Microcystin Levels in Eutrophic South Central Minnesota Lakes

A study of the blue-green algal toxin – Microcystin - based on select lakes in McLeod and Blue Earth Counties

Part of a series on Minnesota Lake Water Quality Assessment

Minnesota Pollution Control Agency

wq-lar3-11

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Lakes included in the study:

Lake	Lake ID #
Madison	07-0044
George	07-0047
Duck	070053
Ballantyne	07-0054
Eagle	07-0060
Loon	07-0096
Hook	43-0073
Marion	43-0084
Otter	43-0085
Stahl's	43-0104
Cedar	43-0115
Silver	43-0034

Minnesota Pollution Control Agency
Environmental Analysis and Outcomes Division

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March 2007

Acknowledgments

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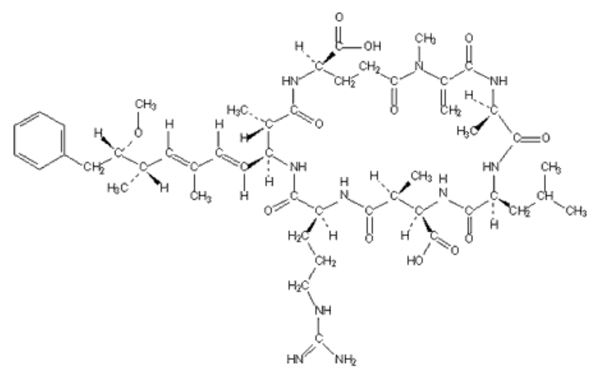
Introduction

Blue-green algae, more appropriately referred to as Cyanobacteria, are a common component of the algal community in lakes and rivers in Minnesota and elsewhere in the world. It has been long known that certain forms of blue-greens have the ability to produce toxins and these toxins have been implicated in animal deaths and human-health related problems. These toxins, which include anatoxin, saxitoxin, microcystin and a more recently described toxin cylindrospermopsin vary in their toxicity. And of these, microcystin is the most commonly measured in most studies. While there has long been concern regarding blue-greens and the production of toxins (Carmicheal, 77), recent literature suggests there are numerous efforts in various countries such as, Australia (Brookes and Bruch, 2004), Germany (Chorus, 2001), and the US (Graham et al. 2005) to improve our understanding of this issue, the factors that lead to the toxicity, and our ability to manage the blooms that cause the toxicity. An example of a response from Australia is the **Queensland Harmful Algal Response Plan** that may be viewed at http://www.nrw.qld.gov.au/water/blue_green/index.html .

Blue-green algae have several properties that allow their success in lake communities. Perhaps the most significant is the ability to control their buoyancy to optimize light and nutrient conditions. This property also allows for the build up of scums under some conditions. Algae at the surface water interface can take advantage of abundant light, as well as atmospheric carbon and nitrogen. The build-up of algal scums is not only related to nutrient concentration and buoyancy but is also influenced by chemical and physical factors such as wind, sunlight and available nutrients.

Microcystin LR chemical structure



MC is an acute hepatoxin (liver affecting toxin) produced by several genera of blue-green algae including: *Anabaena*, *Coelosphaerium*, *Lyngbya*, *Microcystis*, *Oscillatoria Nostoc*, *Hapalosiphon* and *Anabnaenopsis*. MC is also suspected carcinogen. MC production varies among the producing species. The majority of the toxin is retained with in the cell. Strains within species have a wide range of MC production rates (Ingrid and Chorus 1999)

Table 1   Microcystin toxicity and common standards

Microcystin congeners toxicity range	50 to 300 LD_{50} bw
Microcystin LR toxicity	50µg/kg LD^{50} bw
WHO drinking water standards	1 ppb
Commonly used health advisory level in recreation waters	>2 ppb
Commonly used health alert level in recreation waters	> 15 ppb

Blue-green algal toxicity is not a new issue in Minnesota either. Olson (1949, 1954, and 1960) documents several incidences of blue-green algal blooms in Minnesota that have led to animal deaths, including cattle, horses, and dogs. Some of these accounts date back to the late 1800's with animal deaths attributed to contact with blue-green blooms on Lake Elysian (Waterville). Documented incidences were also noted in the Fergus Falls area in 1900 and various other incidents from 1918 to 1934. Studies conducted at that time associated the toxicity with the blue-green genera: **Anabaena**, **Aphanizomenon**, **Coelosphaerium**, **Lyngbya**, and **Microcystis**. Toxic blue-green blooms were noted on Lake of the Isle Lagoon and Kenilworth Lagoon in 1918 (Buell, 1938).

In the mid 1980s isolated reports of animal deaths (typically dogs), presumably caused by blue-green algal toxins, prompted renewed interest in this subject and some work was conducted by the MPCA and collaborators to take a closer look at this issue. More recently three dog deaths in 2004 including one on Fish Lake (Kanabec County) and two on Lake Benton (Lincoln County) prompted further work on this issue. Water quality investigations (after the fact) were conducted by MPCA in each case.

These investigations indicated both lakes had very high nutrient concentrations and bloom levels of blue-green algae. Elevated levels of Microcystin were noted on both lakes along with measurable amounts of anatoxin (Fish Lake) and saxitoxin (Lake Benton). Each of these incidents drew extensive interest in the local and regional news media.

In response to these incidences and an indication of growing interest in blue-green algal toxicity in nearby states as well. For example:

- Indiana has focused efforts on the blue-green alga *Cylindrospermopsis* and its potential for toxicity. Details on this relative "newcomer" to the Upper Midwest may be found at http://www.in.gov/dnr/fishwild/fish/cylind.htm ;
- Nebraska Department of Environmental Quality, in conjunction with Nebraska Health and Human Services System, and the Nebraska Game and Parks Commission, developed a sampling protocol and Health Alert system to notify the public if there were potential hazards. During 2004, NDEQ analyzed over 600 samples for the Microcystin toxin on approximately 110 different waterbodies across the state. Based on the results of these data, health alerts were issued on 26 lakes. NDEQ is working with other state agencies and the University of Nebraska to further develop toxic algae monitoring and notification strategies for 2005. Further details on their efforts may be found at: http://www.deq.state.ne.us/
- Wisconsin has posted an alert for the public noting the potential for human health and animal health related illness that may occur from contact with toxic blue-green algae http://dnr.wi.gov/org/land/parks/safety/bluegreenalgae.html

In 2005 MPCA joined with the Department of Natural Resources (MDNR), Department of Health (MDH) and the Minnesota Veterinary Medicine Association (MVMA) to form the Minnesota Blue-green Algal Toxicity Workgroup for the express purpose of sharing information on blue-green algal toxicity, increasing awareness within agencies and the veterinarian community, and developing a public information campaign to raise awareness among the public. This resulted in development of a poster that was displayed in public places and veterinarian offices, several news release and fact sheets, and an updated web site for further information and links to other states:
http://www.pca.state.mn.us/water/clmp-toxicalgae.html. These discussions also led us to the opinion that MN had minimal information on magnitude of MC and the frequency of occurrences.

In the current study it was our intent to characterize the magnitude of MC concentrations in a set of eutrophic to hypereutrophic lakes over the course of the summer. For this purpose 12 lakes in south central Minnesota were selected with six each in the counties of Blue Earth and McLeod (Table 2). Standard limnological and MC samples were collected at a mid-lake (pelagic) site on each occasion. In addition, on most dates a nearshore site (which will be described later) was sampled for Chl-a (Chlorophyll-a), MC (Microcystin Concentration).

Among the questions we hoped to answer from this study are as follows:

- What is the likelihood of encountering measurable MC at a pelagic site in eutrophic to hyper eutrophic lakes?
- What is the likelihood of the encountering measurable MC at a near shore site?
- What is the distribution of MC values for both mid-lake and bloom sites? Are these distributions significantly different?
- How do values from this study compare to levels found elsewhere? How do they compare to World Health Organization guideline levels?
- Is there some seasonality to MC levels in these lakes?
- As bloom intensity (chl-a) increases is there a greater likelihood of encountering high MC values?
- What limnological and physical factors appear to be associated with high MC concentrations?
- How can these findings be used to communicate risk to lake users?

Background

Study Area

The intent of this study was to measure microcystin levels in a set of eutrophic and hypereutrophic lakes as they could be expected to exhibit frequent blue-green algal blooms of varying intensity. As such, south central Minnesota with an abundance of eutrophic to hypereutrophic lakes was chosen as the geographic location for this study. Selecting lakes within a small geographic area allowed for sampling efficiency as all lakes could be sampled within a two-day period and all lakes would be subject to somewhat similar weather conditions in each sampling period. In particular we focused on counties near the North Central Hardwood Forest and Western Corn Belt Plains Ecoregions transition (Figure 1). All lakes were sampled monthly from May through September

Historical data from STORET data was used to identify lakes with elevated TP and chl-a concentrations of eutrophic and hypereutrophic lakes. Subsequently 12 lakes in south central Minnesota were selected with six each in the counties of Blue Earth and McLeod (Table 1). With the exceptions of Madison, Ballantyne, and Duck, data were rather limited for these lakes. Summer-mean TP ranged from 37 µg/L (Ballantyne) to 208 µg/L (Otter) and chl a concentrations ranged from 23 µg/L (Ballantyne) to 122 µg/L (Otter) based on historic data. To the best of our knowledge there were no previous MC data for any of the study lakes.

Figure 1. Study lake locations and ecoregion map.

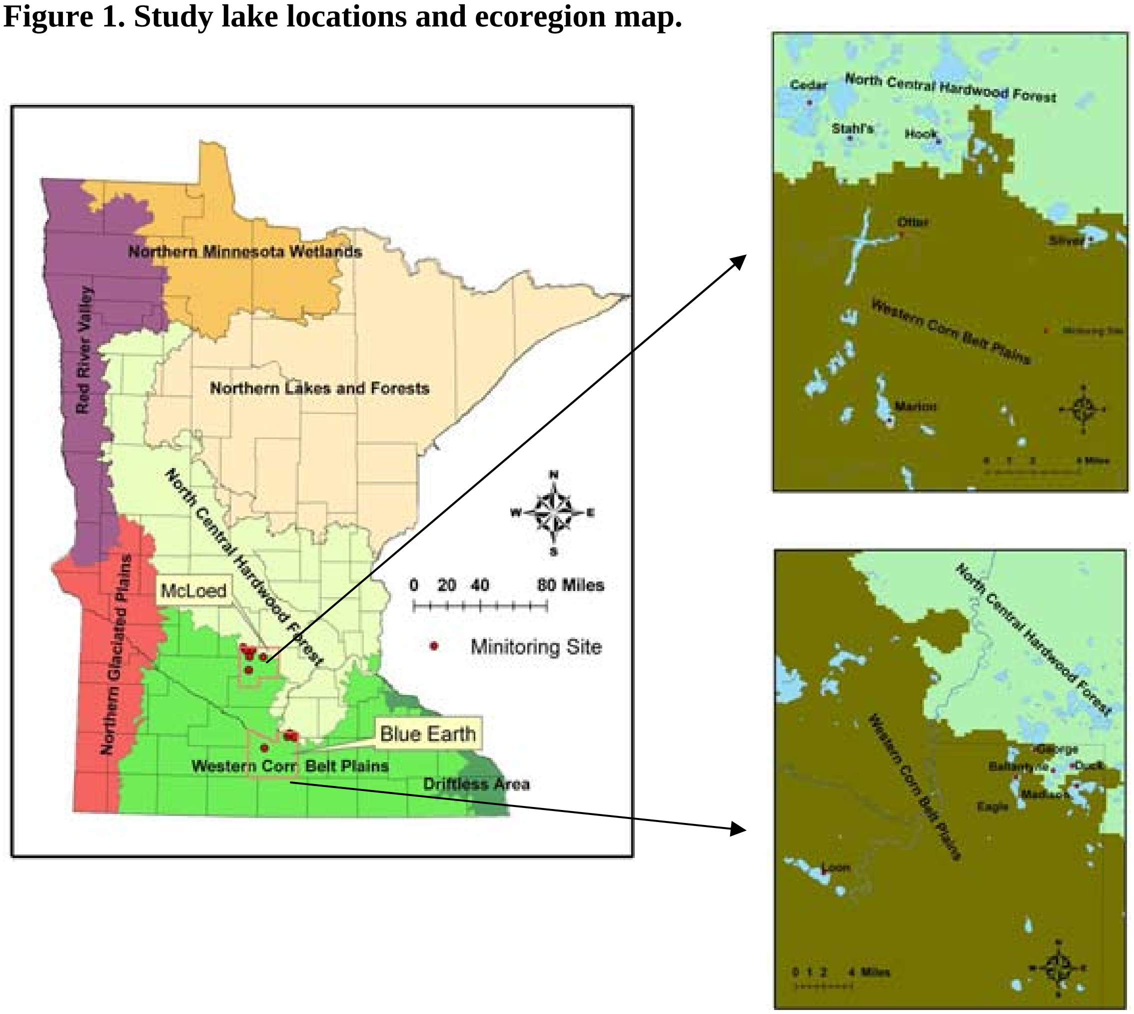


Table 2. Study Lake Morphometric and Watershed Characteristics

ID	Lake	County	Area Acres	% Littoral	Zmax Feet	Zmean Feet	Watershed area Acres
07-0044	Madison	Blue Earth	1,171	65	59.0	10.0	11,098
07-0047	George	Blue Earth	141	76	28.0	6.0	399
07-0053	Duck	Blue Earth	286	82	25.0	8.0	714
07-0054	Ballantyne	Blue Earth	353	86	58.0	6.0	3,470
07-0060	Eagle	Blue Earth	914	100	9.0	3.0	3,636
07-0096	Loon	Blue Earth	818	100	7.0	5.0	2,826
43-0073	Hook	McLeod	327	100	10.5	5.0	3,026
43-0084	Marion	McLeod	586	99	18.0	6.5	4,254
43-0085-01	Otter	McLeod	275	100	12.0	3.0	284,983
43-0104	Stahl's	McLeod	142	100	37.0	13.0	2,548
43-0115	Cedar	McLeod	1,924	100	8.0	5.0	9,078
43-0034	Silver	McLeod	500	100	10.5	5.0	883

Based on the percent littoral area, nine of 12 lakes are considered shallow (>80% littoral; Heiskary and Wilson, 2005). Shallow lakes are often subject to periodic wind mixing and seldom remain thermally stratified for extended periods, which can have an influence on phosphorus sedimentation recycling, and algal productivity. Watershed areas are quite variable ranging from 399 acres (George) to almost 285,000 acres (Otter). This results in watershed: lake area ratios ranging from about 3:1 (George) to over 1,000:1 (Otter). Large watershed: lake area ratios often result in high phosphorus loading from the watershed and in extreme instances like Otter Lake result in very low water residence time (high flushing rate).

Materials and Methods

Sampling location and sample collection

Pelagic site locations were selected based on established mid-lake sampling sites whenever possible. In most instances these pelagic sites were located near the site of maximum depth. Near-shore sites were often located near a downwind shoreline area that allowed for accumulation of algae and often resulted in a distinct algal scum on the surface of the water. While the pelagic site was constant among sample events the near-shore sites varied dependant on the wind direction and intensity and presence of an algal bloom.

Samples were collected monthly from May through September. Standard water quality parameters were collected at the pelagic site using a two-meter integrated sampler. Near-shore and all MC samples were collected as surface grab samples. When scums were present, near-shore samples were collected at the most dense algae location of the scum. Water chemistry samples and field measurements were taken near the MC sample.

Chlorophyll-a (chl-a) samples were filtered on the day of collection; filters were placed in Petri dishes and wrapped in foil. Samples were chilled on ice or frozen prior to shipment to the MDH for analysis. Samples for qualitative assessment of the algae were subset at the time of filtering and preserved in Lugol's solution. These samples were later identified to family or genus in most cases by Dr. Howard Markus using the Minnesota

Rapid Algal Analysis Procedure. This technique provides a semi-quantitative estimate of the relative biomass of the phytoplankton community and focuses on the dominant forms in the sample (Appendix A).

Laboratory and Field Analysis

All water quality samples, with the exception of phytoplankton, were analyzed the Minnesota Department of Health (MDH) lab in St. Paul. Method numbers and associated quality assurance information is noted for several of the parameters (Table 3).

Table 3. MDH laboratory methods and precision estimates.

Parameter	Reporting Limit & Units	Method number	Precision: [1] mean difference	Difference as Percent of observed
Total Phosphorus	3.0 µg.L-1	EPA 365.1	4.8 µg.L-1	2.7 %
Total Kjeldahl N	0.1 mg.L-1	EPA351.2	0.05 mg.L-1	2.8 %
$NO_2 + NO_3$	0.05 mg.L-1	EPA353.2		
Total Suspended Solids	1.0 mg.L-1	SM2540D	2.8 mg.L-1	9.6 %
Total Suspended Volatile Solids	1.0 mg.L-1	SM2540E	--	--
Alkalinity			--	--
Chloride				
Color				
Chlorophyll-a		SM10200H	1.7 µg.L-1	7.4 %
Pheophytin		SM10200H	--	--

[1] Average of individual means of 10 duplicates and expressed as a % of measured concentrations.

Microcystin analysis

MC analysis was done by MDH using a bench-top Enzyme-Linked ImmunoSorbent Assay or ELISA method , with a method detection limit (MDL) of 0.15 ppb. MC samples underwent a triple freezing cell lysis procedure. The MC analysis conducted for this study is summarized as a quantification of microcystin congeners including nodularins. It has an assay method maximum quantifiable range of 5 ppb, which requires dilution of samples when concentrations are above this range. This can result in reduced accuracy depending on the amount of dilution. A summary of MC QA based on samples from the summer of 2006 is provided in Table 4.

Table 4. MC quality assurance summary.

