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MICHIGAN DEPARTMENT OF ENVIRONMENT, GREAT LAKES, AND ENERGY
WATER RESOURCES DIVISION
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STAFF REPORT

ALGAL TOXIN MONITORING IN MICHIGAN INLAND LAKES: 2016-2019 RESULTS

Introduction

The term “harmful algal bloom (HAB)” generally describes accumulations of cyanobacteria that are aesthetically unappealing and produce algal toxins. In 2015 the Michigan Department of Environment, Great Lakes, and Energy (EGLE), Water Resources Division (WRD), developed the following definition of a HAB (Kohlhepp, 2015): “An algal bloom in recreational waters is harmful if microcystin levels are at or above the 20 micrograms per liter (µg/L) World Health Organization non-drinking water guideline, or other algal toxins are at or above appropriate guidelines that have been reviewed by EGLE-WRD.” A key concept of this HAB definition is that while high chlorophyll *a* concentration and visible surface/water column algal accumulations can indicate potential problems, the WRD’s focus is on the potential harm that toxins represent. Thus, water samples must be analyzed for the presence of toxins to confirm that a bloom may, in fact, be potentially harmful to humans, pets, or wildlife. Visible appearance of blooms cannot be used as a reliable predictor of toxin content.

Cyanobacteria are one of the oldest life forms on Earth (e.g., Schirrmeister et al., 2016) that can live in terrestrial, marine, and freshwater environments (Chorus and Bartram, 1999). The potential harmful effects of cyanobacteria on animals have been documented as far back as the 19th century (Francis, 1878; Arthur, 1889). More recent work has focused on the potential harmful effects of cyanobacterial toxins on humans and pets (Koreivienė et al., 2014; Trevino-Garrison et al., 2015; Zhang et al., 2015). Incidences of cyanobacterial blooms have increased worldwide in the last several decades (Carmichael, 2008; O’Neil et al., 2012; Taranu et al., 2015; Scholz et al., 2017). Given future climate scenarios and the increased amount of nutrients required for more intensive agricultural practices, the frequency, duration, and magnitude of cyanobacteria blooms are expected to increase worldwide (Jöhnk et al., 2008; Reichwaldt and Ghadouani, 2011; Posch et al., 2012; Michalak et al., 2013; Paerl, 2018).

In Michigan, previous research on inland lake HABs has focused on zebra mussel (*Dreissena polymorpha*) and quagga mussel (*Dreissena bugensis*) invasions and the subsequent increases in cyanobacteria biomass and microcystin production (Raikow et al., 2004; Sarnelle et al., 2005; Wilson et al., 2005; Knoll et al., 2008; Woller-Skar, 2009; Sarnelle et al., 2010; White et al., 2017; Gaskill and Woller-Skar, 2018). Other research has focused on cyanobacteria and microcystin production dynamics in specific water bodies of interest, particularly in west Michigan (Hong et al., 2006; Rediske et al., 2007; Gillett and Steinman, 2011; Xie et al., 2011; Xie et al., 2012; Gillett et al., 2015) and Ford and Belleville Lakes (Washtenaw and Wayne Counties; Lehman, 2007; Lehman et al., 2009; Lehman, 2014). EGLE has been monitoring the number of citizen and staff complaints regarding nuisance algae and cyanobacteria (Parker, 2014; 2015; 2016a; 2016b; 2018a; Stieber, 2019; Baldwin, 2020) and monitoring the concentration of the cyanobacterial toxins microcystin, anatoxin-a, and cylindrospermopsin in the State of Michigan for the last several years (Holden, 2016; Parker, 2017; 2018b; 2019).

This report summarizes cyanobacteria toxin monitoring from 2016 through 2019. This report is an update to the 2016-2018 data summary by Parker (2019) with 2019 data incorporated. The purpose of this report is to: (1) evaluate the geographical extent of HABs throughout Michigan (i.e., how widespread is the problem?); (2) compare microcystin concentrations between cyanobacterial scums and nearby ambient water; and (3) explore any patterns that can explain cyanobacterial bloom occurrence throughout the state. For information on efficacy of commercial test strips and exploration of microcystin relationships with chemical/physical variables in lakes across the state, see Parker (2019). Raw data from 2016-2018 are available in past reports (Parker, 2017; 2018b; 2019). Raw data from 2019 are available at the end of this report (Appendix 1).

Sites

The lakes that are assessed in this report can be placed in three broad categories: randomly-selected lakes that were sampled for limnological parameters as part of the Inland Lakes Status and Trend Program (Walterhouse, 2015), targeted lakes that were visited because EGLE staff were aware of previous cyanobacteria blooms that had taken place in them, or because they were sampled as part of Total Maximum Daily Load (TMDL) development, and lakes that EGLE received complaints about either from citizens or staff (Figure 1).

