series of physical and chemical properties in Clinton Lake, located in east central Kansas, USA. Our results suggest that nutrients (in particular TN, NO_3–N concentrations), turbidity, and hydrologic regime all played potentially important roles in regulating cyanobacterial production. Specifically, low levels of nitrogen coupled with the internal release of phosphorus from the lake sediment under brief periods of anoxia may have helped promote cyanobacterial blooms. There was also a strong association between cyanobacterial blooms, geosmin production, and most taste and odor events in Clinton Lake. *Anabaena circinalis* appeared to be the source for geosmin production as a result of senescing algal cells just after the primary die-off of cyanobacteria.

Introduction

Reservoirs in agriculturally dominated watersheds are particularly vulnerable to eutrophication. One of the most detrimental consequences of eutrophication is the development of cyanobacterial, or blue-green algae, blooms (Downing et al., 1999; Smith, 2003). Nuisance cyanobacterial blooms are common in drinking water reservoirs, and have been associated with the occurrence of objectionable taste and odor events (Saadoun, 1999; Smith et al., 2002). For example, several taxa of cyanobacteria (i.e. *Anabaena* and *Aphanizomenon*) produce metabolites such as geosmin that cause drinking water to taste and smell unpleasant (de Noyelles et al., 1999; Saadoun, 1999). Based on this relationship between cyanobacteria and objectionable taste and odor compounds, it is apparent that our ability to prevent future objectionable events depends in part on our understanding of the ecological conditions that favor cyanobacterial growth (Elser, 1999; Smith et al., 2002). If these conditions are known, lake and watershed management plans can be implemented to target and control the factors favoring cyanobacterial growth so that there is a long-term reduction in the occurrence of objectionable taste and odor events in drinking water reservoirs.

In controlling eutrophication and cyanobacterial production in lakes and reservoir, a number of studies and management efforts have focused on the relative concentrations of two important growth limiting nutrients, nitrogen (N) and phosphorus (P), (Smith, 1983; Havens & Walker, 2002; Walker & Havens, 2003). Nutrient enrichment often leads to increases in algal biomass (Jones & Knowlton, 1993), and in particular cyanobacterial production and dominance (Downing et al., 1999). Furthermore, many additional factors including seasonal fluctuations in solar light intensity, increased water column stability, and increased temperature are associated with cyanobacterial production (reviewed by Hyenstrand et al., 1998). Elucidating which of these mechanisms, or combination of mechanisms, regulates cyanobacterial production in a particular lake or reservoir, is an important first step towards developing effective lake and watershed management strategies (Smith et al., 2002).

In this study we assessed temporal and spatial patterns of cyanobacterial production in Clinton Lake, a multiple function drinking water reservoir located near Lawrence, Kansas. A series of biological, chemical, and physical data was collected from the reservoir at multiple sites over an 18-month study period. The objectives of this study were to determine (1) temporal and spatial patterns in the relationships between water quality and cyanobacterial growth, (2) the role of hydrologic patterns in structuring cyanobacterial growth, and (3) relationships between cyanobacteria and geosmin production in Clinton Lake. In addition, we discuss the implication of our results with respect to management strategies for Clinton Lake and other drinking water reservoirs.

Materials and methods

Study area and site description

Clinton Lake, located 15 km west of Lawrence, Kansas (Fig. 1), was constructed by the Army Corp of Engineers in 1977 and reached its multi-purpose pool level by 1980. The reservoir is a large (30.81 km^2) multiple function reservoir with an average depth of 5.1 m (Fig. 1). The reservoir has a normal pool surface of 2,833 ha that can be extended to 5180 ha during flood control operations. The hydraulic retention time, based on the rate of abstraction to volume, is approximately 0.82 years. The watershed of Clinton Lake encompasses nearly 95,320 ha and agriculture is the predominant land-use within the watershed. Nearly 88% of the land within the watershed is used for grasslands (such as pasture and hay field) and cultivated cropland, and the remaining 11% is devoted to forests and commercial/industrial uses (Wang et al., 1999).

Annual precipitation was 873 mm in 1997 and 1,196 mm in 1998 as compared to a historical average of 919 mm from 1990 to 1998. Seasonal air temperature pattern differed very little between 1997 and 1998. Typically, the temperature increased from January, reached the maximal level in July and decreased gradually toward December. By contrast, wind intensity increased in spring (April–June) and mid-summer to fall (September to December).

Reservoirs exhibit distinct longitudinal gradients in their physical, chemical, and biological properties due to their river-lake hybrid nature (Kimmel et al., 1990). In order to characterize these gradients, 12 sampling sites based on lake morphology (i.e., location and depth) were selected and divided into three general categories (riverine, transition, and lacustrine) (Fig. 1). The areas where the Wakarusa River, Deer Creek, and Rock Creek first become pooled into the reservoir were selected for the three river-like riverine sites (sites 1, 4, and 9). The transition area of the reservoir was represented by five sites (sites 2, 3, 5, 6, and 10) that were found in areas that exhibited characteristics of both river-like and lake-like sections of the reservoir. Finally, four open water, deep sites (sites 7, 8, 11, and 12) were selected to represent the lake-like lacustrine area. Detailed information of various sampling depths at each site has been documented in Wang et al. (1999).

Water quality and planktonic sampling

Each of the 12 sampling sites was sampled monthly (usually between 9:00AM and 5:00PM) from May to December 1997, and again from April to October 1998. Two additional sampling events were conducted during April and May 1998. To minimize possible diurnal variation in the water quality characteristics, the sites were consistently sampled in the same order from site 1, 2, 3, 4, 5, 6, 9, 10 to the lacustrine sites on each sampling event. Therefore, the sampling time at each individual site was relatively similar throughout the entire study period. For each sampling event, a 2 L Van-Dorn sampler was used to collect individual water samples at a series of discrete depths that were determined by the maximum depth at each site (surface/0.25 m, 1.5 m, 3 m, 6 m, and 10 m). These samples were returned to the Ecotoxicology Laboratory of the Kansas Biological Survey where they were analyzed for a number of water quality variables. Nutrient