Number of replicates	18
Percent Recovery within 90-110%	67 %
Percent Recovery within 75-125%	100 %
C.V. between sample and replicate <15%	56 %
C.V. between sample and replicate < 25%	100 %

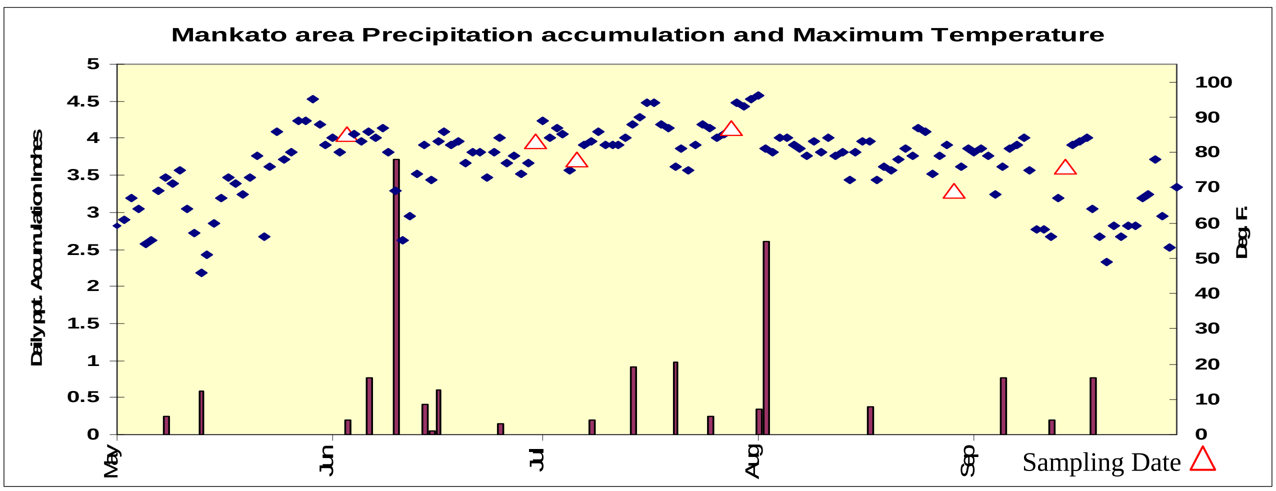
Field observations

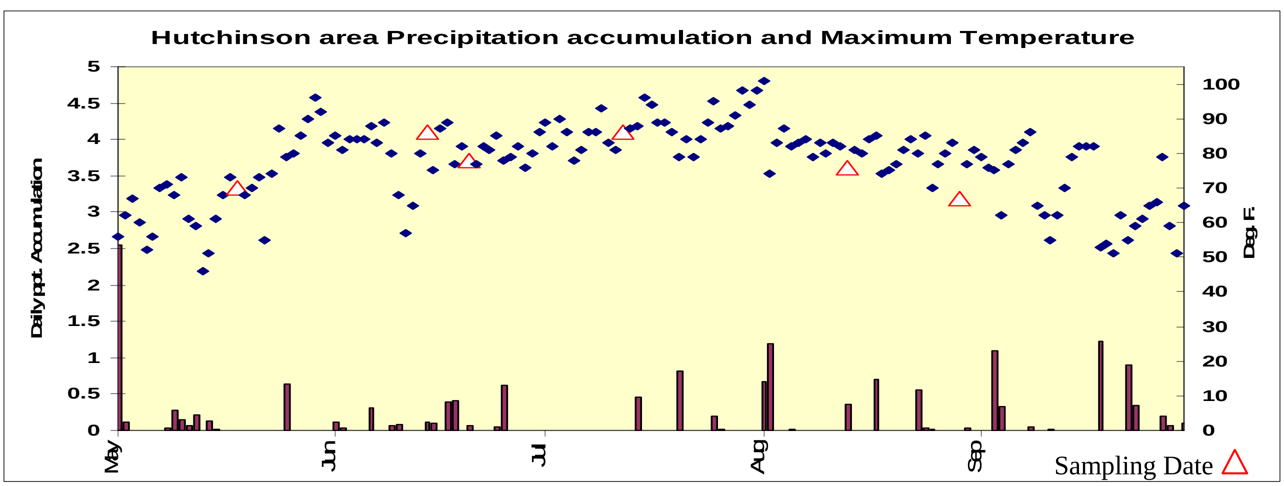
Several field observations were made during sampling. Dissolved oxygen (DO), temperature, pH, and conductivity profiles (at one-meter intervals) were made at each pelagic site and surface measures were typically taken at the near-shore site. Secchi transparency was measured at all pelagic sites. Digital photos were taken frequently throughout the study, providing additional documentation of the appearance of sampling sites, bloom intensity and related features. Other observations included our standard subjective assessment of the physical condition and recreational suitability of the lake and basic observation on wind intensity and direction and percent cloud cover. Relative ranking scales are noted in Appendix A.

Climate

The summer of 2006 was marked by somewhat droughty conditions throughout much of central Minnesota. Temperature data from Hutchinson, the northern area of the study, peaked at or above 100 F°(38°C) in early August. A rapid cooling was noted in September in both areas. The Hutchinson area had five one-inch or greater precipitation events from May through September. Precipitation was rather light throughout the May through September in the Mankato area. Based on temperature data for both areas May through August temperatures were above normal while September was below the long-term norm. Precipitation was generally below normal for the May through August period and returned to normal to above normal in September (Figure 2).

Figure 2. Mankato and Hutchinson area precipitation and maximum temperature for 2006





Results and Discussion

Individual lake data summary

This section details the water quality trends of each lake throughout the summer and makes some basic comparisons among these parameters (Table 2) and MC for each lake. To provide perspective on the water quality of the lakes summer-mean concentrations are compared to ecoregion reference lake values (Table 4). Since the lakes are located near the transition of two ecoregions: NCHF and WCBP, the typical ranges for both are included (Table 4). We also make use of pictures taken during the sampling as one basis for comparing the appearance of the between sample sites and sample dates. A subsequent section of the report will examine relationships among MC levels and lake trophic state, biological, and physical variables based on all lakes in the study.

Table 5. Summer-mean water pelagic quality 2006: McLeod County Lakes. Standard error of mean noted.

	Cedar	Stahl's	Hook	Otter 101	Otter 102	Silver	Marion
TP ug/L	85 ± 10	35 ± 1.9	121 ± 10	296 ± 30	351 ± 44	323 19	82.2 ±6.9
chl a ug/L	45 ± 4	13 ± 0.5	79 ± 18	88 ± 27	88 ± 23	252 ± 40	41 ± 4.8
chl-a max ug/L	55	23	150	194	153	365	52
Secchi meter	0.4 ± 0.04	1 ± 0.1	0.3 ± 0.04	0.2 ± 0.1	0.1 ± .02	0.2 ± 0.02	0.4 ± .08
TKN mg/L	1.9 ± 0.2	1.5 ± 0.3	2.7 ± 0.5	2.4 ± 0.1	2.57 ± 0.17	5.4 ± .5	1.8 ± 0.1
Alkalinity mg/L	172 ± 4	168 ± 4	116 ± 3	238 ± 11	246 ± 10	130 ± 8	142 ± 9.6
Color	20 ± 0	20 ± 0	26 ± 3.7	28 ± 2	32 ± 4	26 ± 2.4	20 ± 0
pH	8.8 ± 0.1	8.5 ± 0.11	9.5 ± 0.1	8.6 ± .0.1	8.5 0.1	9.5 ± 0.1	9.2 ± 0.1
Cl mg/L	14.6 ± 0.2	14 ± 2.4	28.2 ± 0.4	26 ± 0.7	27 ± 1	60.4 ± 1.0	32 ± 2.9
TSS mg/L	26.4 ± 2.6	6.6 ± 1	37.6 ± 4.9	41 ± 4	100 ± 12	49.4 ± 5.3	25.6 ± 2
TSV mg/L	15.8 ± 1.6	4.1 ± 0.3	27.6 ± 3.7	15 ± 4.5	24 ± 4	42.2 ± 5.8	16.6 ± 2
TS Inorganic mg/L	10.6 ± 1.1	2.5 ± 0.8	10.0 ± 1.1	25.6 ± 3.4	75.8 ± 10.4	7.2 ± 1.5	10.6 ± 1.6
Spec. Cond. µ/Scm	280 ± 70	275 ± 69	234 ± 58	623 ± 41	519 ± 133	340 ± 86	340 ± 86
Pheo ug/L	9.9 ± 4	2.7 ± 0.96	7.5 ± 3	20 ± 2	19.7 ± 1.4	60.2 ± 18.8	8.28 ± 2.9
Pheo %	21 ± 9	22 ± 9	11 ± 5	26 ± 9	31.7 ± 12.2	18 ± 7	17 ± 4
Temp. C°	22.6 ± 1.7	23.5 ± 1.4	23 ± 1.4	22.6 ± 1.8	22.4 ±	23 ± 2	22.9 ± 1.6
DO mg/L	9.1 ± 1	7.9 ± 1.3	9.5 ± 3.2	10.8 ± 1.4	9.0 ± 1.2	12.2 ± 3	11.2 ± 1.4
ORP mV	240.8 ± 19	259 ± 20	225 ± 27	271 ± 71	272 ± 23	272 ± 29	263 ± 23
Microcystin µg/L	2.2 ± 0.4	1.8 ± 0.8	30.8 ± 9.5	NA	0.4 ± 0.1	13.0 ± 5.1	2.2 ± 0.23

Table 5 (continued). Summer-mean pelagic water quality 2006: Blue Earth County Lakes

	Ballantyne	Duck	Eagle	George	Loon	Madison	NCHF Range	WCBP Range
TP ug/l	39.8 ± 3	70 ± 9	142 ± 11	105 ± 10	157 ± 15	80.8 ± 11	23 - 50	65 - 150
Chl a ug/L	19.3 ± 2	41.9 ± 9	75 ± 10	40 ± 10	82 ± 6	47 ± 5	5-22	30 - 80
Chl-a max ug/L	24	66	104	76	102	67	7 – 37	60 - 140
Secchi meter	0.8 ± 0.1	0.8 ± 0.2	0.3 ± .04	0.5 ± .2	0.3 ± .02	0.7 ± .06	1.5 - 3.2	0.5 - 1.0
TKN mg/L	1.4 ± .06	1.5 ± 0.1	3.1 ±0.1	20 ± 0.3	2.9 ± 0.2	1.8 ± 0.1	0.60 - 1.2	1.3 - 2.7
Alkalinity mg/L	142 ± 4	154 ± 3	118 ± 3.7	91 ± 4	136 ± 2.4	144 ± 2	75-150	125 - 165
Color Pt-Co	14 ± 2	10 ± 0	30 ± 0	24 ± 2.5	16 ± 2.4	18 ± 2	10 - 20	15 - 25
pH	8.6 ± 0.1	8.7 ± 0.5	9.2 ± .05	9.2 ± 0.4	8.9 ± 0.1	8.7 ± 0.1	8.6 - 8.8	8.2 - 9.0
Cl mg/L	19 ± 1	21.4 0.2	19 ± 0.6	15.8 ± 2	24 ± 0.4	20.6 ± 0.2	4-10	13-22
TSS mg/L	10.0 ± 1	12.6 ±2	42.8 ± 6.1	23 ±5.6	55.4 ± 9.4	10.0 ± 1	2-6	7-18
TSV mg/L	5.7 ± 0.44	9.5 ± 1.8	33.2 ± 3.9	17.4 ± 3.8	67.2 ± 6.0	8.0 ± 0.8		
TS Inorganic mg/L	4.3 ± 0.6	3.1 ± 0.6	9.6 ± 2.4	5.8 ± 2.0	18.2 ± 3.7	2.1 ± .04	1 - 2	3 - 9
Spec Cond µ/Scm	286 ± 75	284 ±71	230.8 ± 57	188 ± 44	246 ± 63	267.5 ± 67	300 - 400	300 - 650
Pheo mg/L	2.7 ± 0.4	8.3 ± 2.3	8.0 ± .06	5.2 ± .06	6.0 ± 2.4	8.8 ± 2		
Pheo %	10.± 3	14 ± 5	8 ± 2	10.7 ± 3.3	5.9 ± 2.6	17 ± 4		
Temp C°	24.8 ± 1	23.7 ± 1.5	23.3 ± 2.1	24.2 ± 1.7	21.8 ± 2.3	23.3 ± 1.3		
DO mg/L	8.6 ± 0.7	8.8 ± 1.7	11 ± 1.3	9.4 ± 4.0	9.3 ± 0.9	8.6 ± 2.6		
ORP mV	207 ± 33	235 ± 18	240 ± 23	206 ± 33	300 ± 36	270 ± 31		
Microcystin µg/L	0.35 ± 0.1	2.7 ± 1.7	8.3 ± 1.7	5.2 ± 0.5	1.5 ± 0.3	3.1 ± 1.6		

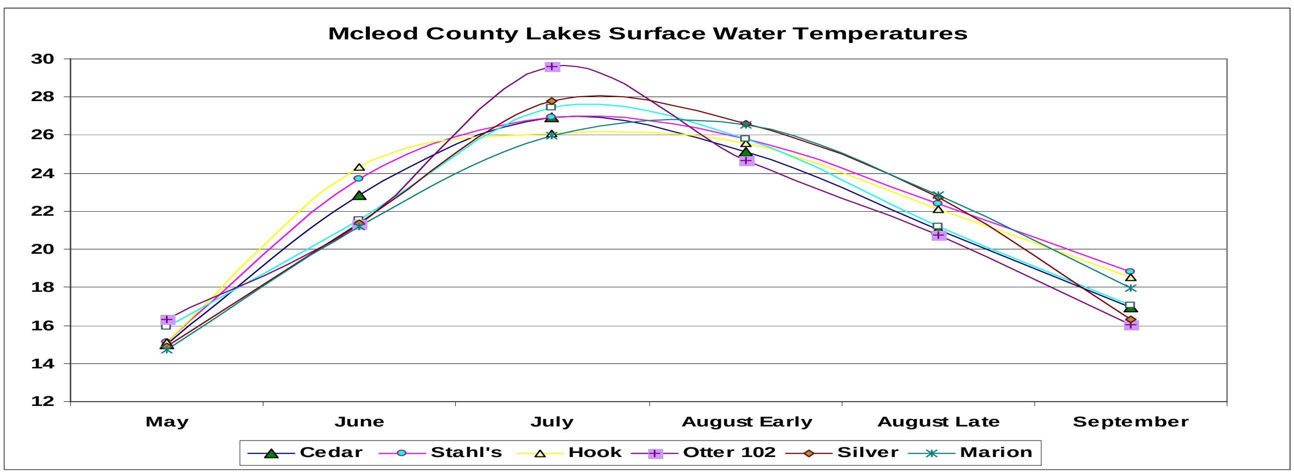
Surface water trends

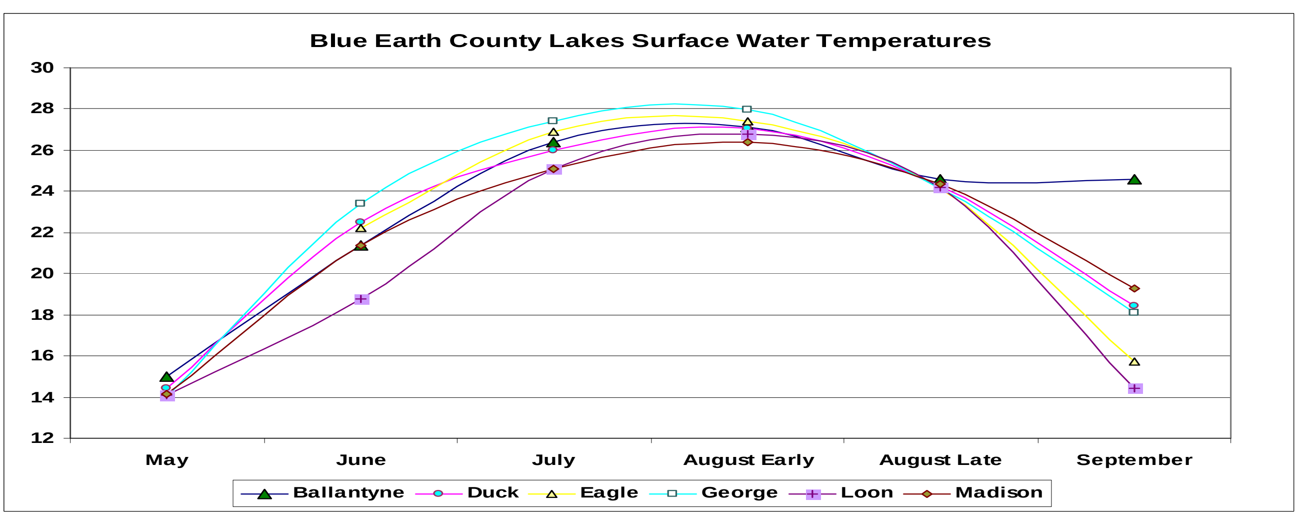
Prior to the individual descriptions, a brief summary of surface water trends in temperature, total phosphorus (TP) and chlorophyll-a are provided to provide some perspective for the individual discussions.

Water temperature has a strong influence on algal growth, as different algal forms prosper over differing temperature ranges. Diatoms, for example, often are dominant in the spring and fall when surface temperatures are rather cool. Blue-green algae in contrast prefer warmer temperatures and their optimal range is from about 25 Deg. C. for most common genera encountered in Minnesota.

Surface water temperatures ranged from about 14-16 C in May to peak temperatures on the order of 26-30 C. Temperatures peaked in the McLeod County lakes in July (Figure 3). The highest observed temperature was at Otter Lake site 102, which is influenced by the Crow River. Blue Earth County lakes peaked in early August. By September all McLeod County lakes exhibited temperatures from 16-19 C. A wider range of temperatures were evident for the Blue Earth County lakes with Ballantyne remaining rather warm at 24 C.