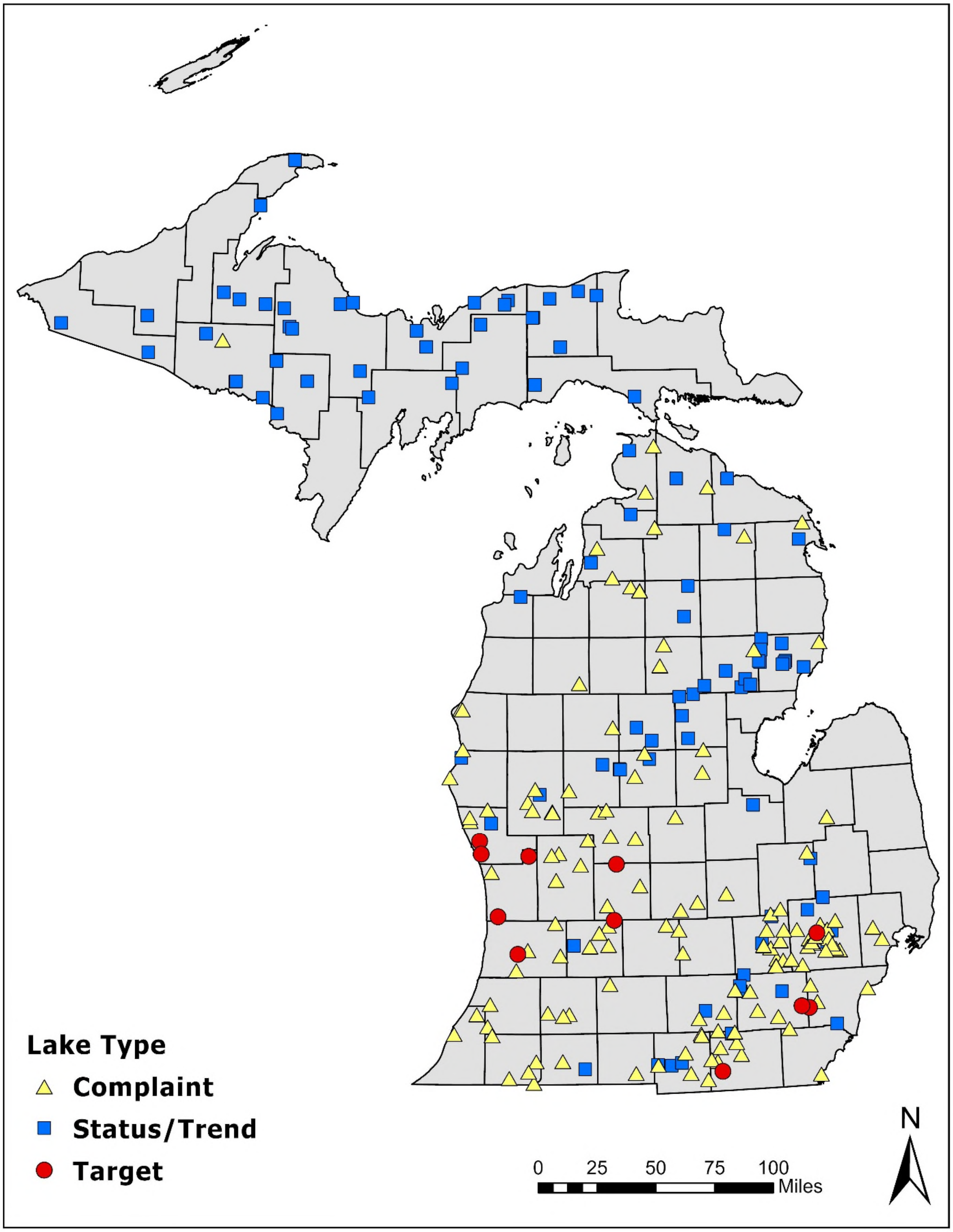

Figure 1. Different types of lakes sampled for cyanobacterial toxins from 2016-2019.

Field Methods

Sampling occurred between early May and late November, with most monitoring occurring in August and September. During a monitoring event at a lake, EGLE-WRD staff typically took pictures of algal conditions, collected general water chemistry in the center of the lake (if accessible by boat), and collected water samples for cyanobacteria toxin analysis from up to four locations around the lake. If a water body was inaccessible by boat, then only shoreline samples were collected for toxin analysis and nutrient and chlorophyll samples were not collected. The cyanobacteria toxin samples were analyzed using both Abraxis (Abraxis, Inc., Warminster, Pennsylvania) test strips to assess microcystin presence/absence and tandem liquid chromatography mass spectrometry (LC/MS/MS) for quantitative assessment of a suite of cyanobacterial toxins including microcystins, cylindrospermopsin, nodularin, and anatoxin-a (Table 1).