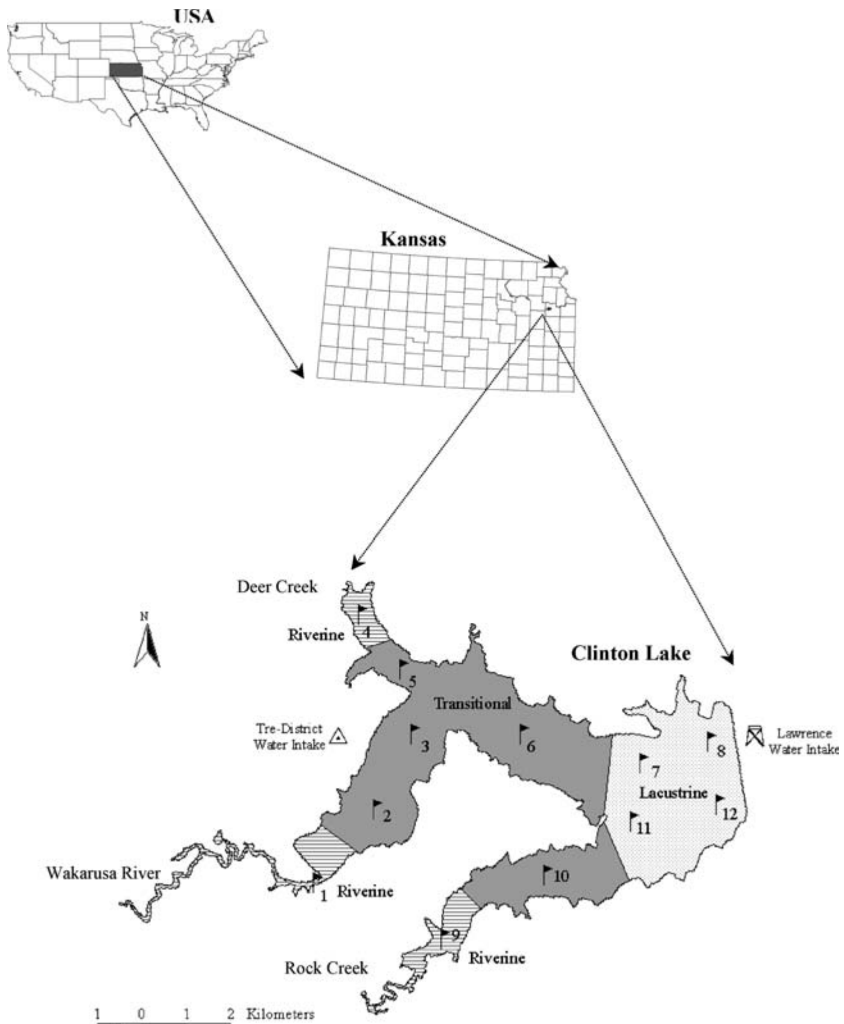

Figure 1. Map of sampling sites and location of Clinton Lake.

concentrations were determined colorimetrically (APHA, 1995) with a Lachat analyzer (Model 4200). Samples for NO_3–N, NO_2–N, NH_4–N, and PO_4–P were filtered through Gelman Sciences ion chromatography acrodisc filters (0.45 μm) before analysis. Total nitrogen (TN) and total phosphorus (TP) concentrations were determined using the automated colorimetric procedures after an acid persulfate digestion (Ebina et al., 1983) of unfiltered samples and total alkalinity was measured titrimetrically with a calibrated pH meter (AHPA, 1995). All nutrient analysis was performed within 48 h of sample collection.

The chlorophyll *a* extractions and concentration determinations were carried out by first filtering the algae from the sample through a Whatman GF/F glass fiber filter. The filter was folded in fourths with forceps, placed in a small vial, capped, and frozen to disrupt the cells. The chlorophyll *a* was extracted using 90% basic methanol (10% saturated $MgCO_3$). After at least 24 h the concentration of chlorophyll *a*, corrected for pheophytin *a*, was determined by measuring the fluorescence of the sample with the Optical Technologies fluorometer before and after acidification (APHA, 1995). This fluorometer had previously been calibrated using standard solutions made from pure chlorophyll *a* (Sigma Chemical Co.) with the concentration verified spectroscopically (APHA, 1995).

In addition, *in situ* measurements of air and water temperature, dissolved oxygen (DO), specific conductance, turbidity, and pH were concurrently measured at the same depths using a Horiba U-10 Water Quality Checker (Horiba, 1991). A Secchi disk was used to measure transparency at each site. The depth of mixing zone (Z_{mix}) was determined from temperature profiles whereas euphotic depth (Z_{eu}) was determined from light profiles collected using a photometer. The ratio of Z_{mix} to Z_{eu} was used as a turbidity index in the mixing zone.

Phytoplankton samples were collected at the surface (0.25 m depth) at each site and preserved in Lugol's solution. Five ml of each phytoplankton sample was settled for a minimum of 24 h and taxa were counted using 30 random non-overlapping fields with an inverted microscope that was calibrated using 40 × objective field and area of Whipple grid (APHA, 1995). A previous study of the algal community in Clinton Lake in 1995–1996 indicated that cyanobacteria were the major contributors to taste and odor problems (written communication with Stamer, Utilities department, City of Lawrence). Therefore, in the present study, cyanobacteria were the only algal taxa that were identified and enumerated. Furthermore, only three cyanobacterial taxa were identified in the algal samples based on the results of an earlier study that indicated that these three taxa accounted for the majority of total cyanobacterial biovolume in Clinton Lake (Meyer, 1998).

Multi-depth phytoplankton samples collected in October 1997 indicated that the majority of algal biomass was located near the lake surface. For example, cyanobacterial biovolume was1.4–1.8 times greater at the surface (0.25 m) than at 1.5 m in the lacustrine zone. In addition, cyanobacterial biovolume in the lacustrine zone was similar between the surface and 1.5 m, which had three times the biovolume of the 3.0-m depth and deeper (deNoyelles et al., 1999).

For this study, total geosmin data was obtained from the Department of Utilities, City of Lawrence where the samples were taken at the city's source water intake near site 8 (see Fig. 1) and analyzed at a certified laboratory according to APHA standard methods (6040B, 1995) while lake water level data was obtained from the Water Management Office, Kansas City District Corps of Engineers.

Statistical analysis

Water quality parameters measured at each site were individually averaged for all depths to characterize each parameter and its association with cyanobacterial communities. Data from each of the sites representing a particular area of the reservoir (riverine, transition, or lacustrine) was then integrated and used for data analyses. One-way ANOVA was used to identify significant differences between the three reservoir zones, and Tukey's HSD ($p = 0.05$) was used to make *post hoc* comparisons between the three areas when significant differences were detected (Minitab version 12.2). Regression analysis between physicochemistry variables was performed using SigmaPlot (Windows version 8.0).