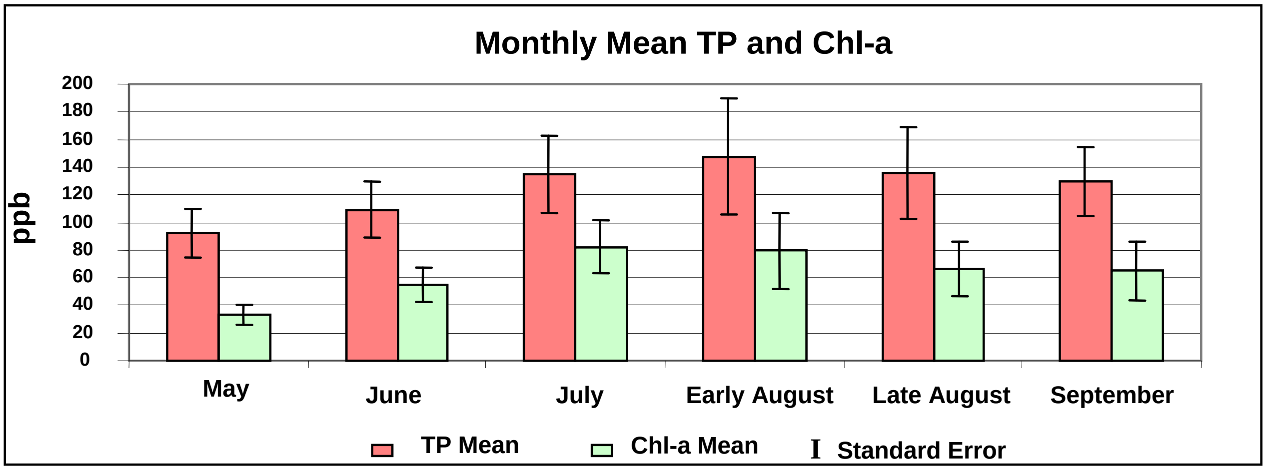
Figure 3. May to September surface water temperatures





The study lakes exhibited a rather consistent pattern of increasing TP from May through early August (Figure 4). Chl-a concentrations increased as well over this time period. This pattern of increasing TP and chl-a is consistent with that observed in other shallow lakes in Minnesota (Lindon and Heiskary, 2004). Based on the levels of chl-a “severe nuisance” (chl-a > 30 ug/L) and “very severe nuisance” (chl-a >60 ug/L) were common throughout the summer on these lakes.

Figure 4. Study lakes 2006 monthly mean TP and Chl-a (SE noted)



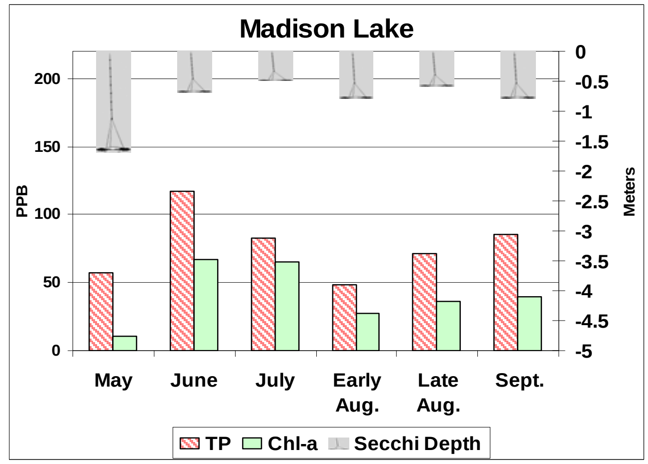
Individual lake results and discussion

Madison Lake

Madison is one of the largest and deepest lakes in the study. It has two distinct bays both having a maximum depth of over 30 feet. The southern bay is the deepest and was stratified from June through September. The northern bay was thermally stratified in July and early August. Surface temperature varied from 14 (May) to 26 C (early August) (Figure 3).

Summer-mean water quality at site 102 was in typical the range on the WCBP ecoregion reference lakes (Table 4). The seasonal pattern of variable, but generally declining TP from June through September is fairly consistent with that of other stratified lakes. The slight TP increase in September coincides with the onset of fall mixing. Chl-a concentrations were quite variable and severe nuisance blooms were common throughout the summer. Secchi was high in May, which is often the result of high zooplankton populations that serve to reduce the algal population – as evidenced by the low chl-a concentration (Figure 5). Algal composition varied from May through September.

Figure 5. Madison Lake 2006 Trophic Status Measurements



MC concentrations at the pelagic site were above detection on all dates and varied from 0.2 to 3.3 ppb, with the maximum occurring in July (Figure 6). Peak chl-a of about 60 ppb was noted in July (Figure 5). No algal scums were observed or sampled in May. Two distinct scums were sampled in June. The more pronounced of the two scums was gray and "cake-like" (suggesting the bloom was in senescence) and located near the access (Figure 7). This scum had one of the highest MC concentrations in the study at 2,200 ppb. The additional scum sampled in June had a MC concentration lower than the pelagic site. In July the scum near the access had dissipated and MC was similar to pelagic site. In early August, under calm and bright conditions, the near-access scum was present again (Figure 7). The appearance of the scum had changed to a brown-green color. MC at this time was elevated compared to the pelagic site (Figure 6), but substantially lower than the June results. In late August and September no scum was present.

Figure 6. Madison Lake 2006 MC

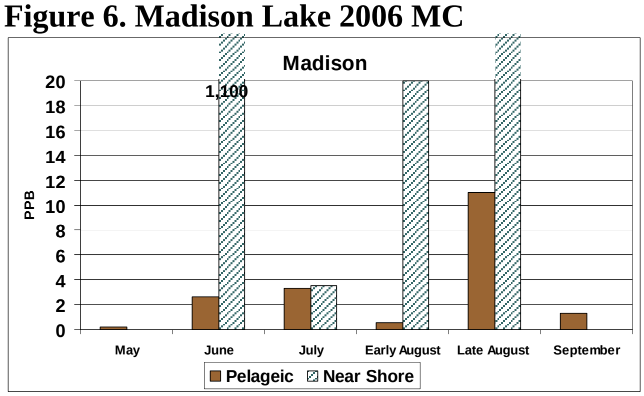
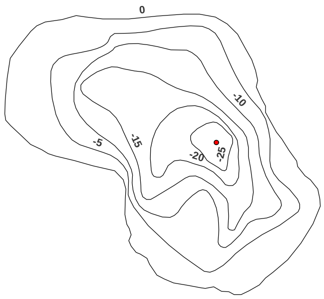


Figure 7. Madison Lake photos

Madison June 2006

Madison August 2006

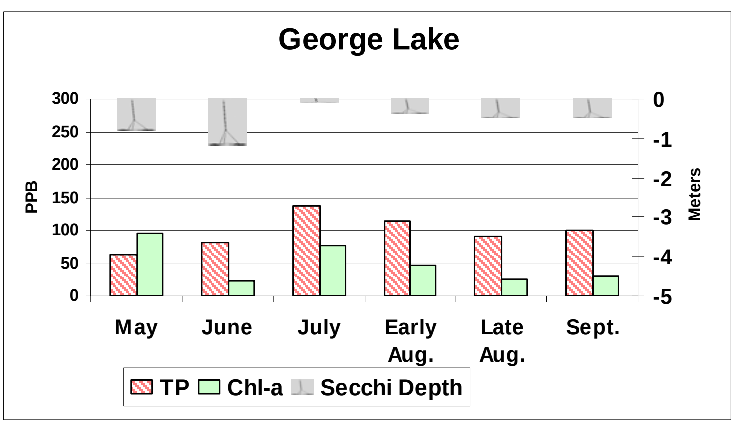
Lake George



Lake George is located in the northeast corner on Blue Earth County. The lake is relatively small, with a small agriculturally-dominated watershed. George is a typically shaped basin with a maximum depth of 28 feet. The lake is 60 % littoral. George was among the WCBP ecoregion reference lakes (Heiskary and Wilson, 2005) and was also included in a statewide diatom-reconstruction study (Heiskary and Swain, 2002).

Lake George was weakly stratified over much of the summer. Surface temperatures ranged from 14 to 28 C with the peak temperature occurring in early August. DO was at or near 0 mg/L below a depth of four meters over much of the summer. Summer mean water quality values at the pelagic site were within the typical range for WCBP ecoregion lakes for all of the monitored parameters except TSS (Table 4). TP concentrations were variable with a peak in July but declining thereafter (Figure 8). Chl-a co-varied with TP concentrations and severe nuisance blooms were common in 2006. With the exception of June, Secchi was less than one meter for most of the summer.

Figure 8. Lake George 2006 Trophic Status Measurements.



Pelagic MC concentrations ranged from 4.0 to 7.7 ppb with the maximum occurring in July (Figure 9). The corresponding chl-a in July was 76 ppb. When the lake was initially sampled on May 17th, the southern portion of the lake was covered with curly-leaf pondweed. A dense algae bloom and scum was visible amongst the curly leaf (Figure 10). The scum on the south end of the lake was sampled in duplicate and yielded the highest concentration in the study -- over 8,000 ppb (8,100 and 8,400 respectively for the duplicates). In June curly-leaf had begun to senescence, water in the southern portion of the lake was turbid but scums were no longer apparent (Figure 10). However, MC was relatively high at 20 ppb (Figure 9). By July the curly-leaf senescence was almost complete. Three sites were monitored in July (including the south bay) and MC was similar among the three sites. By late summer curly-leaf was no longer prevalent in the southern basin and no significant blooms were observed in August and September.

Figure 9. Lake George 2006 MC

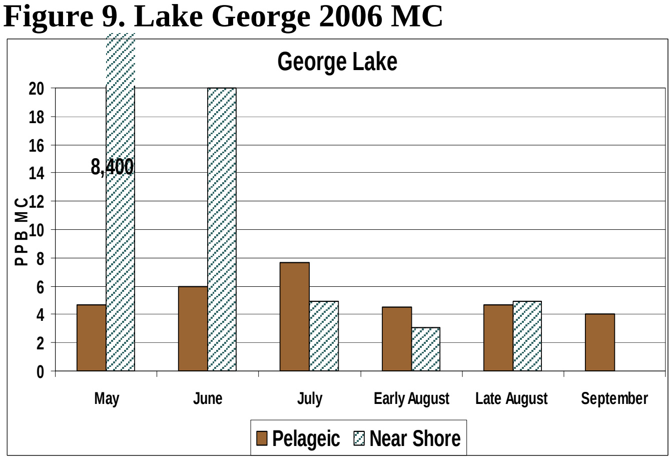


Figure 10 Lake George Photos

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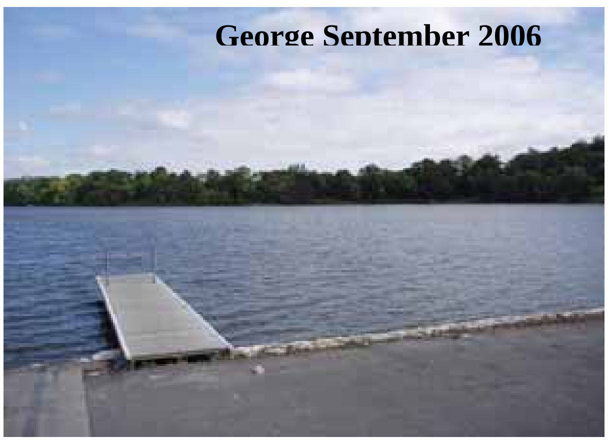
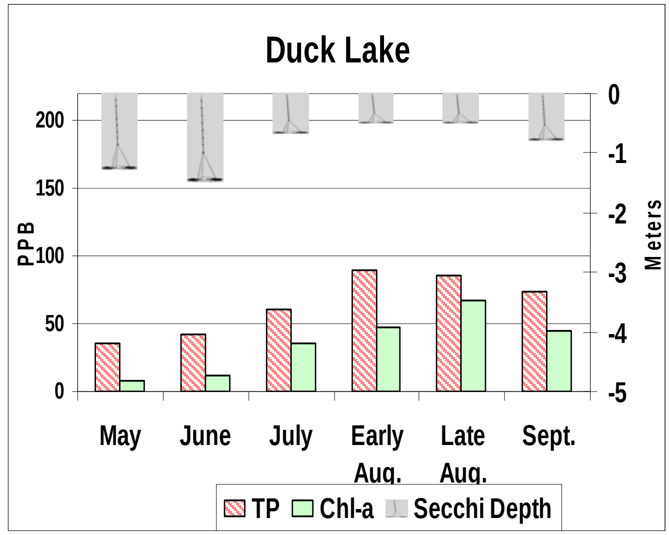


Duck Lake

Duck Lake is one of the smallest lakes in the study at about 286 acre and has a relatively small watershed (~3:1) relative to its size. Its watershed is dominated by agricultural uses but its shoreline is highly developed including a large park and swimming area. The lake has been extensively sampled by MPCA and other collaborators as a part of a Clean Water Partnership project and it was also part of the 55 lake diatom reconstruction study (Heiskary and Swain, 2002). Curly-leaf pondweed was first documented in 1970 and has become a dominant macrophyte in the lake. Lake water quality has improved much on Duck since the 1980's.

The lake was well-mixed on all dates and surface temperature ranged from 14 to 27 C with a peak in early August. Summer-mean water quality measurements for 2006 were all within the WCBP ecoregion reference lake range (Table 5). TP concentrations increased from May through August, consistent with a pattern seen in other shallow well-mixed lakes (Figure 11). Chl-a peaked at 67 ppb in late August and severe nuisance blooms were common from July through September. Secchi was less than one meter from July through September.

Figure 11. Duck Lake Trophic Status Measurements 2006.



MC concentrations were above detection on all dates but were generally less than 3 ppb with the exception of late August with a concentration of 11 ppb (Figure 12). MC concentrations at the near-shore sites were not appreciably different from those at the pelagic site. Distinctive scums were evident at the south inlet throughout the summer (Figure 13).

Figure 12. Duck Lake 2006 MC

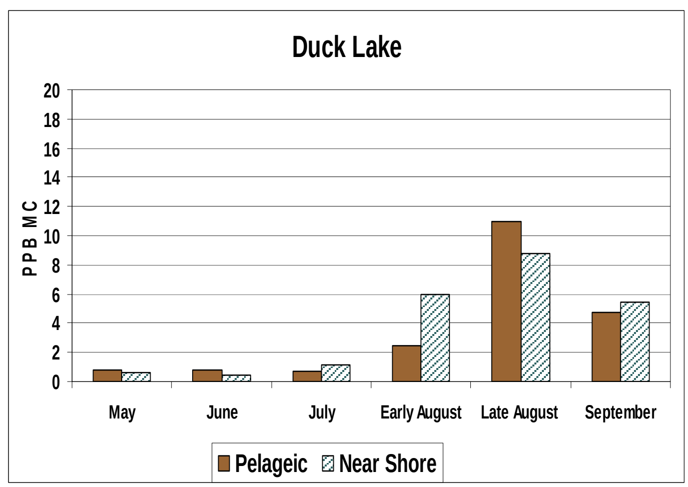


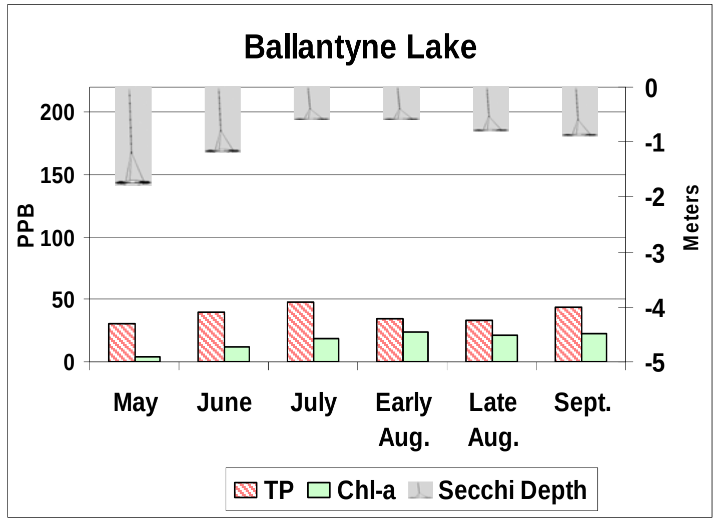
Figure 13 Duck Lake Photos

Lake Ballantyne

Ballantyne is relatively deep compared to other lakes in the study (Table 2) and has two rather distinct bays. The lake has a fair amount of development on the north and west ends. Ballantyne has been previously sampled and is among the NCHF ecoregion reference lakes (Heiskary and Wilson, 2005).

Ballantyne was thermally stratified from June – September. Fall mixing was underway by the September sample date. Surface temperatures ranged from 15 to 27 C with a peak in early August. Summer mean water chemistry values were well within the typical range for NCHF ecoregion lakes (Table 5). TP concentrations were rather stable from June through September (Figure 14). Chl-a concentrations were generally in the 10-20 µg/L range and remained below 30 µg/L (severe nuisance bloom levels) over the summer. Secchi was less than one meter for most of the summer.

Figure 14. Ballantyne Lake Trophic Status



Measurements for 2006.

In general, MC concentrations on Ballantyne were quite low (Figure 15) with all values less than 1 ppb at the pelagic site. In May and July MC were below the detection limit at both near-shore and the pelagic sites. The highest Microcystin result found on the lake was 1.2 ppb in late August. In late August small opaque blooms that were somewhat "bar-soap" or cake-like in appearance were observed and sampled (Figure 16).

Figure 15. Ballantyne Lake 2006 MC

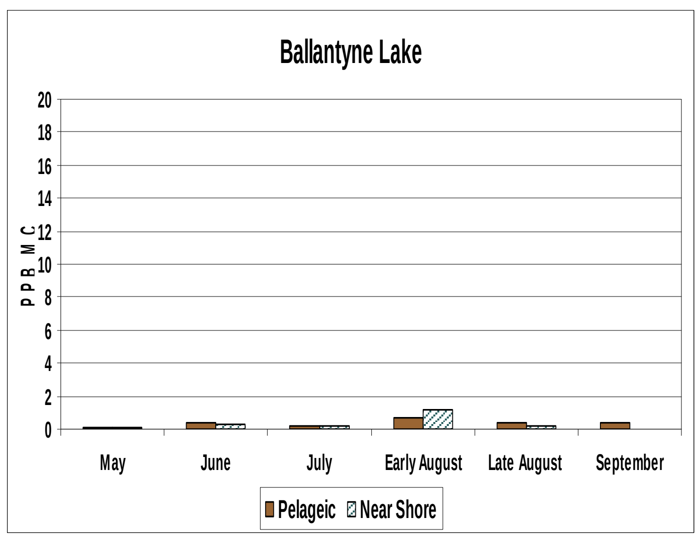


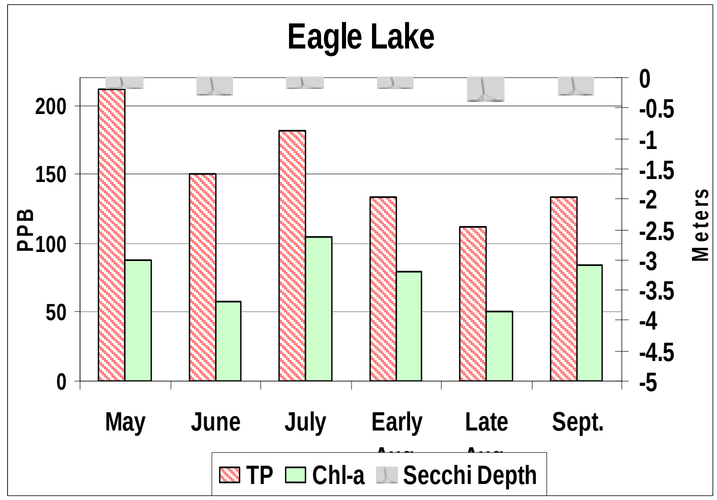
Figure 16 Ballantyne Lake Photos

Eagle Lake

Eagle Lake is one of the shallowest lakes in the study. Low water levels throughout the summer made the south end of the lake inaccessible for monitoring. There is minimal development around the lake and much of the shoreland is covered with emergent plants. Much of the lake's south bay is surrounded by a cattail fringe (Figure 21).