Water Samples - General Chemistry

Water sample parameters collected at the status and trend lakes, targeted lakes, and some response lakes were generally similar. At all lakes, temperature, dissolved oxygen, conductivity, pH, chlorophyll *a* concentration, chlorophyll relative fluorescence unit, phycocyanin concentration, and phycocyanin relative fluorescence unit were measured using an EXO sonde (YSI Incorporated, Yellow Springs, Ohio). In some cases, with the response lakes, the staff who were available to collect the water samples did not have access to an EXO sonde unit. In those cases, only water samples were collected for the purpose of cyanobacteria toxin analysis. Nutrient surface water samples were collected at approximately 0.5 feet below the water surface using new, 250 milliliter (ml) polypropylene sample bottles that were triple-rinsed with site water. At targeted lakes and response lakes where a boat could be taken to the center of the lake, the following samples were collected: total phosphorus, Kjeldahl nitrogen, nitrate+nitrite, ortho-phosphate, and chlorophyll *a*. The total phosphorus, Kjeldahl nitrogen, and nitrate+nitrite were preserved with sulfuric acid in the field. Chlorophyll *a* samples were collected as an integrated sample of the photic zone (twice the Secchi depth) and preserved with magnesium carbonate in the field. The samples were analyzed at the EGLE Environmental Laboratory using standard United States Environmental Protection Agency (USEPA) methods (Table 1). At the status and trend lakes the same nutrient samples were collected, excluding ortho-phosphate. The August status and trend water chemistry samples were collected by the Michigan Department of Natural Resources-Fisheries Division staff and analyzed by the Great Lakes Environmental Center, Traverse City, Michigan. Following collection, sample bottles were placed on ice or refrigerated for transport and storage prior to delivery to the laboratory. At targeted lakes, the nutrient samples were not collected at every sampling event if sampling occurred several times over a week.

Water Samples - Algal Toxins

At most lakes that were sampled by boat, one sample over the deepest part of the lake and at least three shoreline samples were collected in 250 ml polyethylene terephthalate sample bottles at the water surface. Shoreline samples were typically collected at 1- to 6-foot depths. If sampling by boat, the shoreline sampling locations were distributed approximately evenly around the shoreline of the lake. However, downwind locations, areas that may be used for recreation, or beaches were preferentially targeted. When boat access was not available, attempts were made to sample an even distribution of the shoreline; however, sampling locations were limited to areas of public access and/or private property that EGLE workers received permission to access. Prior to sampling, bottles were triple-rinsed with site water and samples were collected from an undisturbed area of water. Cyanobacteria toxin samples at the targeted and response lakes were collected at the water surface (i.e., the bottles were not submerged under water). At the status and trend lakes, sample bottles were collected about

0.5 feet below the water surface. When scum accumulations were present, and accumulated in a localized area, one surface scum sample was collected and one ambient (non-scum) sample was collected outside of the accumulation (Figure 2). The ambient samples were collected within 5-15 feet from the edge of the scum accumulations. In cases where surface scums were omnipresent either throughout an entire lake, or throughout a very large section of a lake with no clear demarcation between the scum and ambient water, only a scum sample was collected.

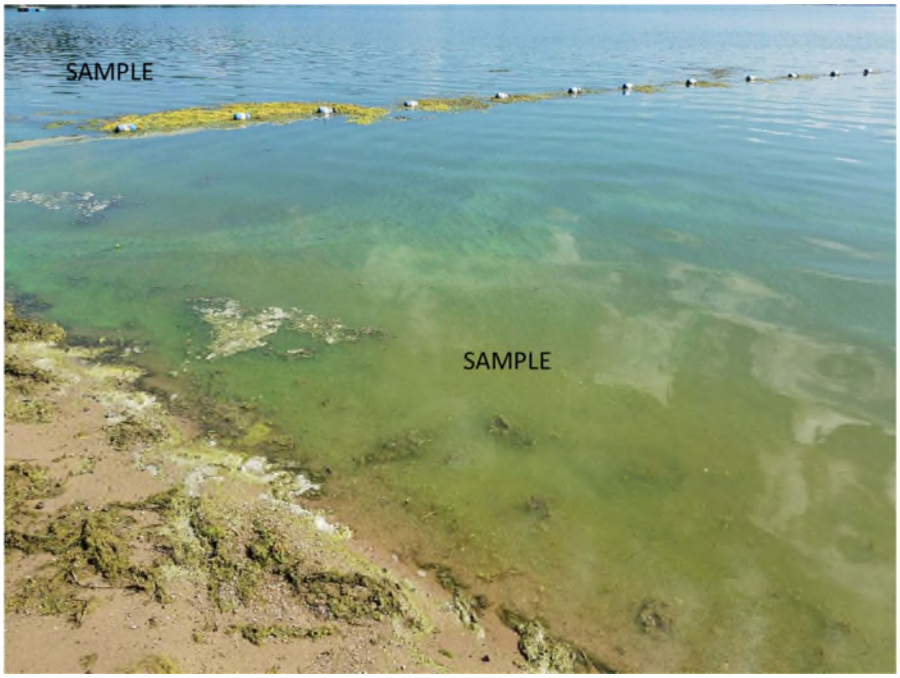

Figure 2. Example of a localized cyanobacteria scum accumulation in which a sample was collected from the scum and the nearby ambient water.