Results

Physical characteristics

The highest water temperature values were observed in July, averaging 29.3 °C for the riverine sites, 28.8 °C for the transitional sites, and 27.4 °C for the lacustrine sites (Table 1). In June 1997, temperature stratification was present at most of the lacustrine sites. A thermocline was consistently observed at a depth of approximately 6 m. As the air temperature increased, the stratified layers became obscure. By September, the reservoir was mixed or homeothermic due to colder temperatures and increased wave actions associated with fall conditions. Although similar patterns in water temperature were observed during late May 1998, no thermocline was observed in the reservoir as outflow was discharged as a result of high inflows received from the watershed.

Low Secchi depth values coincided with increased turbidity due to runoff events. Maximum values, or clear-water phases, appeared in June 1997, and late May and September 1998 (Fig. 2). Secchi depth values were significantly different between the riverine, transitional and lacustrine areas, averaging 35, 61, and 90 cm, respectively (Table 1). Changes in Secchi depth values correlated with turbidity; as turbidity increased, Secchi depth decreased ($R = -0.59$, $p < 0.0001$). Secchi depth values were also negatively related to Z_{mix}/

Table 1. Limnological characteristics of the three zones of Clinton Lake

Variable	Unit	Riverine	Transition	Lacustrine	p
PH		7.7 (0.2)	7.9 (0.2)	7.8 (0.3)	0.134
Temperature	°C	20.4 (8.0)	20.1 (7.8)	19.7 (7.2)	0.968
Specific conductance	$\mu S\ cm^{-1}$	382.5 (61.2)	355.4 (54.1)	353.8 (46.5)	0.253
DO	$mg\ l^{-1}$	7.3 (2.2)	8.0 (2.1)	7.3 (7.6)	0.585
Turbidity	NTU	83.4 (51.7)[a]	45.8 (23.4)[b]	29.4 (15.6)[b]	< 0.001
Secchi depth	cm	35 (13)[a]	60 (18)[b]	98 (31)[c]	< 0.001
TN:TP		8.2 (3.2)[a]	9.84 (3.0)[a]	13.90 (5.1)[b]	< 0.001
TN	$mg\ l^{-1}$	0.83 (0.25)[a]	0.64 (0.18)[b]	0.57 (0.13)[c]	< 0.001
NH_4–N	$\mu g\ l^{-1}$	39.2 (50.6)	35.2 (36.6)	42.9 (31.4)	0.865
NO_3–N	$mg\ l^{-1}$	0.20 (0.25)	0.16 (0.16)	0.21 (0.16)	0.811
TP	$\mu g\ l^{-1}$	109.1 (33.1)[a]	68.0 (16.0)[b]	43.6 (10.2)[c]	<0.001
PO_4–P	$\mu g\ l^{-1}$	13.9 (9.4)	11.4 (5.7)	10.5 (6.4)	0.398
Chlorophyll *a*	$\mu g\ l^{-1}$	33.6 (16.9)[a]	19.2 (8.8)[b]	11.1 (7.5)[c]	<0.001
Cyanobacteria	$\times 10^5\ \mu m\ ml^{-1}$	1.1 (2.0)[a]	3.4 (5.9)[b]	3.5 (5.9)[b]	0.036

Each value represents a study average (±SD). All data was logarithm transformed, except for pH and specific conductance, and compared using one-way ANOVA. Statistically significant differences between the reservoir zones are represented by different letters.

Z_{eu}, with correlation coefficients of −0.79 for the transitional zone and −0.96 for the lacustrine zone ($p < 0.0001$).

Nutrient conditions and general water chemistry

Total phosphorus concentrations generally ranged between 30 and 100 $\mu g\ l^{-1}$. For a given sampling event, TP concentrations were highest in the riverine sites, sometimes by more than twofold, indicating that inflow from the watershed was a major source of nutrients into the reservoir. It may also indicate a combined effect of wind-driven resuspension of sediment in the shallow sections of the lake and dilution of the inflow as it entrains ambient reservoir water and/or settling of TP

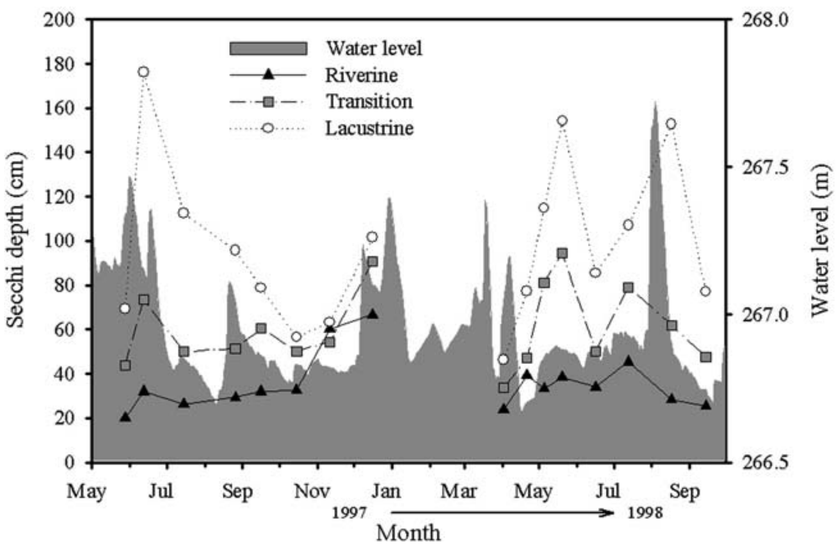

Figure 2. Monthly Secchi depth and daily water level values for the riverine, transition, and lacustrine zones at Clinton Lake during 1997–1998.

particles in the deeper sections of the reservoir. Total N concentrations were consistently above 350 μg l^{-1}, and above 600 μg l^{-1} for roughly half of the sampling events. Both concentrations of TN and TP exhibited a down gradient trend with concentrations decreasing from the riverine to the lacustrine areas (Fig. 3). Likewise, NO_3–N, NH_4–N, and PO_4–P, the principal dissolved forms of N and P, displayed longitudinal gradients in the reservoir with the riverine areas having the highest concentrations. However, TN:TP ratios showed an opposite spatial trend. On average, TN:TP ratios were 8 for the riverine, 10 for the transitional, and 14 for the lacustrine areas. In general, TN:TP ratios were high in the spring and decreased in the summer and gradually increased in the fall.