Because of its shallowness Eagle Lake remained well-mixed throughout the summer. Surface temperatures ranged from 15 – 27 C and peaked in early August. DO was often supersaturated near the surface and concentrations near the sediments remained above 2 mg/L. Eagle Lake would be considered hypereutrophic based on TP, chl-a and Secchi measurements and its summer-mean values were generally above the typical range for lakes in the WCBP ecoregion (Table 4). TP concentrations were quite variable in 2006 and exhibited somewhat of a decline from May through September (Figure 17), which is not consistent with other shallow lakes. Chl-a concentrations ranged from about 50 – 100 ppb and severe nuisance blooms would have been the norm for 2006. Secchi readings were less than 0.5 meters throughout the summer.

Figure 17. Eagle Lake Trophic Status Measurements for 2006.



MC was above detection on all sample events with values at the pelagic site ranging from 2.1 (September) to 14 ppb (May) (Figure 18). No distinct scums were evident on the six sample dates (Figure 19); as a result, MC samples from the near-shore sites were not significantly different than measurements taken at the pelagic site. The location of the near-shore site varied on the lake.

Figure 18. Eagle Lake 2006 MC

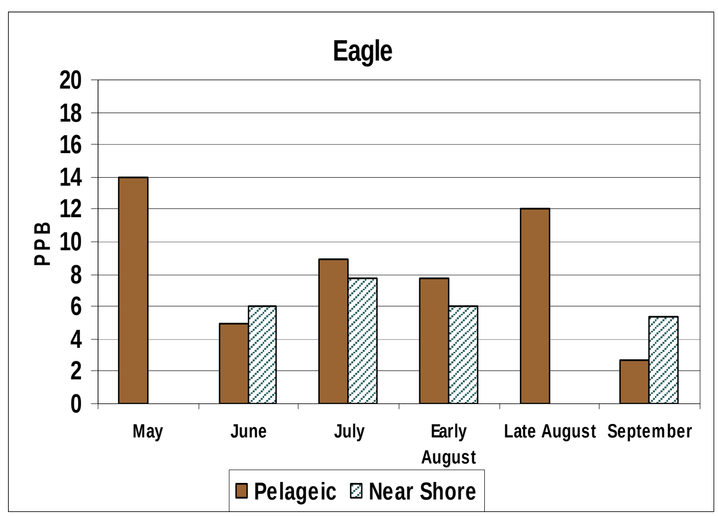


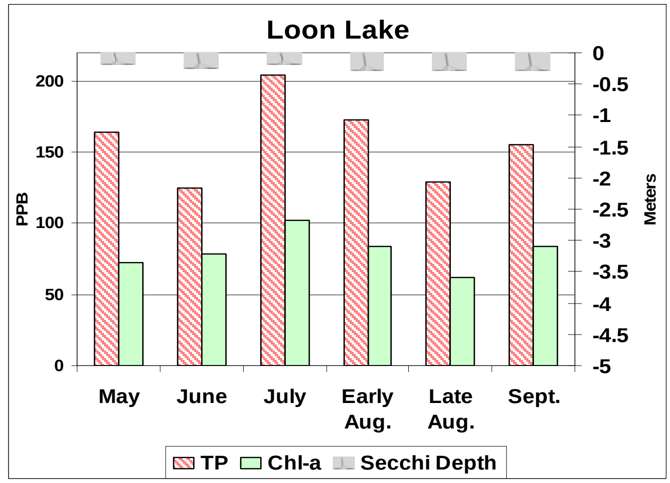
Figure 19. Eagle Lake Photos

Loon Lake

There is minimal development around the Lake. Loon Lake has a relatively large surface area but is quite shallow.

Because of its extreme shallowness Loon was well-mixed on all sample dates. Surface temperature ranged from 14 (May) to 27 C (early August) (Figure 5). Summer-mean measurements were above the typical range for WCBP ecoregion reference lakes (Table 4) for several parameters. TP was quite variable throughout the summer and no distinct pattern was evident. Chl-a was at severe nuisance blooms levels throughout the summer (Figure 20). Transparency was very low through the summer (0.4 m or less). Though algal concentrations were high through the summer no scums were observed during the monitoring.

Figure 20. Loon Lake Trophic Status Measurements for 2006.



While chl-a was high throughout the summer there were no significant surface scums observed on the six sample dates (Figure 22). All MC concentrations were above detection and ranged between 1-3 ppb at the pelagic and near-shore sites on most dates (Figure 21). The highest concentration was 11 ppb at a near-shore site.

Figure 21. Loon Lake 2006 MC

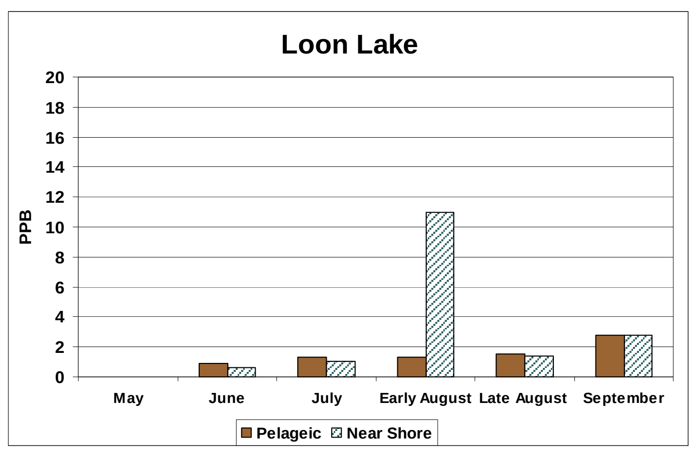
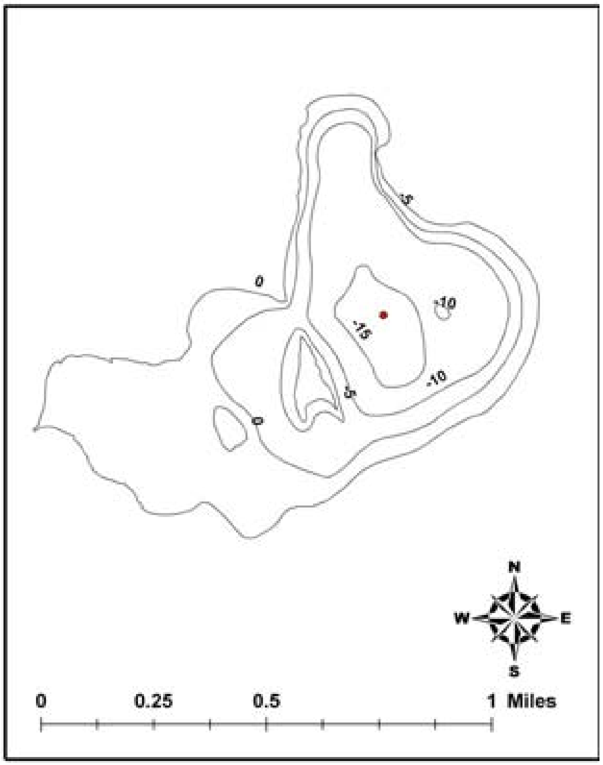


Figure 22. Loon Lake photos

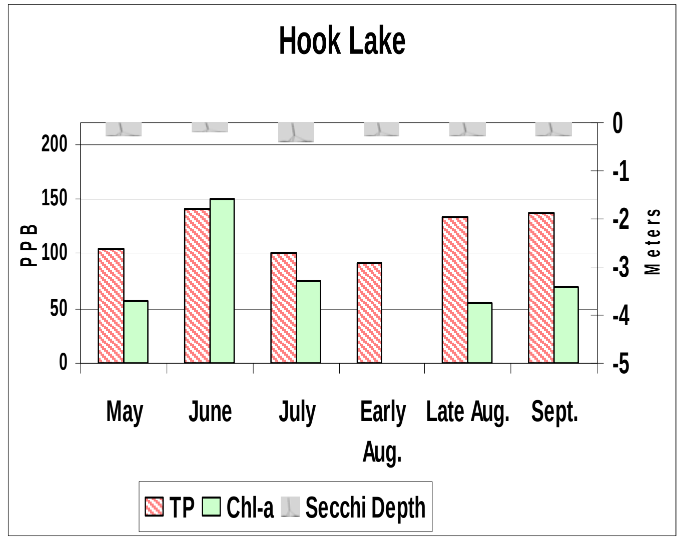
Hook Lake



Hook Lake is a moderate-sized but very shallow lake with a maximum depth of 10 feet. The lake has a small watershed relative to its surface area. The majority of the lakeshore is undeveloped. Hook Lake was previously monitored as a part of a statewide 55 lakes sediment diatom reconstruction study (Heiskary and Swain, 2002).

The lake was well-mixed throughout the summer with surface temperatures ranging from 15 (May) – 26 C (July). DO concentrations were supersaturated near the surface and often declined with depth. Summer mean water quality values for Hook Lake were generally above the typical range based on WCBP ecoregion reference lakes (Table 4). Based on the trophic status measures (Figure 23 and Table 4) the lake would be considered hypereutrophic. TP and Chl-a measurements were highly variable and there was no distinct pattern over the summer (Figure 23). Hook Lake exhibited among the highest chl-a measures in the study and severe nuisance blooms were the norm for summer 2006. Secchi was very low at less than 0.5 M throughout the summer.

Figure 23. Hook Lake 2006 Trophic Status Measurements.



Pelagic site MC concentrations were 20 ppb or more from May through September (Figure 24). A high concentration of 73 ppb was noted in June, which corresponded to the maximum chl-a of 150 ppb as measured at the Pelagic site. Near-shore MC result were significantly higher in May and June in comparison to the pelagic sites. No visible scums during were observed during the monitoring events, rather the lake seemed universally green (Figure 25). The highest MC concentrations were measured in May and June at near-shore sites with concentrations of 99 ppb and 140 ppb respectively (Figure 26).

Figure 24. Hook Lake MC results

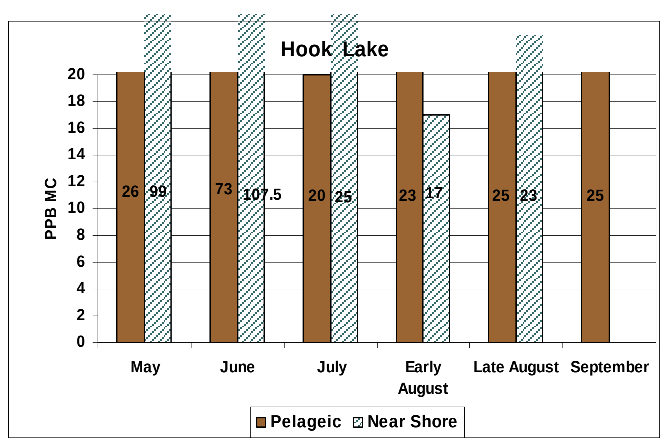
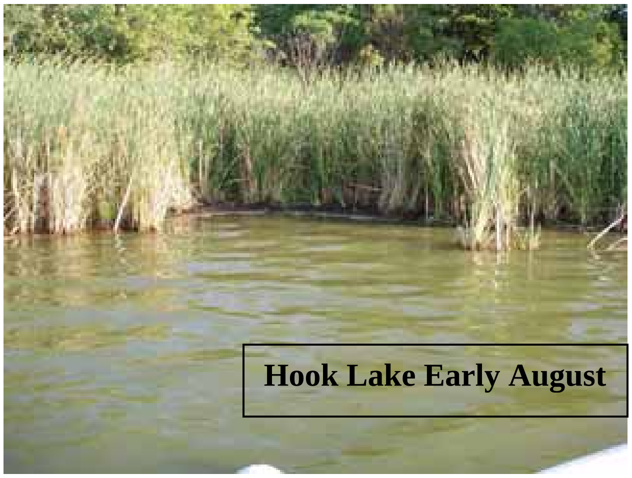
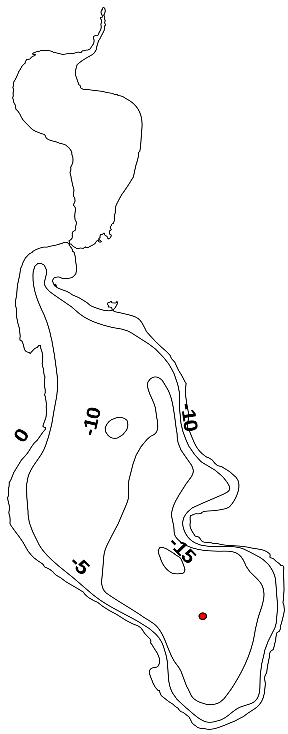


Figure 25 Hook Lake Photos



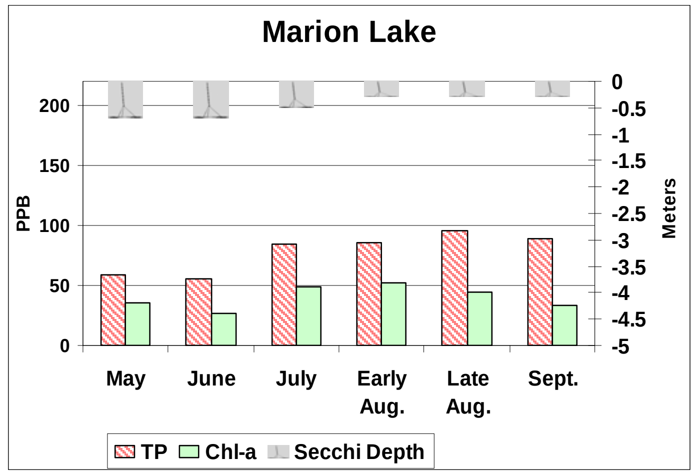
Lake Marion



Lake Marion is a rather large but shallow lake (100% littoral) with a moderate-sized watershed (about 7:1 ratio) (Table 1). A 2003 MDNR fishery survey notes that the lake has abundant aquatic plants. During summer 2006 Lake Marion was a bright green color during all monitoring events but no surface scums were observed (Figure 30).

Given its shallowness the lakes was well-mixed on all sample dates. DO remained at 5 mg/L or above down to a depth of three meters. Surface temperatures ranged from 15 (May) to 27 C (August). Summer-mean water quality measurements were above the typical range for WCBP reference lakes for most parameters (Table 4). TP concentrations increased from May through September consistent with other shallow lakes. Chl-a concentrations increased as well and concentrations of 25-50 ppb were typical throughout the summer. Secchi was correspondingly low with measures below 0.5 meter for most of the summer (Figure 26).

Figure 26. Lake Marion 2006 Trophic Status Measurements.



While the lake was distinctly green on all sample dates there was no obvious scum formation on any of the sample dates (Figure 28). MC concentrations were above detection on all dates but did not exceed 3 ppb at the pelagic site (Figure 27). In June the MC concentration at the near shore site was moderately high at 17 ppb. The corresponding chl-a on that date was 284 ppb.

Figure 27. Lake Marion 2006 MC

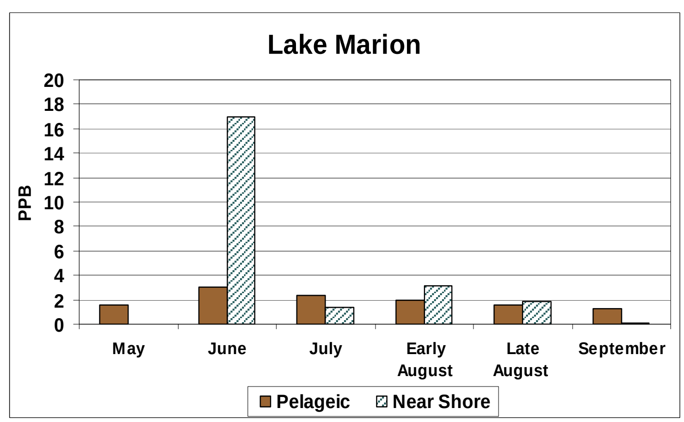


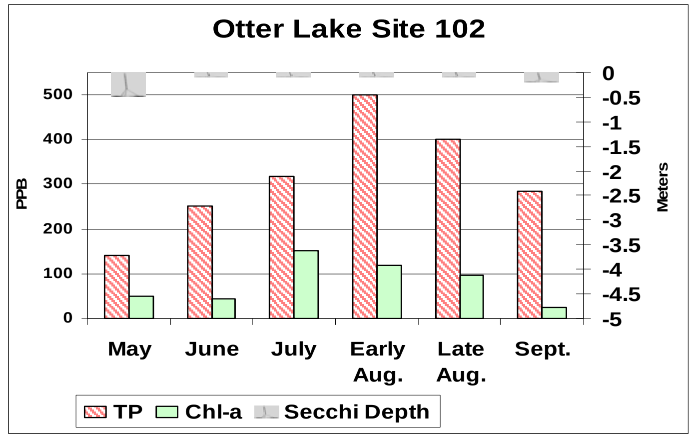
Figure 28. Marion Photos

Otter Lake

Otter Lake is more accurately characterized as a reservoir and is located on the South Fork of the Crow River in the City of Hutchinson. The north section of the reservoir is referred to as Campbell's Lake and was not sampled. Samples were taken at the main and eastern bay of the lake. Otter Lake's watershed is significantly larger than the other lakes in this study (as is characteristic of reservoirs) and has a watershed: lake ratio of about 1,036:1. As a result phosphorus, sediment and water loading to the lake is very high and water residence time is likely quite short. The lake is quite shallow with a mean depth of three feet. Otter Lake was monitored consistently through the summer in the main bay along with the eastern end of the reservoir.