At response lakes, often only shoreline samples were collected from an area with a cyanobacteria accumulation present, or in an area that previously had high concentrations of microcystins. Most of the samples were collected by EGLE staff, although in some cases citizens collected water samples and turned them into EGLE district offices.

Ambient water and scum samples that were analyzed using qualitative and quantitative methods were kept on ice during transport back to the laboratory. Microcystin presence/absence and relative concentration estimate was determined using test strips. If the initial test strip indicated that microcystins were present in the sample, then it was delivered to the Michigan Department of Human Health and Services (MDHHS) laboratory for quantitative analysis. Quantitative analysis of anatoxin-a, cylindrospermopsin, and 10 microcystin congeners (Table 1) was performed using LC/MS/MS. If the Abraxis test strips indicated that no microcystin was present in any samples from a lake, then only one sample was sent to the MDHHS laboratory for further quantitative analysis. As detailed in Parker (2019), commercially-available microcystin test strips have proven to be reliable indicators of microcystin presence/absence.

Microcystin samples were held on ice or refrigerated for no more than 48 hours prior to analysis. If microcystin samples needed to be held longer than 48 hours, they were frozen with care taken to reduce volume to allow for expansion. EGLE-WRD staff analyzed the July status and trend samples and all targeted lake samples using the test strips. The August status and trend samples were analyzed by staff of the Great Lakes Environmental Center and one sample from each lake was analyzed by the MDHHS laboratory.

Table 1. Analytical methods and reporting limits.

Parameter	Analytical Method	Reporting Level (µg/l)
Microcystin RR	LC/MS/MS	0.5
Microcystin YR	LC/MS/MS	0.5
Microcystin HTYR	LC/MS/MS	0.5
Microcystin LR	LC/MS/MS	0.5
Microcystin LR ASP3	LC/MS/MS	0.5
Microcystin WR	LC/MS/MS	0.5
Microcystin LA	LC/MS/MS	0.5
Microcystin LY	LC/MS/MS	0.5
Microcystin LW	LC/MS/MS	0.5
Microcystin LF	LC/MS/MS	0.5
Nodularin	LC/MS/MS	0.5
Anatoxin-a	LC/MS/MS	0.5
Cylindrospermopsin	LC/MS/MS	0.5
Qualitative total microcystin	Abraxis test strips (PN52022)	1
Total Phosphorus	EPA 365.4	10
Kjeldahl Nitrogen	EPA 351.2	100
Ammonia	EPA 350.1	10
Nitrate+Nitrite	EPA 353.2	10
Ortho-phosphate	EPA 365.1	10
Chlorophyll a	10200H (Standard Methods)	1

Data Analysis

The number of water bodies that experienced at least one cyanobacteria bloom between 2016 and 2019 was quantified by reviewing field and laboratory data, photographs from sites that were visited by EGLE staff, and by reviewing photographs that were sent to EGLE from citizens and staff. The distribution of cyanobacteria blooms was assessed along a north-south gradient in Michigan. Centroid latitudes for each Michigan county were calculated with the Calculate Geometry tool function in ArcMap 10.4 (ESRI, 2011) using the NAD 1983 Geographic Coordinate System. For coastal counties, islands were excluded from the calculations, so latitude centroids were only for the mainland. A linear regression was performed on the number of confirmed cyanobacteria blooms (log +1- transformed) in a county versus the centroid latitude for all 83 Michigan counties.

Shoreline development factors (SDF) and maximum depths of water bodies that had experienced cyanobacteria blooms were compared between three lake types: reservoirs, natural lakes with dams, and natural lakes with no water level control structure. “Natural” lakes were defined as having no dam or water control structure at the lake outlet, “natural with dam” is defined as a naturally occurring lake but with some type of water level control structure at the outlet, and “reservoir” was defined as an impoundment (lentic environment only exists because flowing water was impounded). Lake type classifications were mostly obtained from the MiSwims database. Depths and SDF were compared using Analysis of Variance (ANOVA) with Tukey’s honestly significant difference post-hoc testing. Maximum lake depths were mostly obtained from the MiSwims database. In some cases, where depth data were not available for a lake, other reliable sources were located, such as consultant or Michigan Department of Natural Resources reports. A database of calculated SDF values for all Michigan lakes was provided by P. Tyning (Progressive AE, Grand Rapids, Michigan). SDF is the degree of a lake’s shoreline irregularity and is expressed as the ratio of shoreline length to the circumference of a circle of area equal to the lake’s area (Horne and Goldman, 1994). A lake with the least amount of shoreline would be perfectly circular and would have an SDF of 1.0. As shorelines become more irregular (less circular) the SDF increases. A Welch t test was used to compare the microcystin concentrations of all side-by-side scum and ambient water samples that were collected from 2016-2019. Statistical significance for all tests was set at $\alpha = 0.05$.