The seasonal patterns of specific conductance were similar for the transitional and lacustrine sites, which followed the same pattern observed for the riverine sites. The water column in the

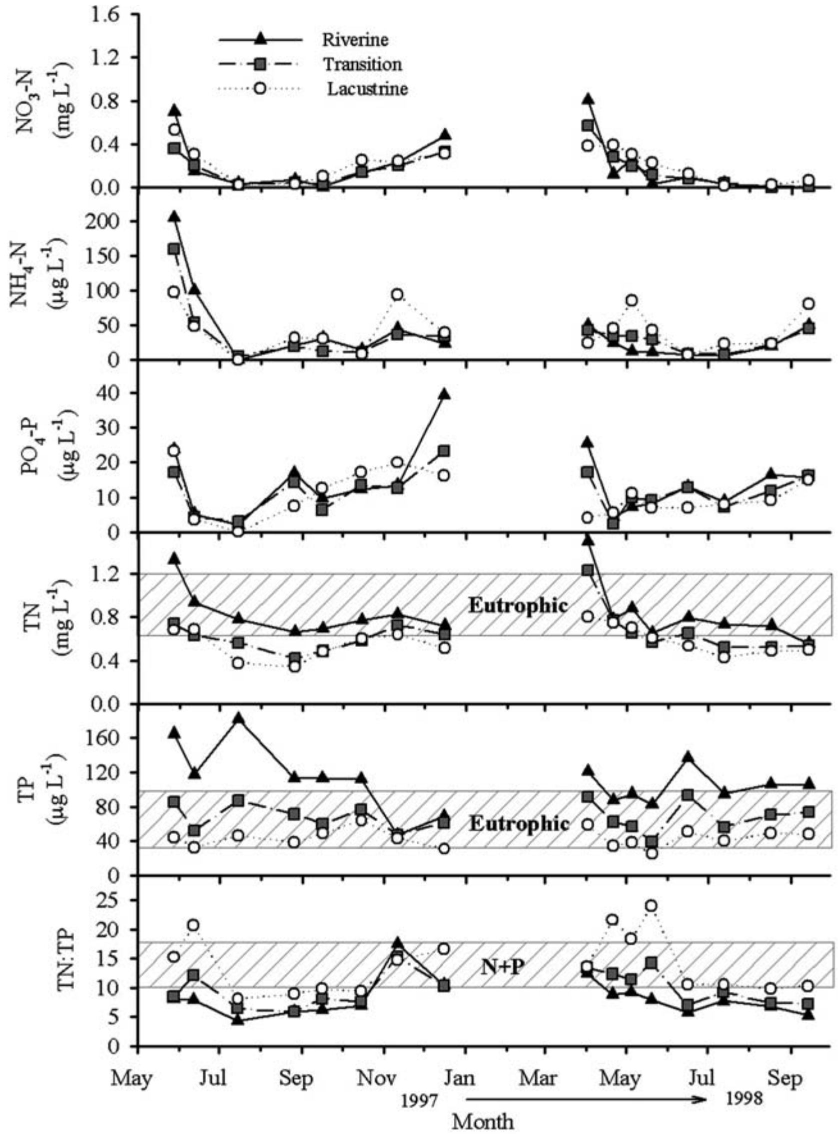

Figure 3. Concentrations of nutrients (NO_3–N, NH_4–N, PO_4–P, TN, and TP) for the riverine, transition, and lacustrine zones at Clinton Lake during 1997–1998. Eutrophication and nutrient limitation criteria were used based on US EPA (1988) and Smith (1998), respectively.

near-bottom had slightly higher values than the surface water in the months when anoxic conditions were present. The highest monthly conductance values (440 and 422 μS cm^{-1} for the transitional and lacustrine sites, respectively) were observed in May 1997 soon after spring runoff events occurred, whereas the lowest values appeared in August 1997, with average of 269 μS cm^{-1} for the transitional area and 285 μS cm^{-1} for the lacustrine area (Fig. 4).

The monthly average DO concentrations during the study period ranged from 4.6 to 11.2 mg l^{-1} for the riverine sites, 5.5–12.2 mg l^{-1} for the transitional sites, and 3.6–12.9 mg l^{-1} for main basin sites. Typically, DO concentrations stratified with depth at the lacustrine sites from June through August, and anoxic conditions (0 mg l^{-1}) occurred at the bottom of the reservoir (Fig. 5). pH values exhibited patterns similar to the DO concentrations, with higher values observed in the transition sites than elsewhere in the reservoir (Fig. 4). In general, pH values tended to decrease in the summer.

Variations in phytoplankton biomass

Chlorophyll *a* (corrected for pheophytin *a*) is considered to be one of the most valuable biological

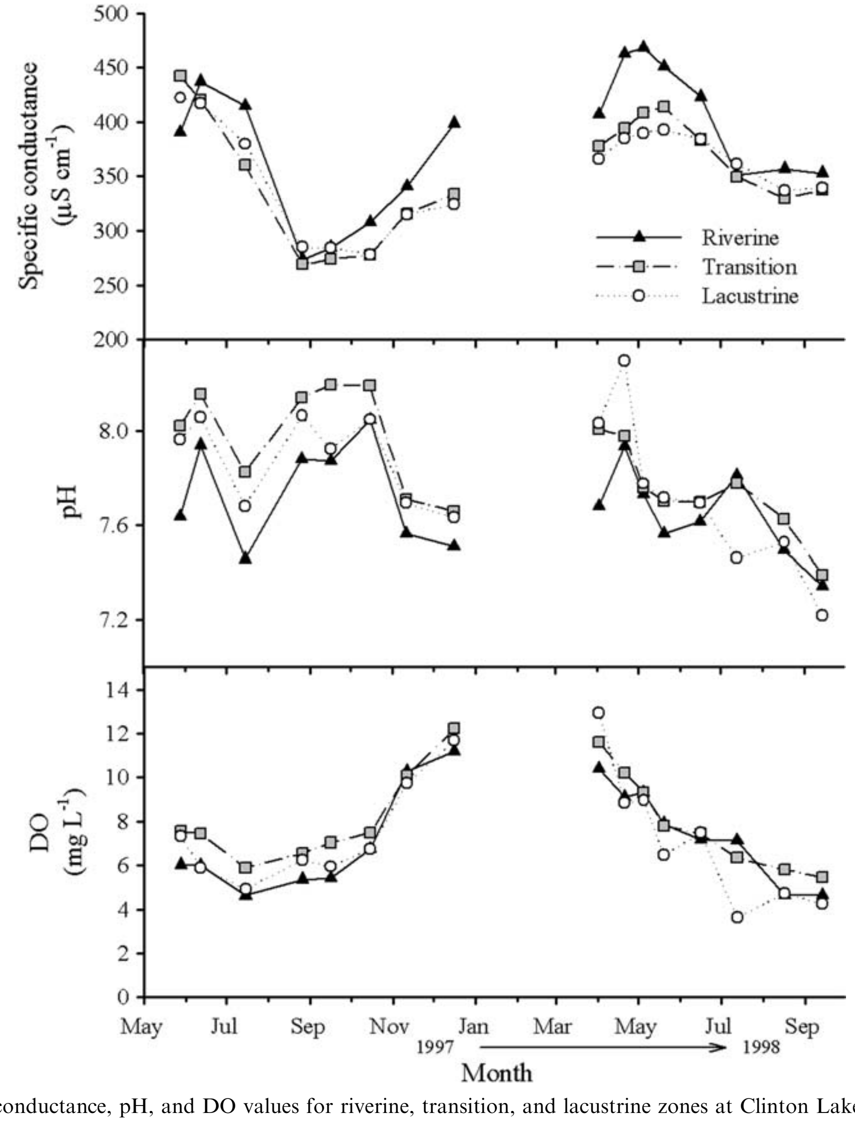

Figure 4. Specific conductance, pH, and DO values for riverine, transition, and lacustrine zones at Clinton Lake during 1997–1998.