As a result of its extreme shallowness Otter was quite well mixed on all dates. Surface temperatures ranged from 16 (May) to 28 C (July) and was likely strongly influenced by the Crow River. All water quality measures are far in excess of the typical range for WCBP lakes (Table 4). TP increased from May through early August and declined thereafter. Chl-a was very high and peaked at about 150 ppb in July and severe nuisance blooms would have been the norm for June through August 2006. Secchi was extremely low throughout the summer with measurements of 0.2 m or less (Figure 29). This is a reflection of high algae and suspended solids concentrations.

Figure 29. Otter Lake 2006 Trophic Status Measurements.



Though chl-a was very high throughout the summer MC concentrations were quite low at the pelagic site with concentrations less than 1 ppb (Figure 30). Four of the eight below detection limit results for microcystin were from samples taken from Otter. Again while the lake appeared quite green throughout the summer (Figure 31) there was a lack of surface scums and concentrations at the near-shore site were low as well (Figure 30).

Figure 30. Otter Lake 2006 MC.

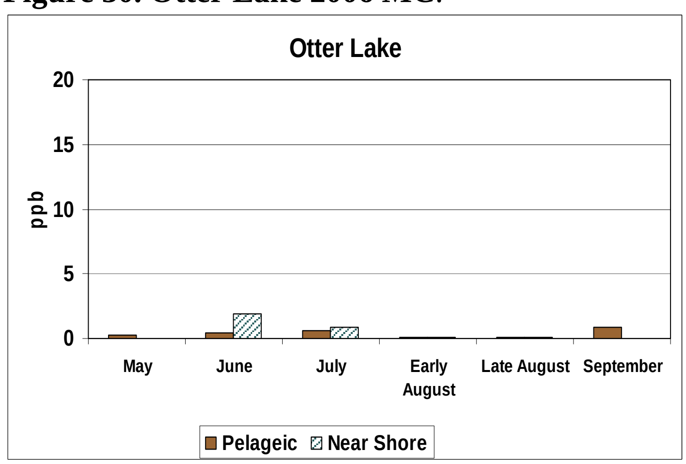


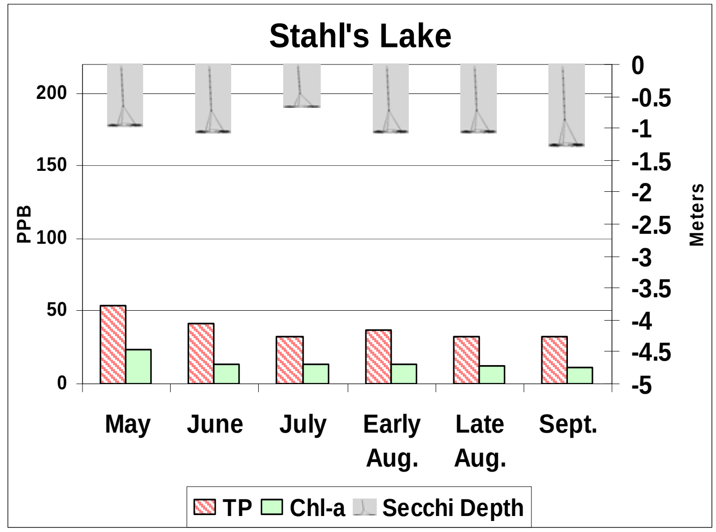
Figure 31. Otter Lake Photos

Stahl's

Stahl's Lake is among the smaller (142 acres) but deeper lakes (13 meters max depth) in the study. It has a moderate-sized watershed (11:1) relative to its surface area. Stahl's was previously monitored as a part the 55 lake sediment diatom reconstruction study (Heiskary and Swain 2002).

Temperature profiles indicated Stahl's Lake was stratified from June through September. Surface water temperatures ranged from 14 (May) to 27 C (July). DO concentrations were at or above saturation in the upper waters and fell to 1 mg/L or less at depths of five meters or more. Water quality results for Stahl's Lake were within or near the NCHF range for minimally impacted lakes (Table 4). TP concentrations declined from May through September, which is consistent with other stratified lakes (Figure 32). Chl-a was fairly stable from June through September and concentrations remained below 20 µg/L. Based on these concentrations only mild blooms were likely evident in 2006. Secchi was fairly stable at about 1.0 to 1.2 m over most of the summer and was much greater than most of the other study lakes (Figure 32). As a result emergent and floating-leaf plants were noted throughout the lake.

Figure 32. Stahl's Lake 2006 Trophic Status Measurements.



No scums were observed during the study and as noted previously chl-a levels were not indicative of severe nuisance blooms. MC concentrations were relatively low overall but tended to be higher in May and June as compared to concentrations later in the summer (Figure 33). Overall concentrations remained below 5 ppb during the study. Since there were no distinct scums noted on any of the sample dates Figure 34), samples from the near-shore site were not significantly different from the pelagic site .

Figure 33. Stahl's Lake MC results

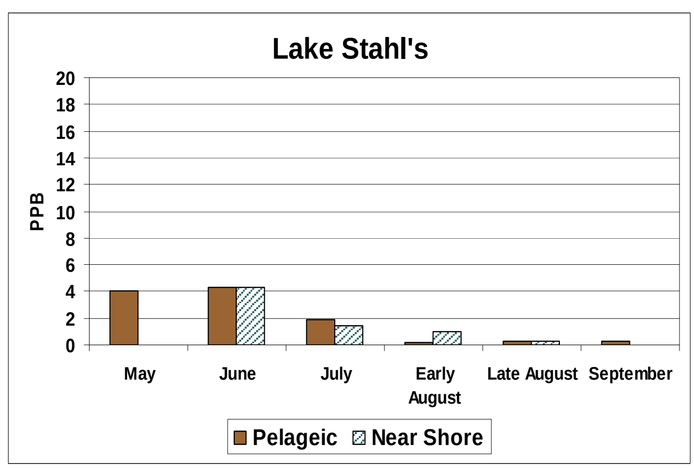


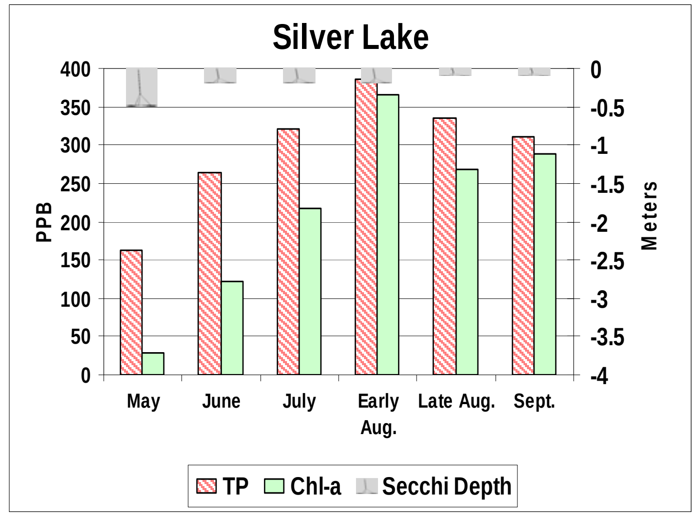
Figure 34 Stahl's Lake photos

Silver

Silver Lake is located just south of the City of Silver Lake. It is a fairly large (500 acres) but shallow (100% littoral) lake. The lakeshore is fairly undeveloped. The public access for the lake is located in a small bay, which was characterized by high algae through most of the summer.

Silver Lake was well-mixed throughout the summer. Surface temperatures ranged from 15 (May) to 27 C (July). Summer mean water quality measurements were well above the typical range for WCBP reference lakes. All trophic status measurements suggest hypereutrophic conditions throughout the summer. TP concentrations increased through early August (Figure 34). Chl-a concentrations were among the highest in the study and were above 100 µg/L June through September at the pelagic site and exceeded 300 µg/L in early August, suggestive of extreme nuisance conditions throughout the summer. Secchi was less than 0.5 m all summer and fell to about 0.1 m by late summer (Figure 35).

Figure 35. Silver Lake Trophic Status Measurements for 2006



Dense algal blooms were present throughout the summer (below). In July surface scums were quite evident (Figure 37). Since chl-a was universally high across the lake there was often not real distinct differences among the appearance of the pelagic and near-shore sites. As such, pelagic and near-shore MC concentrations were somewhat similar (Figure 36). Concentrations were higher in the late summer. The highest MC result was seen at the pelagic site in late August (Figure 36).

Figure 36. Silver Lake 2006 MC

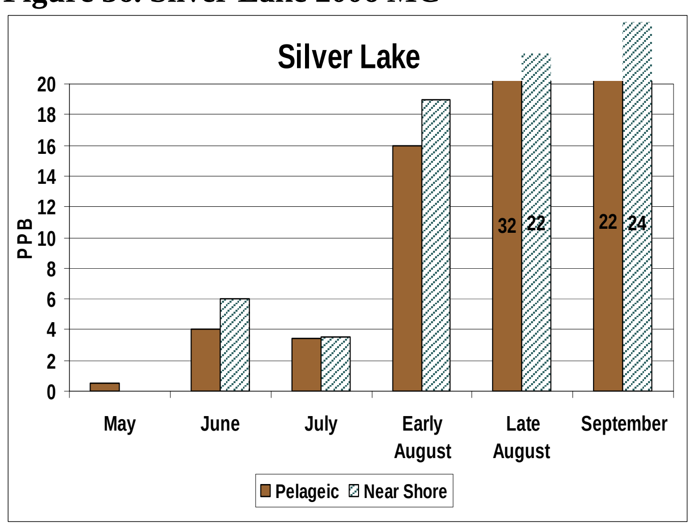


Figure 37. Silver Lake: 2006

Cedar Lake

Cedar Lake was the largest lake in the study as well as one of the shallowest. The lake is irregular shaped with 4 semi distinct bays.

Cedar Lake was well- mixed at both sites during summer monitoring, with only a slight gradient developing in September. Summer-mean TP and chl-a were well above the typical range for NCHF lake (Table 4). Chl-a levels were significantly lower in May and increased with TP through late August (Figure 38). Transparency varied inversely to chl-a and declined throughout the summer (Figure 38).

Figure 38. Cedar Lake 2006 Trophic Status

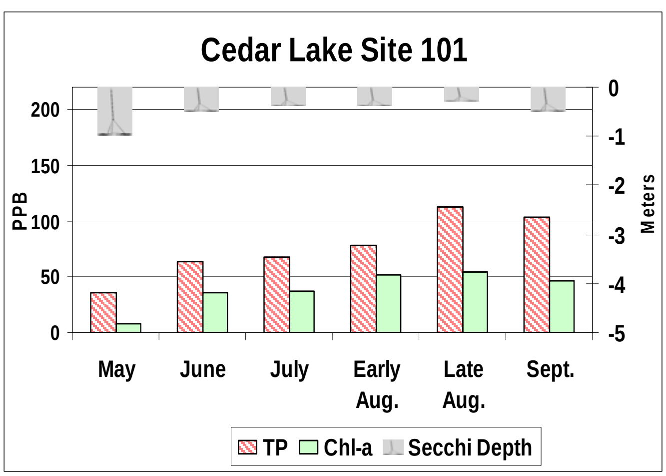
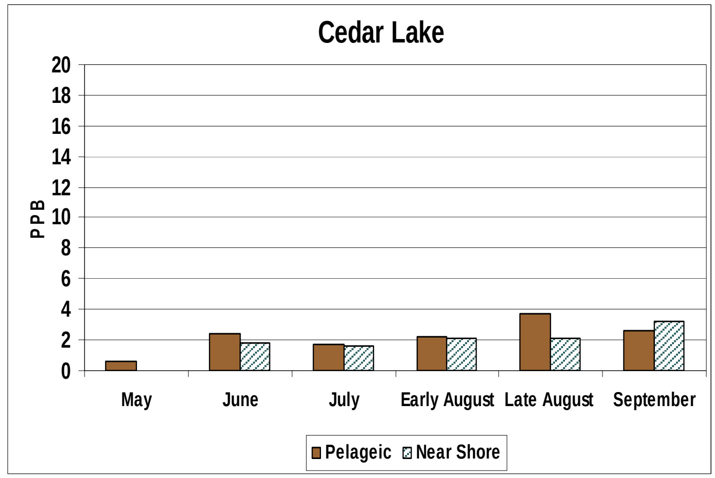
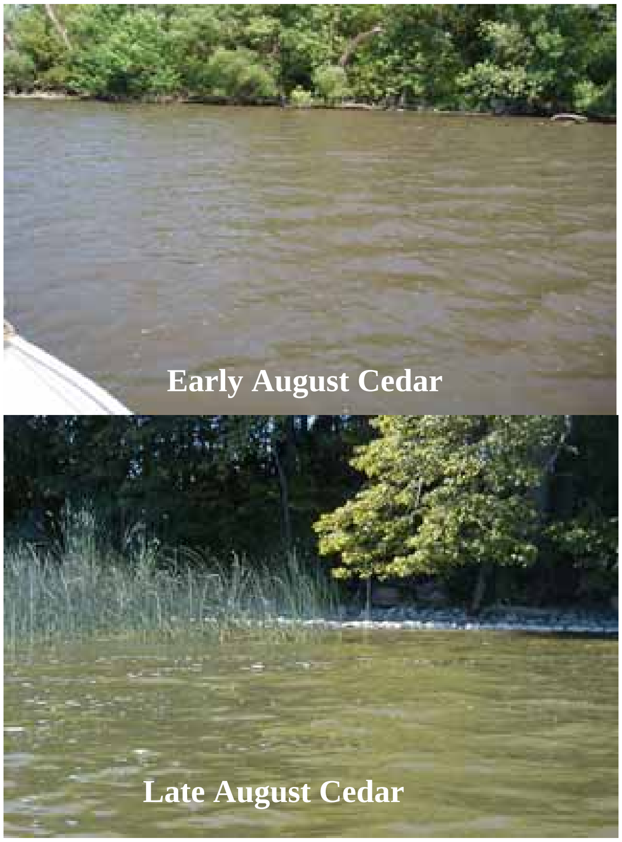


Figure 39. Cedar Lake 2006 MC



MC results at near-shore and pelagic were similar through the summer ranging form 0.6 to 3.7 ppb. Maximum MC was observed in late August and corresponded with maximum chl-a (Figures 39 and 40)

Figure 40. Cedar Lake Photos



Comparative analysis

MC results were not normally distributed and highly variable (Table 5). Over 25% of the data is between 0.9 ppb and the non-detect substitution on 0.075 ppb (Figure 41). 1 ppb and greater results were unevenly distributed up to 8,400 ppb. Since maxima events are of the most concern they were not considered as outliers. Six percent of MC results were below detection limit.

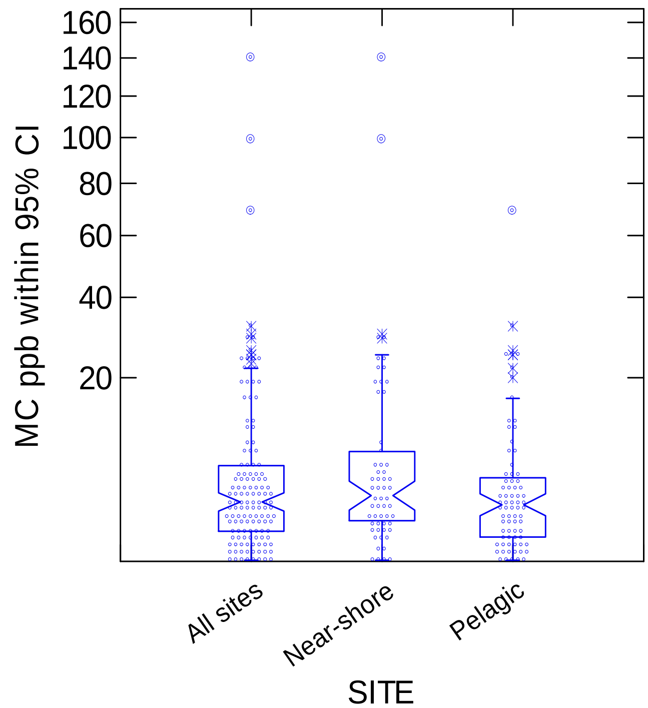
Table 6. MC Statistical summary by site type.

	All Sites	Pelagic	Nearshore
N of Cases	133	74	59
Minimum	ND <0.15	ND <0.15	0.075
Maximum	8,400	69	8,400
Range	8,399.9	68.9	8,399.9
Median	2.6	2.4	3.5
Mean	87.4	5.6	189.9
95% CI upper	216.7	8.0	482.4
Std. Error	65.1	1.2	146.3
Std. Dev.	750.9	10.2	1124.2
Variance	563,865	103.8	1,263,938
C.V.	8.6	1.8	5.9
Below Detection	8	4	4

Near-shore and Pelagic Comparison

Results from the near-shore and pelagic sites have different distributions and have statistically different means based on a log normalized t-test. 95% confidence intervals of Nearshore Pelagic site medians overlapped (Figure 41).

Figure 41. MC Box and Whisker plot by site.



MC Health Risk Categories

WHO risk guideline categories, established for recreational waters and drinking water provide a basis for placing the MC data in perspective and describing relative risk. The guidelines are detailed in the WHO document <u>Guidelines for safe recreational water environments </u> (WHO, 2003).