Results

From 2016-2019, water samples were collected and analyzed for cyanobacteria toxins from 100 different status and trend lakes, 112 complaint water bodies, and 11 targeted lakes. Of the 100 status and trend lakes that were sampled, only three had samples with detectable concentrations of microcystin, with the highest being 6.8 µg/l. Nine of the 11 targeted lakes contained microcystin. Of those nine targeted lakes with microcystin, six had samples with elevated concentrations that were >20 µg/l (Parker, 2017; 2018b).

The number of water bodies that EGLE has received complaints about has increased in the last three years (Figure 3; Parker, 2019). From 2016-2019, EGLE received complaints about algae in 162 different water bodies. A categorization of the number of samples collected from those water bodies, whether cyanobacteria blooms were present, and whether cyanobacterial toxins were found is shown in Figure 4 and detailed as follows: The 162 different water bodies that EGLE received complaints about can be placed into one of three broad categories:
(1) water bodies that could be sampled by EGLE staff within a few days of receiving the complaint; (2) water bodies that were not sampled because EGLE staff were able to determine that the material was not cyanobacteria (typically filamentous green algae, pollen, duckweed), staff were not available to sample, or a bloom had dissipated by the time staff were available to sample; and (3) EGLE received a complaint about algae of cyanobacteria after it occurred (sometimes in the winter months).

Because some complaints about cyanobacteria blooms were confirmed, but never sampled, it was important to separate the number of water bodies with confirmed blooms (86) from the number of water bodies that were sampled (112) in Figure 4. Of the 86 complaint water bodies with confirmed cyanobacteria blooms, 63 of them were sampled by EGLE. Of those 63 water bodies, 38 contained toxins. An important caveat about the mismatch of the 25 water bodies that had confirmed blooms, but no toxins detected, is that most of those lakes were sampled after the bloom had dissipated (sometimes after one day). Only in rare cases were cyanobacterial scums sampled and no toxins detected. Thus, the number of lakes that contained toxins is likely under-estimated. Finally, of the 38 water bodies with detected cyanobacterial toxins, 24 of them contained elevated toxin concentrations. In this case "elevated" toxins were defined as total microcystin concentrations ≥10 µg/l (23 water bodies) and one water body with elevated concentrations of anatoxin-a. Although recreational standards for anatoxin-a have not been established by the USEPA or World Health Organization, it was found in high concentrations in a private pond after several canine deaths occurred following contact with it (Parker, 2020).