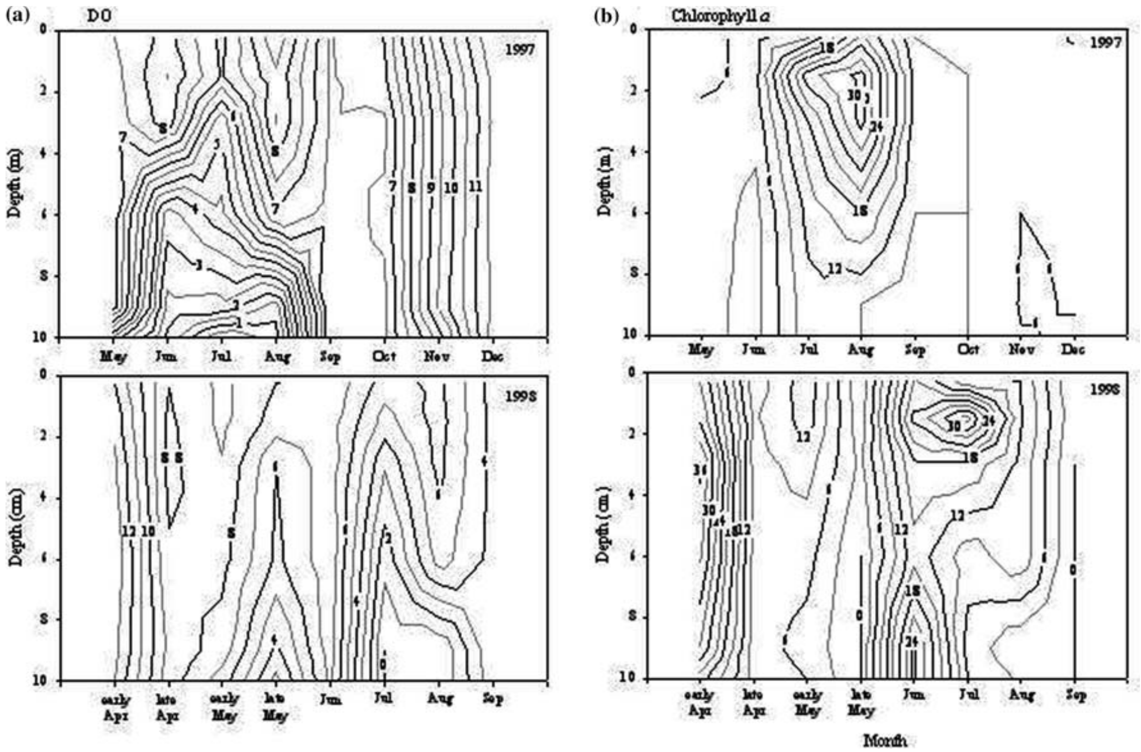

Figure 5. Vertical profiles of (a) DO levels and (b) chlorophyll *a* concentrations at site 8 during 1997–1998.

parameter because it provides an estimate of overall reservoir productivity and information regarding recreational desirability. In 1997–1998, the highest chlorophyll *a* concentrations were typically observed in July when the temperature was warmest, and then decreased as the temperature decreased. Because of nutrient influxes from the watershed, the shallow riverine sites tended to have high chlorophyll *a* concentrations (Fig. 6). During the periods of July–August 1997 and June–July 1998, a clear profile occurred in most of the main basin sites (Fig. 5). Although the lake was thermally stratified in June 1997, this stratification did not impose significant effects on the vertical phytoplankton profile because light limitation was an important factor affecting the algal communities.

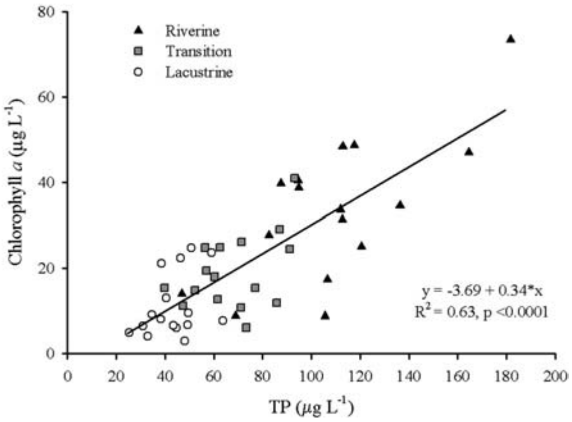

Figure 6. Relationships between chlorophyll *a* values and TP concentrations at Clinton Lake.

Cyanobacterial abundance and composition

Cyanobacterial biovolume in the surface waters of Clinton Lake during the period from May 1997 to September 1998 ranged from approximately 0 to 7.46×10^5 μm^3 ml^{-1} in the riverine zone, 131 to 2.45×10^6 μm^3 ml^{-1} in the transitional zone, and 491–1.89×10^6 μm^3 ml^{-1} in the main basin zone. The average cyanobacterial abundances in the transitional (3.40×10^5 μm^3 ml^{-1}) and main basin zones (3.51×10^5 μm^3 ml^{-1}) were not significantly different. However, there was a significant difference in cyanobacterial abundances between the riverine (1.12×10^5 μm^3 ml^{-1}) and transitional and lacustrine zones ($p < 0.05$). Peak cyanobac-