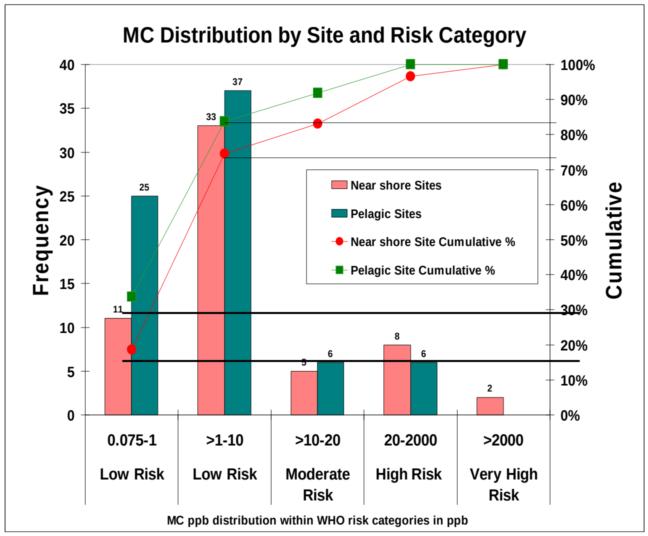
The categories we used are as follows:

- 0.075 – 1 ppb very low risk
- 1- 10 ppb low risk
- 10 - 20 moderate risk
- 20 – 2000 ppb high risk
- > 2,000 ppb very high risk

The four categories from 1 to >2,000 ppb were drawn directly from the WHO guidelines. The very low risk category was added to include those measurements that were very near the MDL for MC and below the 1 ppb drinking water guideline for microcystin LR. A high percentage of the pelagic samples were in this category and about 85 percent would have been considered very low to low risk (Figure 42). Likewise a high percentage of the nearshore samples were in these categories as well. Distributions for the moderate to high risk categories were not substantially different among the pelagic and nearshore sites; however the only very high risk measures were found at the nearshore sites (Figure 42).

Distinguishing among the nearshore sites with scums as opposed to those without scums did yield a slightly different distribution (Figure 42b). In this case it was evident that the sites that exhibited a distinct scum had a higher percentage of MC concentrations (40 percent) in the moderate to very high risk categories as compared to the sites without a distinct scum (10 percent).

Figure 42. MC frequency distributions by site



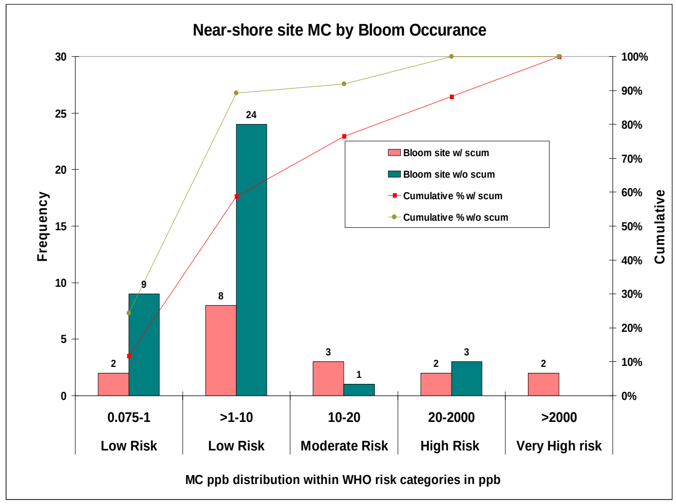
Scum occurrence and MC

Toxic incidents involving MC or other blue-green algal toxins are most frequently associated with large surface bloom forming genera (Chorus and Bartram, 1999; Chorus, 2001). Though it was common for the pelagic sites to have distinct green coloration and high chl-a, surface scums were limited to the nearshore sites. Even at the near-shore sites distinct surface scums were not very common (Table 7). In a comparisons of sites with and without surface scums it was evident that the sites with surface scums exhibited higher and more variable MC concentrations as compared to sites without scums (Table 7). Also, the likelihood of moderate to very high risk MC concentrations are greater at sites with a distinct surface scum (Figure 43). These results are consistent with observations by Graham et. al. (2004) when they note that microcystin concentration in scums may be much greater than at pelagic locations.

Table 7. MC concentrations for nearshore sites with and without scums.

	Scums	No Scum
Mean	968 ppb	10 ppb
Median	4 ppb	1.9 ppb
SE	624 ppb	4.0 ppb
N	17	42

Figure 43. Nearshore sites MC distribution with scums vs. those without



Seasonal Patterns

MC concentrations exhibited no consistent seasonal pattern at either the pelagic or nearshore sites (Figure 44) though there was some evidence of a slight increase from July through September at the pelagic sites based on monthly medians (Figure 44). For the pelagic sites Silver and Hook Lakes exhibited the highest concentrations and had the only concentrations that fell in the moderate risk level (Figure 43). In contrast, seven of the 12 lakes in the study were below the low risk threshold (10 ppb) for the entire summer at the pelagic site. High to very high risk concentrations were noted at the nearshore sites on three lakes: Madison, Hook and George (Figure 44). These elevated levels were found in samples from May and June, which we would not have expected. Based on monthly median MC concentrations tended to be highest in May and June across the study lakes.

Figure 44. MC results by lake, site and date

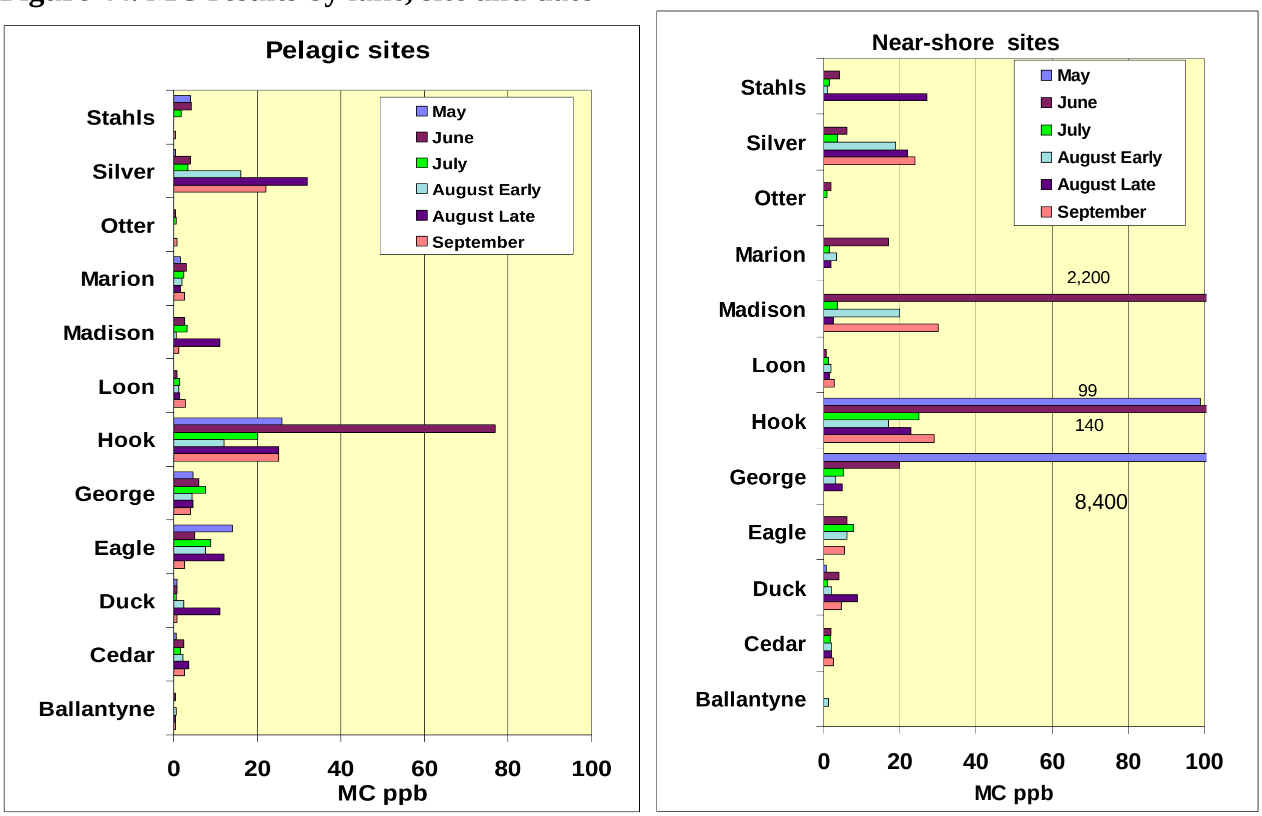
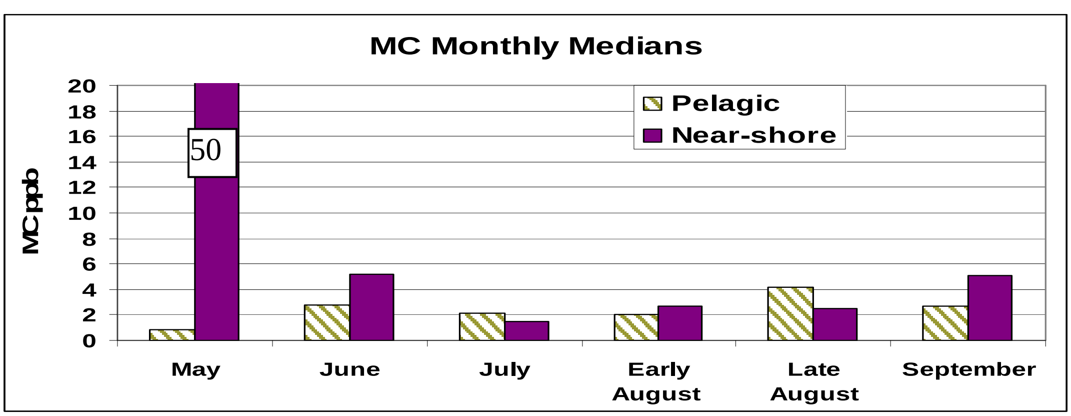


Figure 45. Monthly Median MC

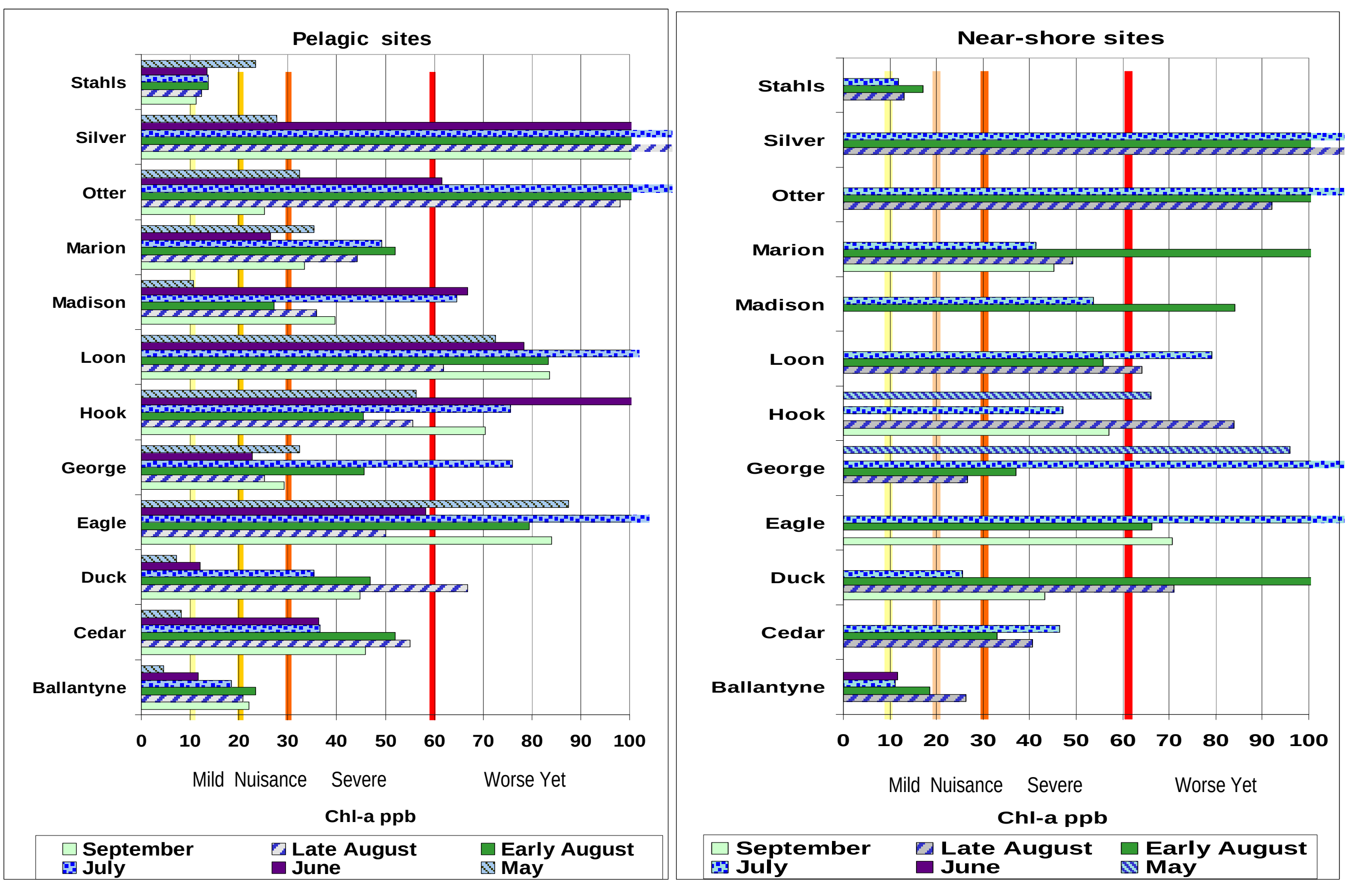


Chlorophyll-a, bloom frequency and MC

Chlorophyll-a is our principal measure of algal biomass. Heiskary and Walker (1988) associated various concentration ranges of chlorophyll-a with varying levels of blooms, patterned after some earlier work by Walmsley (1984). Based on that work chl-a > 10 is considered a “mild bloom”, >20 ppb “nuisance bloom, >30 ppb “severe nuisance” and >60 ppb “very severe nuisance.” Photos from the 2006 study lakes provide a visual example of the appearance of the lakes relative to these nuisance bloom levels (Appendix I). The relationship among TP and bloom frequency and intensity has been used as one of the basis for establishing nutrient criteria (Heiskary and Wilson, 2005). Here, we will examine how chlorophyll-a and bloom frequency relate to MC.

Summer chlorophyll-a concentrations and trends were highly variable among the study lakes (Figure 45). Several lakes had extremely algae level through the majority of the summer. Pelagic site chlorophyll-a concentrations from Silver and Hook lakes were among highest in the study as was the case for MC (Figures 45 and 43). In contrast, monthly Chl-a results for Loon and Otter Lakes were also very high but MC concentrations were very low (Figure 45 and 43). As with MC, no distinct seasonal trends in chl-a were evident. Based on monthly median chl-a, July had the highest concentrations for the pelagic sites and early August for the nearshore sites.

Figure 46. Chlorophyll-a concentrations by lake, site and date



Combining median MC and chl-a for each lake provides an opportunity to look for patterns among these two measurements for the study lakes (Figure 47). No strong pattern is evident based on this comparison; however it does appear that when median chl-a remains below about 40 ppb, median MC remains below 5 ppb.

Figure 47. Chl-a monthly medians by site

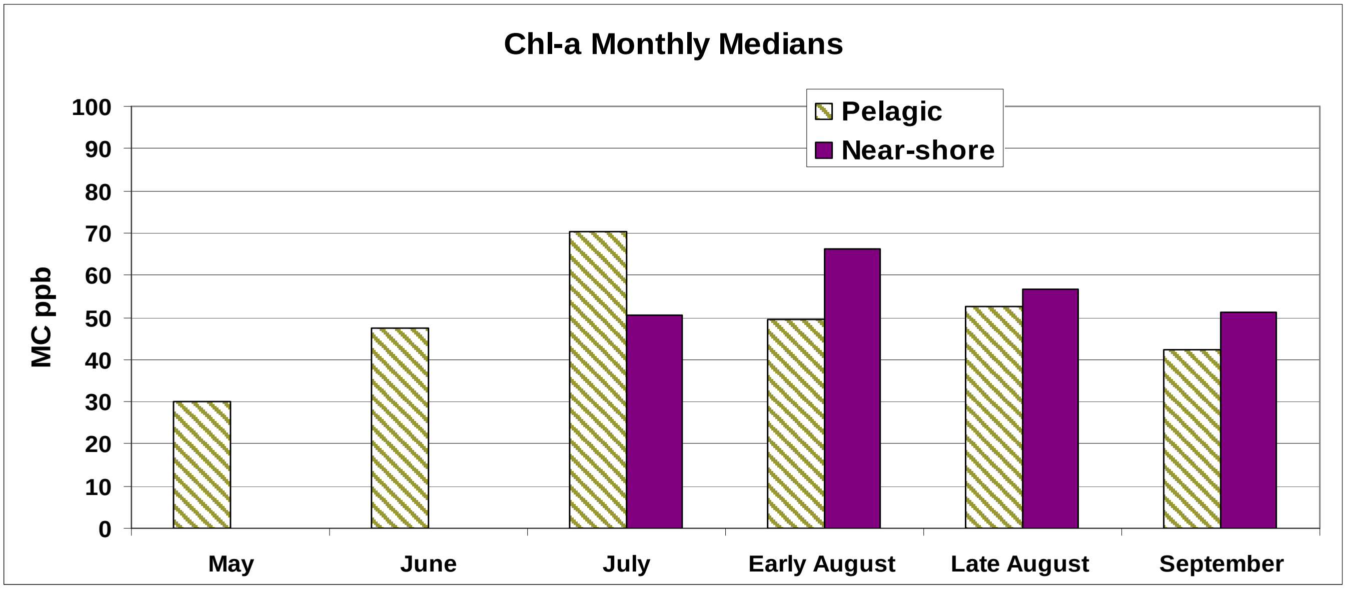
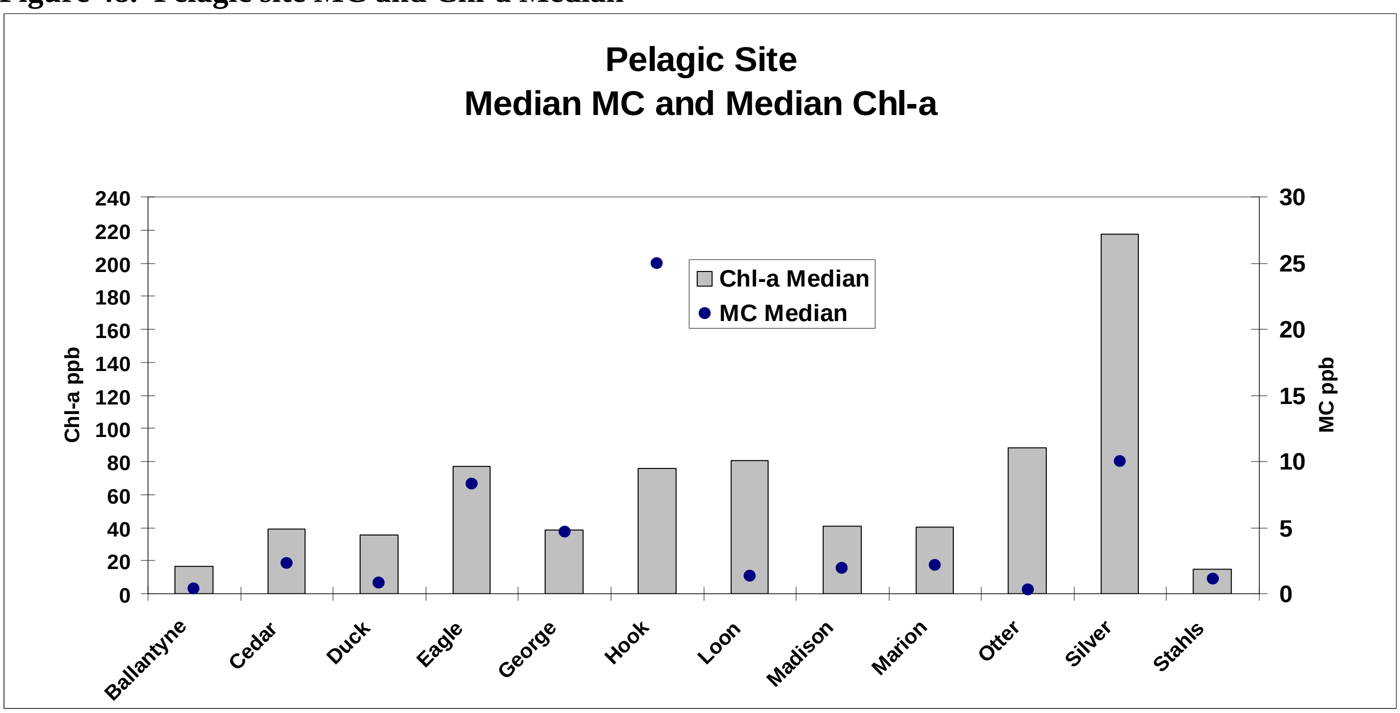