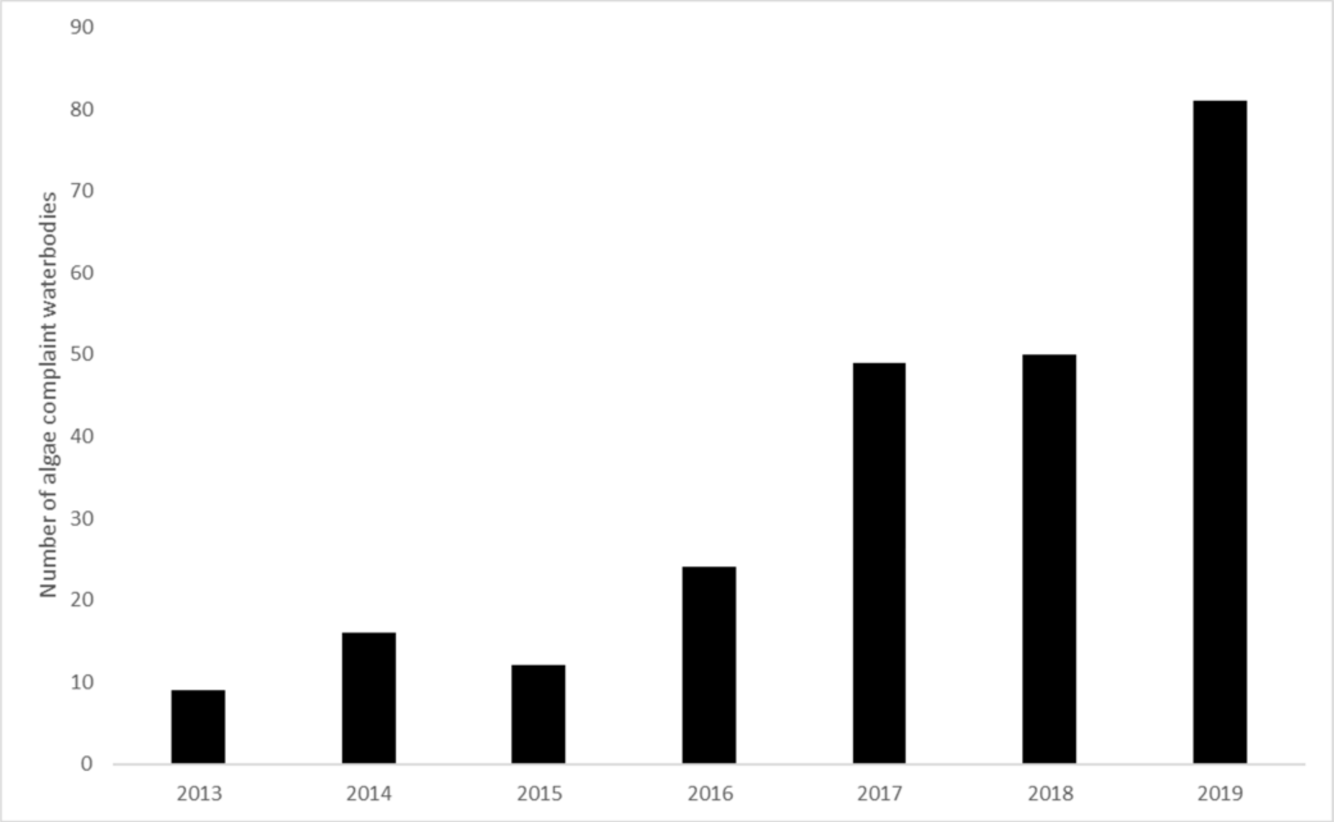

Figure 3. Number of different water bodies with complaints about algae or cyanobacteria from 2013-2019.

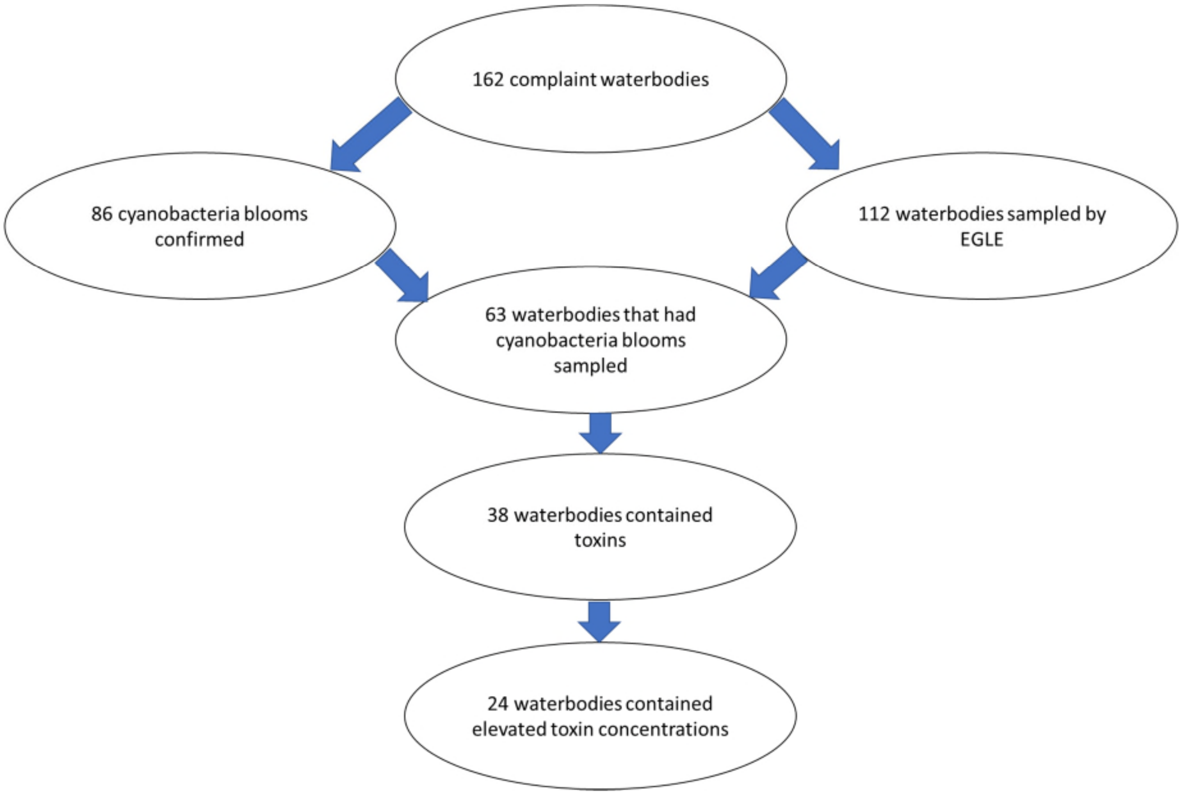

Figure 4. Diagram of the number of complaints received and the break-down of water bodies containing cyanobacteria and toxins.