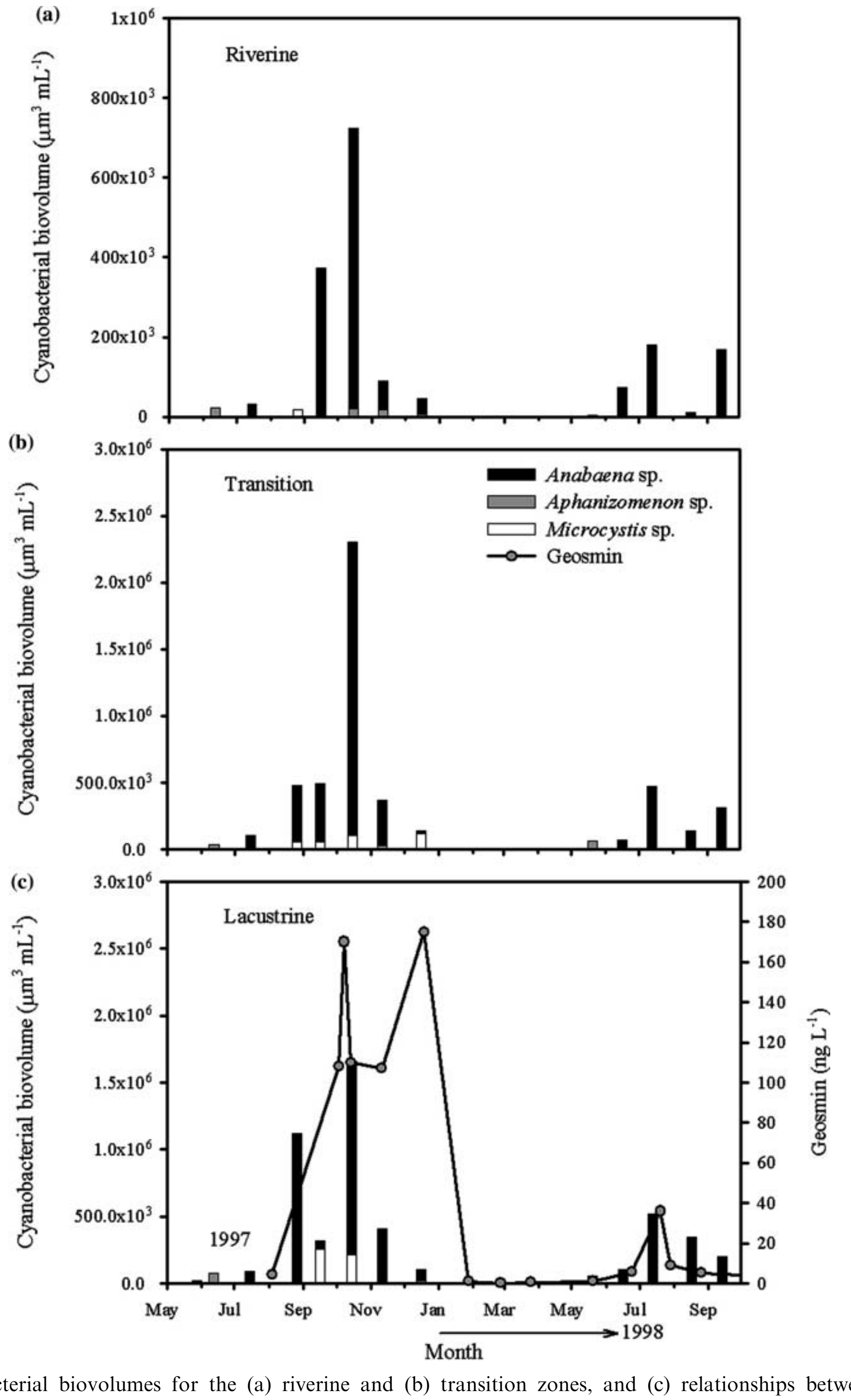

Figure 7. Cyanobacterial biovolumes for the (a) riverine and (b) transition zones, and (c) relationships between cyanobacterial biovolumes and geosmin concentrations for the lacustrine zone.

terial abundances in 1997 were on average four-fold, five-fold, and four-fold higher than in 1998 for the riverine, transitional, and main basin zone, respectively.

Seasonal trends in cyanobacterial community composition existed throughout the course of the study (Fig. 7). *Microcystis* sp., *Aphanizomenon* sp., and *Anabaena* sp. were the dominant taxa identified in the reservoir. While *Aphanizomenon* sp. dominated in the late spring (May–June), *Anabaena* sp. were more abundant in the summer and in the early fall. *Anabaena circinali* was the predominant species, accounting for over 90% of the total biovolume during the period from June to October. Detailed analysis of the composition of cyanobacterial populations in Clinton Lake was documented in Meyer (1998).

Variations in the concentrations of geosmin were closely related to increases in cyanobacterial biovolume (Fig. 7). In 1997, high geosmin concentrations were recorded in the months of October–December, with a maximal value (175 ng l^{-1}) measured in December. In contrast, concentrations in 1998 tended to be much lower (36 ng l^{-1} in July) coinciding with low cyanobacterial biovolume. During the rest of the study period, geosmin concentrations were below 5 ng l^{-1}, the detectable taste-and-odor concentration for human senses (per. comm. Randtke, Dept. Environmental Engineering, University of Kansas).

Discussion

The nutrient state of Clinton Lake is within the range typically reported for eutrophic lakes and