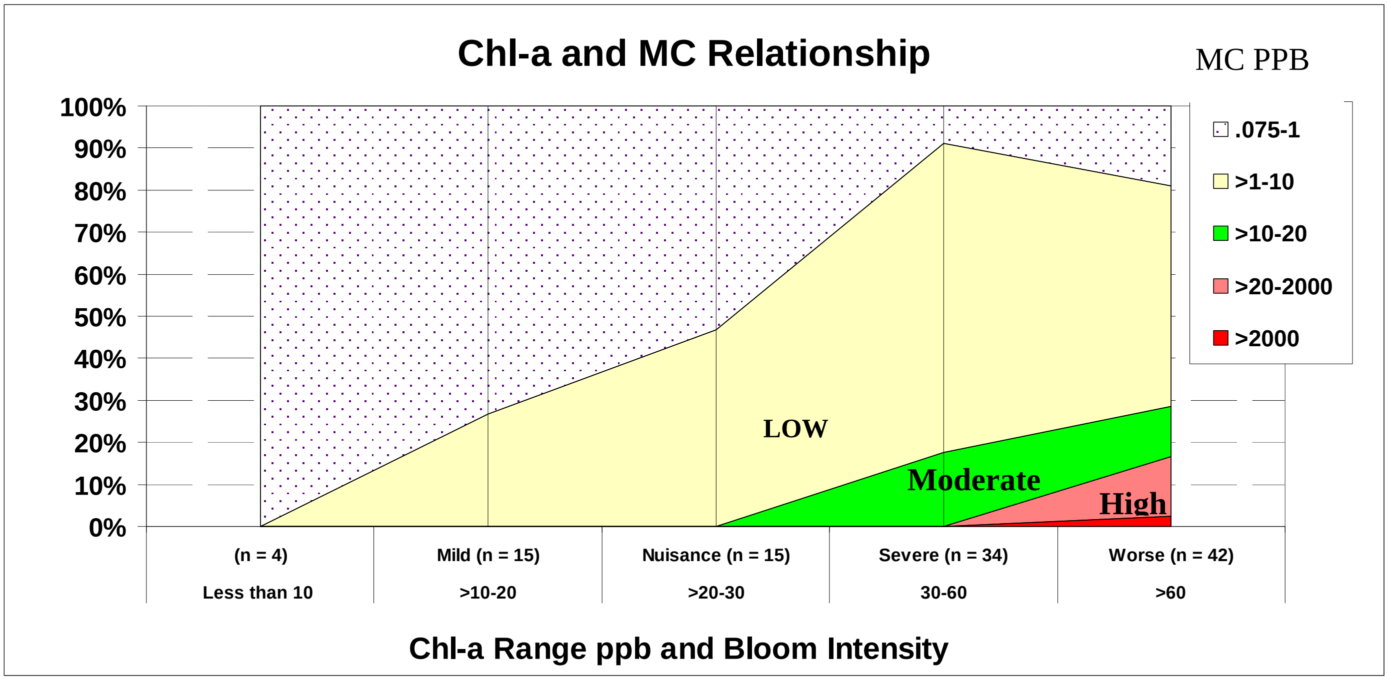
Figure 48. Pelagic site MC and Chl-a Median



Chl-a and MC relationships

Combining MC and bloom intensity provides a basis for describing the "risk" of encountering specified levels of MC as a function of bloom intensity. Based on Figure 49, moderate MC concentrations were not encountered until blooms exceeded 20 ppb (nuisance level). As blooms exceeded 30 ppb (severe nuisance) the frequency of moderate MC increased to 20 percent and by 60 ppb the likelihood of encountering moderate MC increased to 30 percent. All high risk MC were associated with chlorophyll-a > 30 ppb.

Figure 49. Bloom intensity and MC

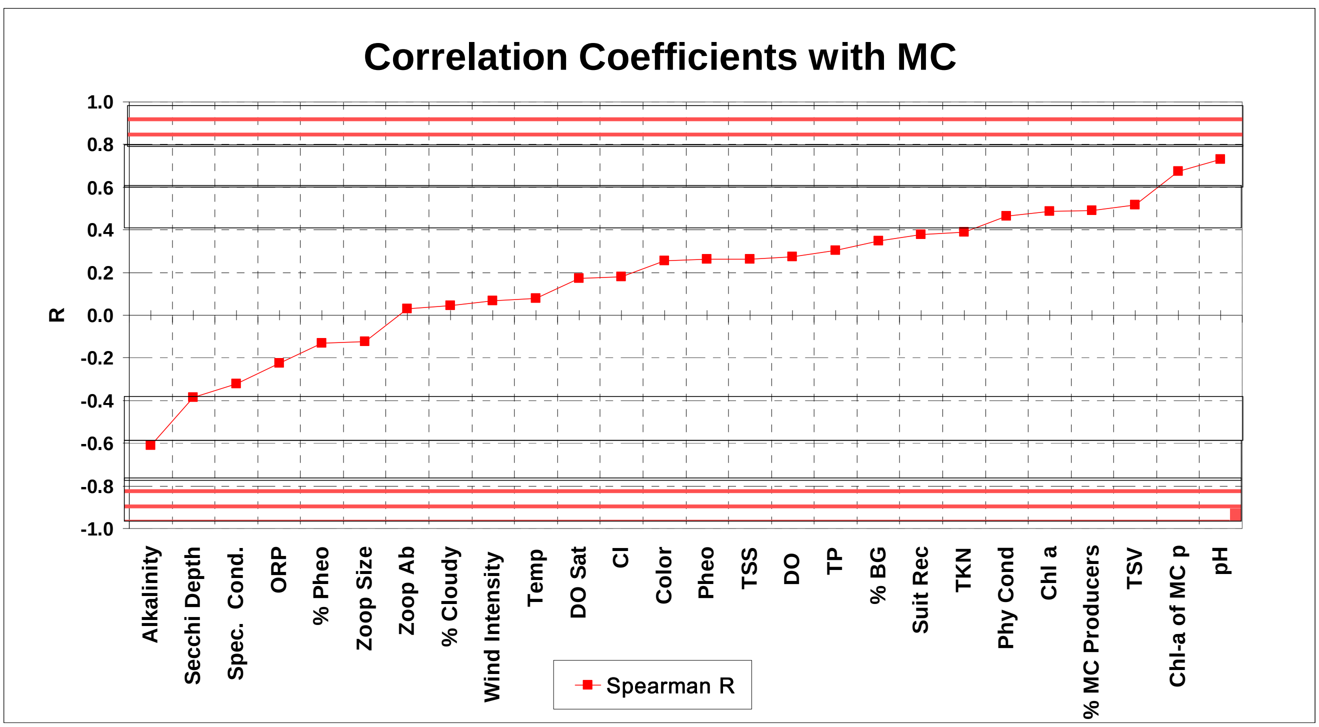


MC and other environmental factors

Field and laboratory studies have demonstrated that the relationship between cyanobacteria, MC concentration, and environmental factors is invariably complex (Graham et al, 2004). Some work indicates that variations in toxin producing-strains have more impact on MC than environmental (Ingrid and Bartram 1999). Thus without getting to the DNA level of analysis, isolating key environmental factors affecting MC is problematic.

Associations were evaluated between MC and several chemical, biological, and physical variables. The wide range of MC concentrations makes direct correlation to environmental variables difficult to assess. The non-normal distribution of the data suggest that rank statistics may provide the most appropriate means for characterizing associations among MC and the wide array of environmental data collected. Spearman's rank correlation coefficient (R_s) resulted in four moderately and three highly correlated relationships (Figure 50). In contrast, Pearson Correlation Coefficient (R_p) identified only three moderate correlated relationships. All of the factors exhibiting high correlation with MC were also highly correlated with algal biomass or productivity as well (Appendix II). Factors exhibiting strong positive R_s with MC include: pH, MC producer chl-a (Chl-a * % MC producers), % MC producers, TSV, chl-a, and subjective measures of physical condition. Negative relationships were found with alkalinity, Secchi depth, and specific conductance. Several of these associations will be explored in greater detail below.

Figure 50. Spearman Correlation Coefficients



pH

The strongest relationship found with MC was pH with a R_s=0.73 (Figure 51) and a R_p of 0.55. This is not necessarily intuitive since waters of moderate to high alkalinity (Table 3) often have high buffering capacity and high pH as well. In this instance the high correlation with pH is likely a reflection of the algal productivity. "Rapid photosynthesis can rapidly reduce the total DIC and increase pH "(Wetzel 2001). In this study higher pH values were seen in chl-a conditions above 40 ppb (Figure 52). These results were consistent with the chl-a and pH correlations observed by Paerl and Ustach (1982). As a matter of perspective the state water quality standard for pH is 9. In general Cyanobacteria prefer a high pH environment. Shapiro (1973) notes that, "At a low pH, cyanobacteria have lost their competitive advantage over eukaryotic algae". With a single exception, all the high risk MC events corresponded to pH levels greater than 9.3.

Chl-a of MC producers

Algal analysis, which focused on dominant algal forms, allowed us to characterize the proportion of the algal community that potentially produces MC (referred to as MC producers or MCP). This percentage when used in conjunction with the chl-a concentration we were able to estimate the percent of the chl-a attributed to these taxa. The resulting relationship between MC and Chl-a of MCP was significant with R_s = 0.67 (Figure 53) but not significant when analyzed with direct linear regression R_p= 0.089.

Figure 51. pH and MC relationship

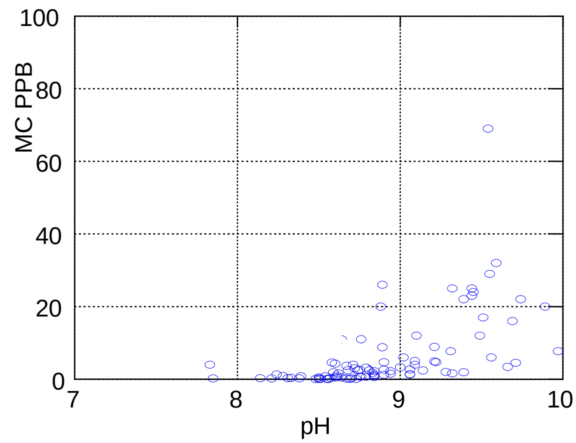


Figure 52. pH and Chl-a relationship

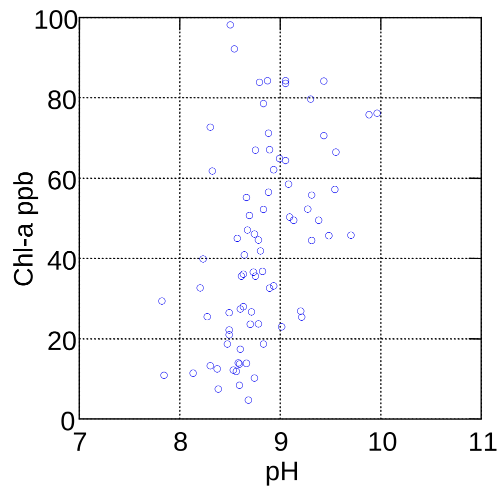
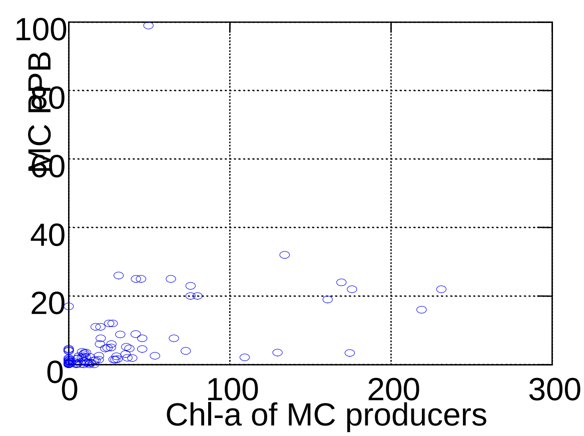


Figure 53. MC producers Chl-a vs. MC



Alkalinity

Alkalinity showed a moderate negative relationship with MC based on a R_s of 0.61 (Figure 54a) Several species of cyanobacteria are capable of precipitating calcium carbonate (Wehr and Sheath 2003) and this may contribute to this relationship. Again as with pH it is likely a reflection of high blue-green algal productivity rather than a factor that may contribute to elevated MC. The relationship between alkalinity and pH for these lakes is depicted in Figure 54b, which suggests an inverse relationship – presumably caused by the high algal productivity in these lakes.

Total Volatile Solids

MC is had a moderate linear relationship with a R_s of 0.51 (Figure 55). This relationship is thought to simply be a function of the high co-linearity with chl-a as algae make up much of the TSV in these lakes.

Figure 54. Alkalinity vs. (a) MC and (b) pH

a.

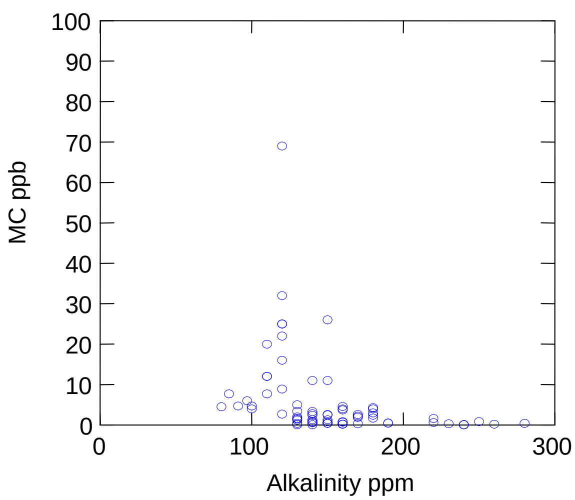


Figure 54

b.

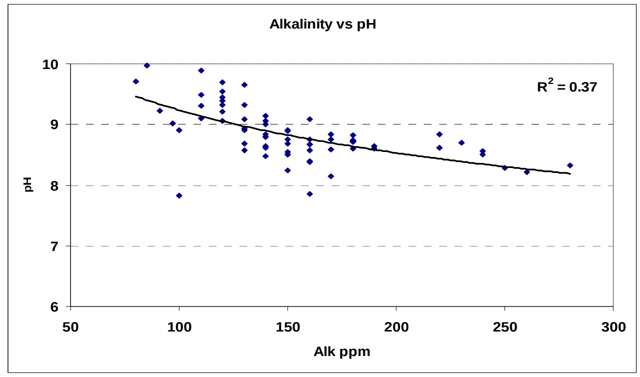
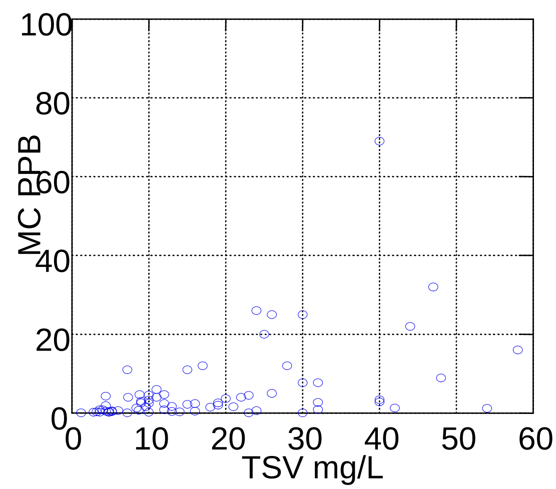


Figure 55. MC vs. TSV



% MC producers

Higher concentration of MC producing taxon showed a moderate relationship with MC levels (Figure 56). All of the high risk MC events were from algal communities of 50% or greater MC producing taxon.

Secchi

A strong inverse relationship between Secchi and algal biomass (chlorophyll-a) has long been noted. This relationship is not best defined in linear terms but rather suggests somewhat of a “threshold” effect. MC also negatively related to Secchi depth (Figure 57). The MC Secchi relationship showed a threshold effect as well, Secchi declines below about 0.5 m the “risk” of moderate to high MC increases (Figure 57). This relationship may be even more pronounced if we had Secchi data from some of the nearshore sites with the very high MC.