Throughout the state from 2016-2019, EGLE staff either observed, or were alerted to, 93 confirmed cyanobacteria blooms (note: this number includes the 86 complaint water bodies and water bodies that were targeted for monitoring [targeted and TMDL lakes] by EGLE). All but three of those blooms were in the Lower Peninsula, with the majority of those in the southern half. There was a significant inverse relationship ($R^2 = 0.21$, $p < 0.001$; Figure 5) between the number of blooms per county and the county centroid latitudes, which confirmed our visual interpretation of the map in Figure 6.

Of the lakes that had blooms, a slight majority were either reservoirs or natural lakes with a lake level control structure (24 percent reservoir, 30 percent natural with a dam, 46 percent natural; Figure 6). The exact number of impounded lakes throughout the state has been an elusive number for some time. Brown (1943) estimated that there were 700-800 impoundments (defined as any lake with a dam greater than 2 feet high) throughout the state, although dams were constructed after that report. The United States Army Corps of Engineers has a list of 1,059 impoundments in Michigan in its National Inventory of Dams, although that list includes many small dams that create impoundments < 5 acres in size. Nevertheless, even with the 1,059-impoundment figure, that would put the total number of Michigan lakes that are impounded in some way at approximately 10 percent of all lakes in the state.

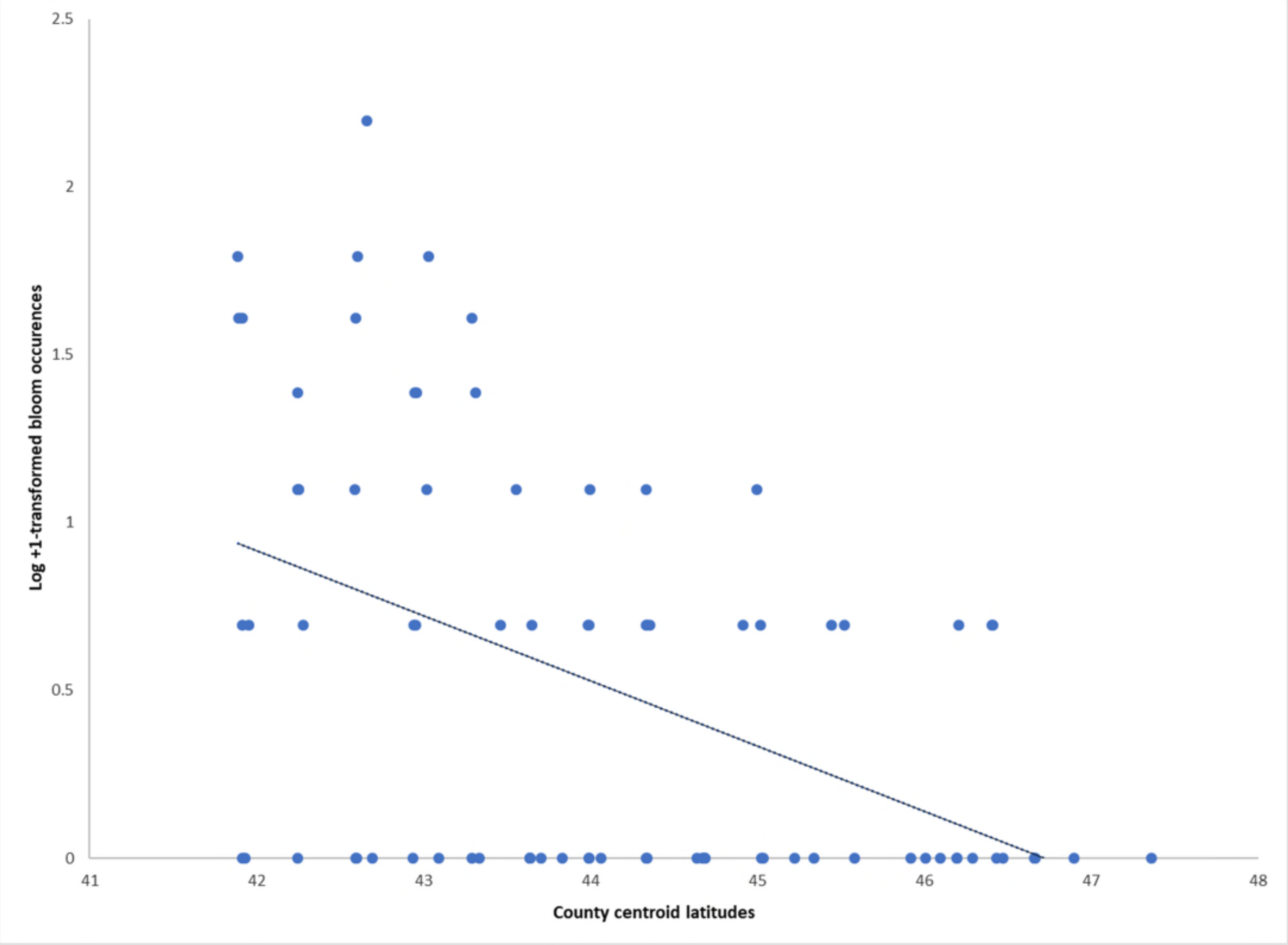

Figure 5. Regression of Log +1-transformed bloom occurrences per county and county centroid latitude.