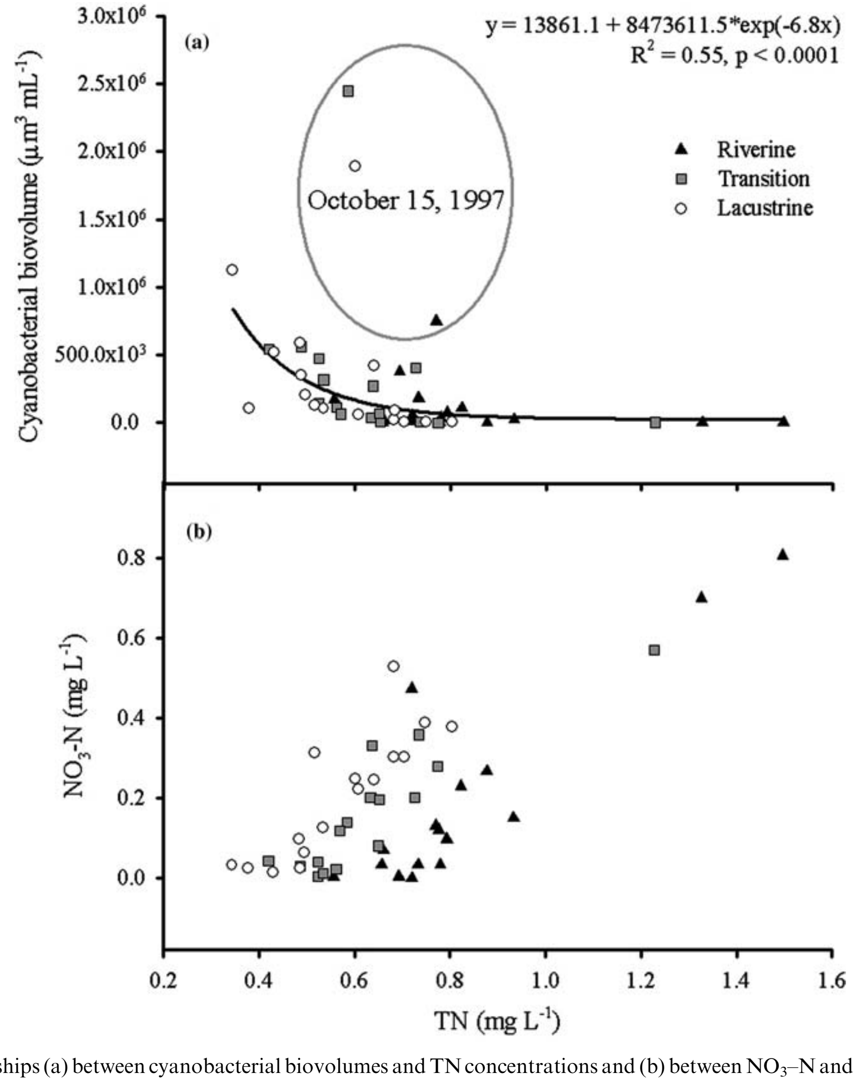

Figure 8. Relationships (a) between cyanobacterial biovolumes and TN concentrations and (b) between NO_3–N and TN at Clinton Lake.

reservoirs (US EPA, 1988; Wang et al., 1999) and is comparable to other Midwestern reservoirs (Walker, 1985; Jones & Knowlton, 1993; Smith et al., 2002). Large nutrient pulses in the spring at the shallow riverine sites (Fig. 3) were closely associated with runoff events (deNoyelles et al., 1999) and increases in chlorophyll *a* concentrations (Fig. 6). As the morphology of the reservoir changed from the riverine zone to the lacustrine zone, there was a longitudinal gradient in nutrient and chlorophyll *a* concentrations with lower values observed at the lacustrine sites. High chlorophyll *a* concentrations measured in the riverine zone were likely due to nutrient input from the watershed and frequent resuspension of sediment from both wind-driven mixing and disturbance by flow intrusion within this shallow zone. Nutrient enrichment is of particular concern in Midwestern reservoirs because it often leads to cyanobacterial production and dominance. Using nutrient data and additional physiochemical data, we were able to study the potential mechanisms facilitating cyanobacterial blooms in Clinton Lake.

Effects of nutrient availability

Nutrient availability helped to regulate cyanobacterial production in Clinton Lake. Considerable evidence suggests that nutrient conditions can facilitate dominance by cyanobacteria (Smith 1983; Downing et al., 1999; Smith et al., 2002). With the exception of October 15, 1997, there was a strong negative relationship between TN concentrations and cyanobacterial biovolume in Clinton Lake (Fig. 8). Cyanobacteria tend to have a competitive advantage in low N environments because taxa such as *Anabaena* sp. are able to fix N_2 (Van Baalen, 1987; Havens et al., 2003). Therefore, our data provides further support for the hypothesis that low TN and NO_3–N concentrations favor cyanobacterial dominance (Hyenstrand et al., 2000; Mataloni et al., 2000; Negro et al., 2000).

Influence of hydrological regime and stratification

While nutrient concentrations were important in facilitating cyanobacterial development, the hydrologic regime of the lake may have also played an important role. The appearance of cyanobacterial blooms occurred when the water level of the reservoir remained at a relatively consistent level with little and/or no flow being discharged from the dam (Oudra et al., 2002). During this period, the reservoir experienced a brief period of stratification and parts of the hypolimnion became anoxic potentially resulting in the internal release of nutrients from the sediment. This release of nutrients may have helped to further facilitate cyanobacterial blooms as has been reported in other waterbodies (Hyenstrand et al., 1998; Johnston & Jacoby, 2003). Figure 9 shows such an

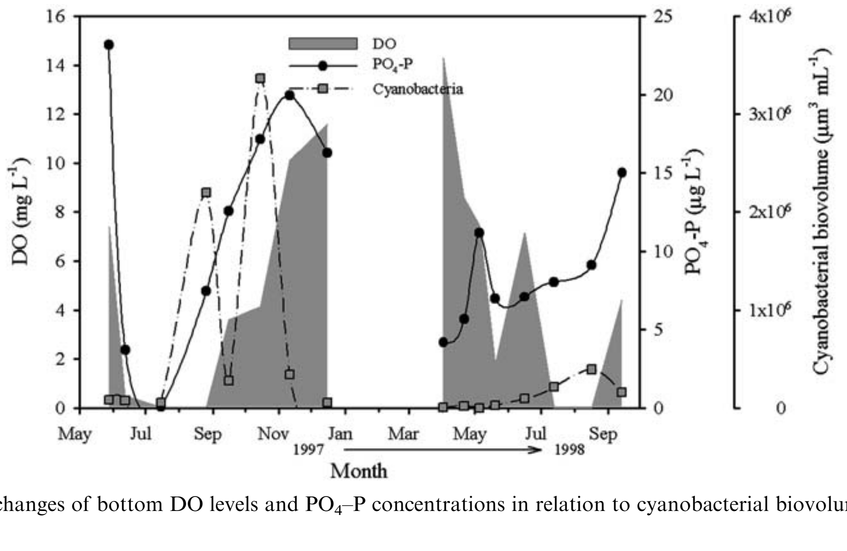

Figure 9. Monthly changes of bottom DO levels and PO_4–P concentrations in relation to cyanobacterial biovolume at Clinton Lake.