Chlorophyll-a

No significant linear relationship (R_p) was noted among Chl-a and MC. Other MC studies have shown strong shown stronger R_p relationships, such as the Daechung Reservoir (Oh et. al. 2000), but do not have the extreme MC results. In contrast the Rs of pH and MC in of the south central Minnesota lakes is much stronger at 0.462. All high risk events occurred at Chl-a levels >45ppb (Figure 58).

Figure 56. MC vs. % MC producers

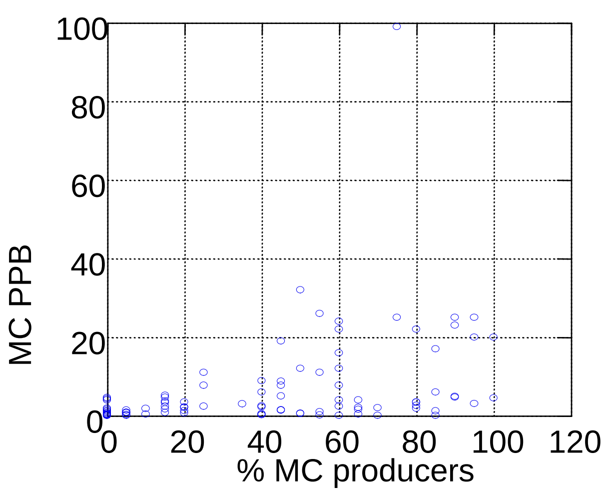


Figure 57. MC and Secchi relationship

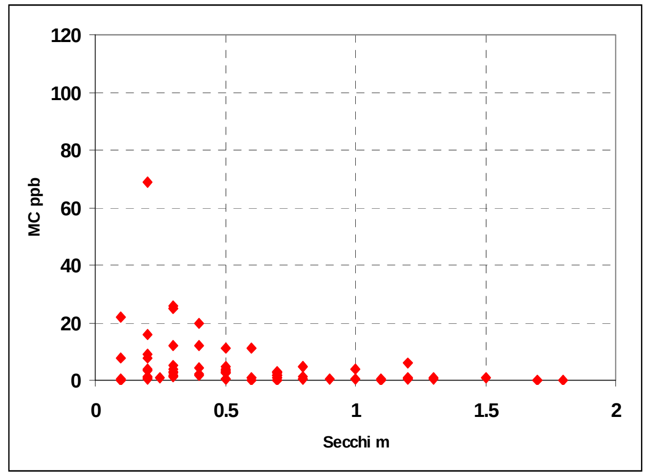
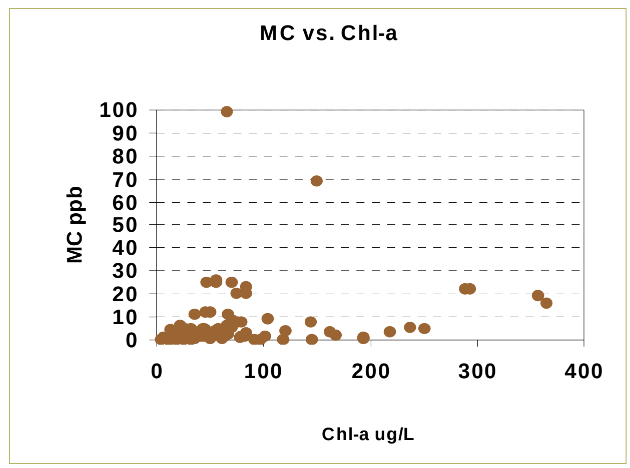


Figure 58 Chl-a and MC correlation



Summary

Cyanobacteria have the ability to produce several different toxins, which may be acutely and chronically toxic. There has been extensive study world-wide on this issue and numerous articles in the literature document toxic events attributed to cyanobacteria, describe the toxicity and action of the various toxins, and describe development of action levels and thresholds that express the relative risk of these toxins. Other studies, such as Graham et al. (2004) describe the distribution of particular toxins (MC) and some environmental factors that may contribute to production of the toxin.

Our study focused on a single algal toxin, Microcystin, and in we chose to focus on several eutrophic to hypereutrophic lakes in south-central Minnesota. While developing our study we posed several questions intended to advance our knowledge on the extent, magnitude and frequency of MC in Minnesota lakes, describe factors that are associated with high MC and use this information in shaping our risk communication on this topic. The questions re-stated below, provide a basis for organizing our summary comments:

1. What is the likelihood of encountering measurable MC at a pelagic site in a eutrophic to hyper eutrophic lake?
2. What is the likelihood of the same when measuring MC in a near-shore site?
3. What is the distribution of MC values for both pelagic and near-shore sites? Are these distributions significantly different?
4. How do values from this study compare to levels found elsewhere? How do they compare to World Health Organization guideline levels?
5. Is there some seasonality to MC levels in these lakes?
6. As bloom intensity (chlorophyll-a) increases is there a greater likelihood of encountering high MC values?
7. What limnological and physical factors appear to be associated with high MC concentrations?
8. How can these findings be used to communicate risk to lake users?

MC was above the MDL (>0.15 ppb) in over 94% of the 133 samples collected from May – September at both near-shore and pelagic sites. Over 60% of the pelagic MC samples were 1 ppb or less as compared to 25% of the near-shore samples. The near-shore samples exhibited a much larger range (Table 5) and much higher maximum value (8,400 ppb) as compared to the pelagic samples (69 ppb). Likewise near-shore mean and median MC was higher than the pelagic samples (Table 5). This finding of elevated MC in the Nearshore area is consistent with observations made by Watzin et. al. in 2004.

WHO guidelines provided a basis for evaluating the relative risk of the MC levels measured in this study. The concentrations ranges and risk categories are as follows: 0.075 – 1 ppb very low risk, 1- 10 ppb low risk, 10 - 20 moderate risk, 20 – 2000 ppb high risk, and > 2,000 ppb very high risk. 80% of all MC values were in the WHO low risk category for recreational waters (82% pelagic and 72% near-shore). The remainder of the pelagic samples were in the moderate to high risk category. Only two near-shore samples were in the very high risk category.

We anticipated that there would be some seasonality to the MC concentrations, perhaps consistent with patterns we often observe for chlorophyll-a and nuisance algal blooms – whereby late summer is often characterized by elevated chlorophyll-a and severe nuisance blue-green algal blooms. However, for this group of lakes and this particular year, there was no distinct seasonality to the MC concentrations. This was due in part by three lakes exhibited very high MC in May and June at near-shore sites. If the pelagic sites are considered separately there was a weak seasonal trend with MC peaking in late August (Figure 44).

A relatively distinct relationship was observed among MC and algal bloom intensity. When chlorophyll-a remained <20 ppb (less than nuisance bloom condition) MC was in the very low to low risk categories (Figure 48). As chlorophyll-a increased to >30 ppb MC was in the moderate risk range in about 20% of the samples and as chlorophyll-a increased to >60 ppb the risk increased to 30%. High and very high risk MC were found only when chlorophyll-a was >60 ppb.

Several limnological and physical factors were tested for their association with MC. Because of extreme values and a non-normal distribution it was felt the non-parametric Rs was the most appropriate correlation to use in this case. Based on this exercise, strong positive relationships with MC were noted (in decreasing order of Rs) for pH, chl-a of MCP, TSV, %MCP, chlorophyll-a, and physical condition rating (Figure 50). Strong negative relationships were found for alkalinity, Secchi and specific conductivity. As the relative abundance of MC producers (in terms of algal composition and biomass) increases, MC tends to increase as well. Alkalinity shows a moderate negative relationship with MC (Rs = 0.61; Figure 53a). It is unlikely that alkalinity itself is a direct driver of MC production. The correlation with TSV is most likely due to the fact that most of the TSV is comprised of algae. The correlation with pH and alkalinity to some degree is an expression of the algal productivity of the lake and the fact that some blue-greens are capable of precipitating calcium carbonate. We also noted that, with the exception of one sample, all lakes with MC in the moderate to high range had a pH of 9.3 or greater. The negative correlation with Secchi is a function of both the overall abundance of algae (chlorophyll-a) and to some degree the fact that several of the MCP have rather small cells that form dense colonies that limit light (hence low Secchi). In contrast to the non MCP Aphanizomenon, which forms large "rafts" that float at the surface and may allow for higher transparency. In the case of these lakes moderate – high MC was found only when Secchi was 0.5 or less.

This study, as is the case with most studies on MC, does not allow us to accurately predict which algal blooms will produce MC in the moderate to very high risk range. However, the study does suggest that our current recommendations to the public to avoid contact with severe nuisance blooms, which we have depicted on a poster and Appendix I of this report, is sound advice. These severe and very severe nuisance blooms are readily recognizable to staff and the public in general. Further we found that high pH (9.3) and low Secchi (two parameters that are easy to measure) were commonly associated with moderate to high MC as well.

Risk Communication

Minnesota does not have widely accepted thresholds (nor do most states) for assessing MC risk for aquatic recreational use. Hence for this study we have used the WHO thresholds but have made no attempt to assess their validity for assessing risk in Minnesota's waters. It may be desirable to more closely review these and other thresholds and try to arrive at some general agreement among resource management agencies such as MDH and MDNR to see if mutually agreed upon thresholds can be developed for the purpose of assessing the risk to humans and animals that may come in contact with or consume water containing MC. Also from a risk communication standpoint, it is important to remember that there are several other toxins (e.g. saxitoxin and anatoxin) that may be produced by Cyanobacteria as well as other algae. It may be important to determine their relative concentration and how they may vary relative to MC, chlorophyll-a and other factors we have considered in this study.

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Appendix I Methods details

Phytoplankton Assessment

Minnesota Phytoplankton Rapid Assessment Method

1. Pour preserved sample into settling chamber. Allow to settle (often overnight).
2. Scan sample using an inverted microscope and identify genera (and species where identified) of algae present in sample.
3. Under lower power, scan a large enough proportion of sample to estimate percent abundance by volume, for each genera identified. Estimate should consider size and density of types. Typically do not count anything less than 5% based on biovolume.
4. Record estimated percent abundance for each taxon.
5. Optional: Calculate estimated chlorophyll-a value for each taxon based on measured chlorophyll-a concentration for the sample.

[Method as originally described by Dr. Ed Swain and Carolyn Dindorf, Minnesota Pollution Control Agency, 6/16/1989. Comments or questions on methodology can be directed Dr. Howard Markus at howard.markus.pca.state.mn.us, or (651) 296-7295.]

Table of physical condition and recreational suitability rankings

Physical Conditions		**Suitability for Recreation**	
Crystal Clear	1	Beautiful	1
Some Algae Present	2	Minor Aesthetics Problems	2
Definite Algae Present	3	Swimming Slightly Impaired	3
High Algae Color	4	No Swimming Slightly Impaired	4
Severe Bloom (odorous scum)	5	No Aesthetics Possible	5

Wind intensity categories

Category	**Wind Speed mph**
1	0 – 5
2	6 – 10
3	11 - 15
4	16 - 20
5	>21

Zooplankton categories

Abundance		**Size**	
None	0	Very Small	1
Few	1	Small	2
Moderate	2	Medium	3
Fair	3	Large	4
High	4		

Appendix II

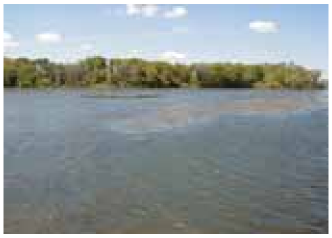
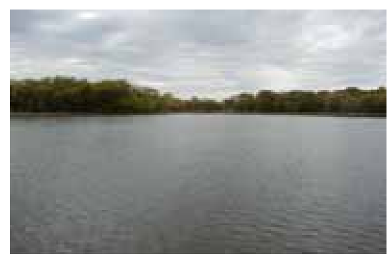
Correlation matrix for Spearman Rank (R_s)

	MC	Temp	DO	Spec Cond	pH	ORP	DO Sat	TSS	TSV	Color	Alk	Cl	TP	TKN
MC	1.00	.	.	.	.	.	.	.	.	.	.			
Temp	0.07	1.00	.	.	.	.	.	.	.	.	.			
DO	0.28	0.04	1.00	.	.	.	.	.	.	.	.			
Spec Cond.	-0.32	-0.10	0.04	1.00	.	.	.	.	.	.	.			
pH	0.73	0.36	0.42	-0.26	1.00	.	.	.	.	.	.			
ORP	-0.22	-0.54	0.24	0.30	-0.34	1.00	.	.	.	.	.			
DO Sat	0.18	0.37	0.92	0.02	0.43	0.05	1.00	.	.	.	.			
TSS	0.28	0.06	0.16	0.09	0.43	-0.06	0.22	1.00		.	.			
TSV	0.53	0.18	0.21	-0.11	0.67	-0.16	0.27	0.91	1.00	.	.			
Color	0.27	0.11	0.20	0.02	0.38	-0.18	0.31	0.54	0.49	1.00	.			
Alkalinity	-0.60	-0.29	-0.09	0.63	-0.68	0.25	-0.14	-0.10	-0.37	-0.15	1.00			
Cl	0.18	-0.03	0.19	0.26	0.32	0.10	0.16	0.55	0.53	0.18	-0.05	1.00	.	.
TP	0.32	0.01	0.20	0.05	0.45	-0.01	0.19	0.92	0.87	0.54	-0.13	0.60	1.00	.
TKN	0.39	0.20	0.17	-0.07	0.54	-0.12	0.23	0.81	0.87	0.50	-0.25	0.49	0.84	1.00
Chl-a	0.49	0.18	0.28	-0.05	0.59	-0.09	0.33	0.83	0.91	0.43	-0.25	0.57	0.85	0.84
% pheo	-0.11	-0.27	-0.29	-0.09	-0.24	-0.02	-0.46	-0.06	-0.16	0.02	0.22	0.01	0.01	0.06
Pheo	0.27	-0.09	0.04	0.01	0.20	-0.03	-0.07	0.56	0.51	0.41	0.01	0.46	0.63	0.56
Pheo + Chl	0.48	0.13	0.25	-0.05	0.55	-0.10	0.26	0.85	0.90	0.44	-0.22	0.57	0.86	0.84
Wind Intensity	0.03	-0.47	-0.04	-0.48	-0.09	0.21	-0.22	-0.14	-0.14	-0.02	-0.14	0.22	0.16	0.12
Cloudy	0.07	-0.17	-0.03	0.08	-0.11	0.02	-0.20	0.11	0.07	-0.01	0.16	0.07	0.15	0.03
Zoop Abundance	-0.04	-0.32	0.02	0.20	-0.13	0.33	-0.13	-0.32	-0.28	-0.25	0.01	0.05	0.21	0.23
Zoop Size	-0.19	-0.19	0.16	0.39	-0.05	0.24	0.07	0.00	-0.04	0.01	0.12	0.17	0.02	0.00
Phy Cond	0.45	0.35	0.08	-0.23	0.40	-0.15	0.21	0.38	0.50	0.25	-0.28	0.12	0.38	0.41
Suit Rec	0.36	0.21	-0.03	-0.44	0.27	-0.17	0.08	0.33	0.40	0.15	-0.32	0.16	0.38	0.43
Secchi Depth	-0.40	-0.31	-0.13	0.04	-0.57	0.17	-0.26	-0.89	-0.90	-0.54	0.20	0.53	0.88	0.83
BG %	0.35	0.40	0.10	-0.37	0.57	-0.33	0.12	0.03	0.23	0.20	-0.61	0.09	0.15	0.27
MC Pro %	0.49	0.32	0.12	-0.42	0.63	-0.38	0.15	-0.08	0.19	0.07	-0.72	0.17	0.04	0.20
Chl-a of MCP	0.67	0.29	0.31	-0.36	0.75	-0.28	0.28	0.14	0.44	0.17	-0.75	0.31	0.32	0.44

	Chl a	% pheo	Pheo	PheoChl	Wind Intensity	Cloudy	Zoop Ab	Zoop Size	Phy Cond	Suit Rec	Secchi Depth	BG %	MC Pro %	Chl-a of MPT
Chl a	1.00													
% pheo	-0.07	1.00	.	.	.	.	.	.	.	.	.	.	.	
Pheo	0.67	0.59	1.00	.	.	.	.	.	.	.	.	.	.	
PheoChl	0.99	0.04	0.75	1.00	.	.	.	.	.	.	.	.	.	
Wind Intensity	-0.18	0.34	-0.06	-0.14	1.00	.	.	.	.	.	.	.	.	
Cloudy	0.06	-0.01	0.10	0.08	0.05	1.00	.	.	.	.	.	.	.	
Zoop Ab	-0.18	-0.18	-0.29	-0.20	0.05	0.20	1.00	.	.	.	.	.	.	
Zoop Size	-0.02	-0.28	-0.20	-0.03	-0.16	0.19	0.63	1.00	.	.	.	.	.	
Phy Cond	0.48	-0.01	0.30	0.45	-0.23	-0.17	-0.34	-0.41	1.00	.	.	.	.	
Suit Rec	0.40	0.14	0.35	0.41	0.04	0.00	-0.38	-0.46	0.75	1.00	.	.	.	
Secchi Depth	-0.88	0.03	-0.58	-0.88	0.23	-0.12	0.33	0.06	-0.48	-0.42	1.00	.	.	
BG %	0.21	-0.19	-0.03	0.18	0.02	-0.15	-0.10	-0.14	0.21	0.15	-0.24	1.00	.	
MC Pro %	0.07	-0.10	-0.06	0.05	-0.05	-0.17	-0.01	-0.11	0.15	0.22	-0.11	0.59	1.00	
Chl-a of MPT	0.50	-0.11	0.29	0.48	-0.06	-0.13	0.01	-0.10	0.28	0.28	-0.36	0.53	0.76	1.00

Appendix III

Study Lake photos based on Chl-a range with MC results

	Duck	May	MC 0.8ppb	Ballantyne	May	MC ND	Cedar	May	MC 0.6ppb
Chl-a < 10									
	Stahl's	June	MC 4.3ppb	Ballantyne	June	MC 0.4ppb	Duck	June	MC 0.8
Chl-a 10-20									
	Marion	June	MC 3.0ppb	Madison	June	MC 0.6ppb	Stahl's	June	MC 4.3ppb
Chl-a 20-30									
	George	Early August	MC4.7	Eagle	Early August	MC 7.7	Cedar	Early August	MC 2.2
Chl-a > 30