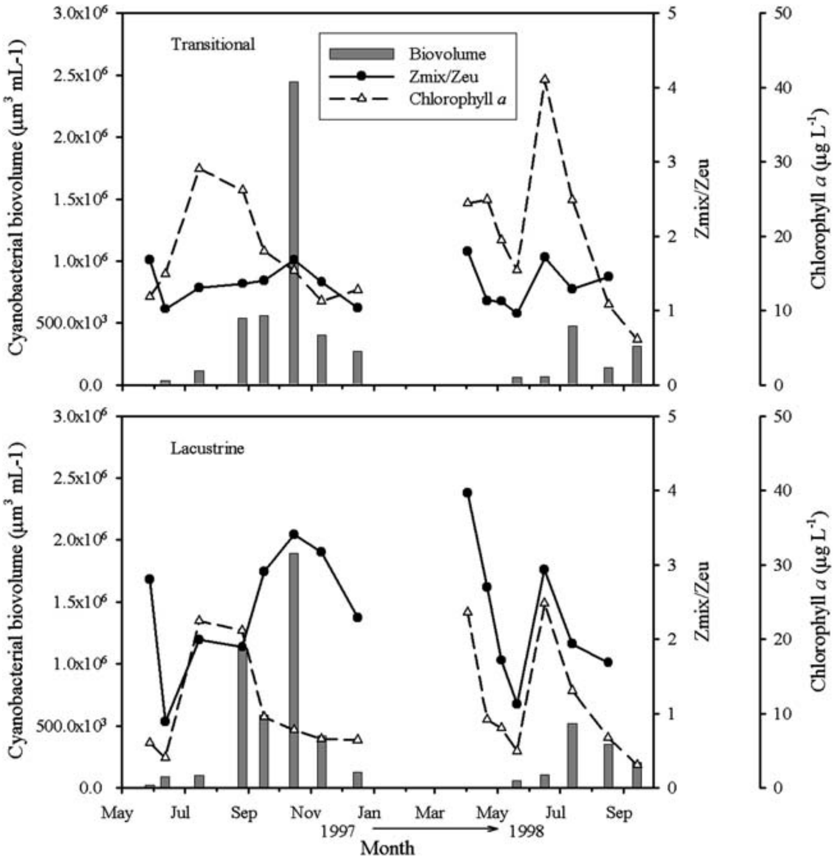

Figure 10. Monthly changes of cyanobacterial biovolume in relation to chlorophyll *a* concentrations and Z_{mix}/Z_{eu} values for (a) the transitional and (b) lacustrine zones at Clinton Lake.

example from site 12 of the main basin where anoxic conditions were observed in the hypolimnion. A recent study of internal nutrient regeneration conducted by the Kansas Biological Survey revealed that internal P-release rates under anoxic conditions in the lacustrine area (48 mg m^{-2} day^{-1}) were approximately three times higher than in the riverine area (18 mg m^{-2} day^{-1}) (unpublished data, 2003). The sediment survey conducted by the Army Corps of Engineers in 1991 also indicated that nearly all the sediment was settling in the conservation pool where the minimal water is stored for allocation (e.g., drinking water). Therefore, internal nutrient release may have played an important role in promoting cyanobacterial production in the lacustrine zone. Similarly, Johnston & Jacoby (2003) hypothesized that internal nutrient release was an important factor in fueling cyanobacterial blooms in a large lake in Seattle, Washington.

Following this brief period of stratification, the lake began to mix as wind speed and rainfall events increased, and temperature gradients were minimal in the early fall (Wang et al., 2000). Because no flow was discharged from the dam during this period, strong circulation patterns persisted within the lake as indicated by increased nutrients (Fig. 3), specific conductance (Fig. 4), suspended materials, and decreased Secchi depths (Fig. 2). As light is a limiting factor for algal growth, algal biomass (i.e., chlorophyll *a*) was reduced. However, the turbid conditions created by the wind disturbance may have been more favorable for cyanobacterial growth since some taxa have a greater tolerance for turbid conditions (Hyenstrand et al., 1998; Scheffer, 1998). As expected, increased cyanobacterial biovolumes appeared to be associated with high ratios of Z_{mix}/Z_{eu} in the later summer and fall (Fig. 10), except for in June 1998 where the high Z_{mix}/Z_{eu} ratio was likely attributable to hydrologic factors associated with runoff events (Fig. 2). In addition, there may have been a positive feedback in the reservoir with increased biovolume of cyanobacteria promoting more turbid conditions, which in turn, enhanced cyanobacterial growth (Hyenstrand et al., 1998). Presing (1996) found that low light conditions created by cyanobacterial blooms facilitated their persistence.

Hydrologic regime may have also played an important role in the decline of cyanobacterial populations. Sharp increases in both the water level and the amount of water that was discharged from the reservoir may have created a flushing effect that helped to disrupted cyanobacterial blooms (Figs. 2 and 8). For example, a noticeable decrease in cyanobacterial biovolume during September 1997 and August 1998 was primarily related to large runoff events from the watershed.

Relationships between geosmin and cyanobacteria

A major byproduct of cyanobacterial blooms observed in Clinton Lake was the occurrence of the organic chemical, geosmin, which in one of the most common causes of earthy/musty taste and odor problems in lakes and reservoirs. (Saadoun et al., 2001). *Anabaena circinalis* appeared to be the source for geosmin production as a result of senescing algal cells just after the primary die-off of cyanobacteria (Fig. 7). Taste and odor problems are common in Clinton Lake and other Midwestern drinking water reservoirs (Smith et al., 2002). For example, in December of 1995 a high number of customer complaints (46 phone calls) associated with drinking water led to a temporary shutdown of the City of Lawrence Clinton Lake Water Treatment Plant (per. comm. Stamer, Department of Utilities, City of Lawrence). Geosmin levels above 20–50 ng l^{-1} cannot be removed efficiently in most water treatment plants (per. comm. Randtke). As a result, residential taste and odor complaints increased in December of 1997 (39 phone calls).

Management implications and conclusions

The results of this study strongly suggest that there is a positive association between cyanobacterial blooms, geosmin production, and taste and odor problems in Clinton Lake. Therefore, identifying the causal factors related to cyanobacterial blooms is an important first step to managing taste and odor problems. Our data suggests that nutrients play an important role in regulating cyanobacterial production in Clinton Lake. Low nitrogen levels in combination with internal phosphorus inputs from the watershed and sediment may have created conditions that were favorable for cyanobacterial production. Furthermore, mixing patterns helped to create an environment suitable for cyanobacterial growth.

Based on the observed chlorophyll- and cyanobacteria-nutrient relationships, we suggest that management efforts should focus on controlling watershed nutrient inputs into the reservoir as suggested by others (Gonzalez, 2000; Seda et al., 2000; Smith et al., 2002; Mankin et al., 2003). Additional research is needed to determine the relative impact of internal nutrient recycling on the overall nutrient budget of the lake, and on cyanobacteria production. Furthermore, it is likely that the scale of monitoring (i.e. monthly) used in this study was too coarse to measure many of the diurnal mechanisms and factors that influence cyanobacterial distribution. Monitoring programs that incorporate shorter time intervals between sampling events are needed to further resolve relationships between physical and chemical conditions and cyanobacteria production in Clinton Lake. We are currently addressing these issues in additional Midwestern drinking water reservoirs to provide additional information on the mechanisms facilitating cyanobacterial production. We hope this data will be useful in the development of long-term watershed management plans for drinking water reservoirs.

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