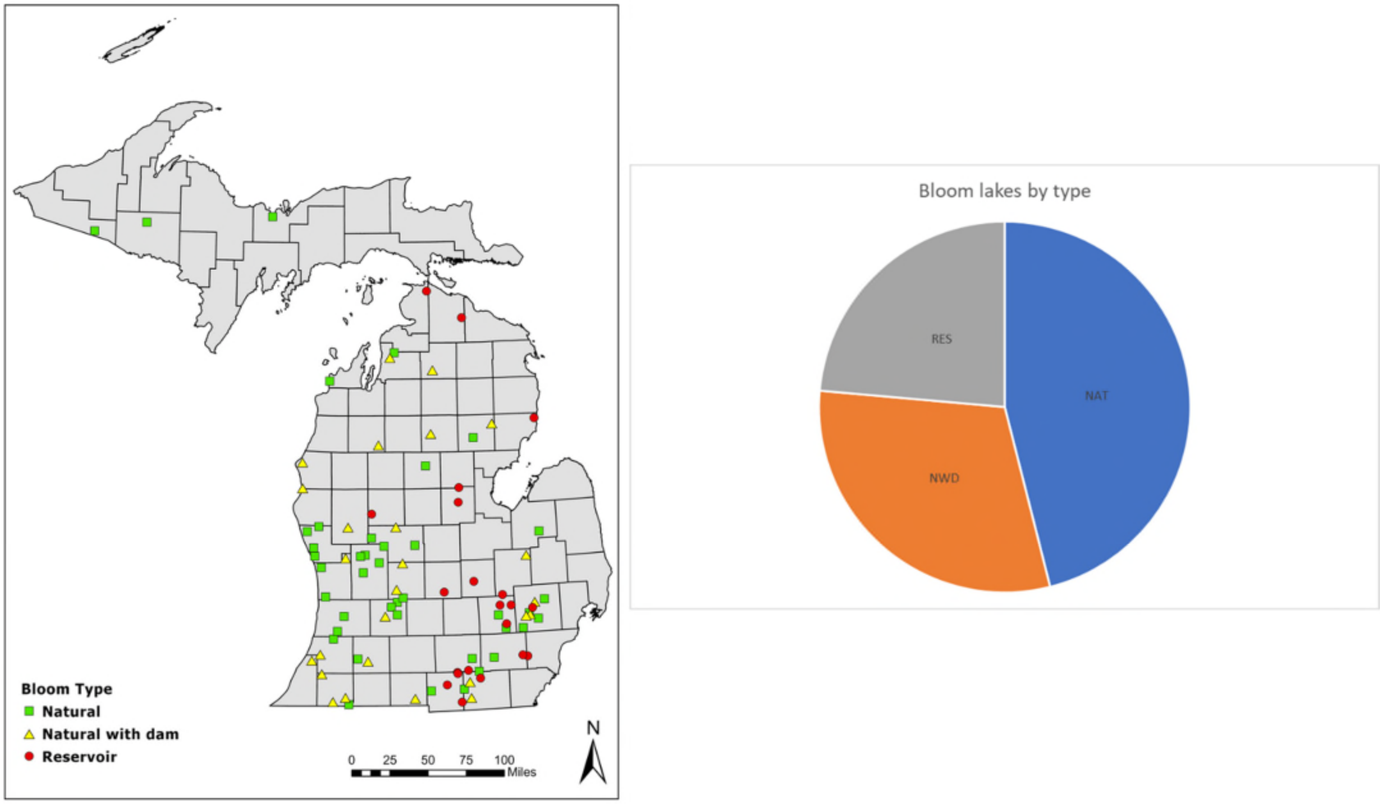

Figure 6. Map of confirmed cyanobacteria blooms by lake type and pie chart of different lake types that experienced blooms (NAT = natural, NWD = natural with dam, RES = reservoir). Note: Map does not include five cyanobacteria blooms that occurred in rivers, wetlands, or private ponds.

An initial comparison of depths between natural lakes, natural lakes with dams, and reservoirs that had experienced cyanobacteria blooms revealed no differences between lake types (ANOVA: F = 1.6, df = 2, 80, p = 0.2). However, this was largely driven by Hardy Dam Pond.

The Hardy Dam Pond is a very large water body (2,772 acres) that was created by impounding the Muskegon River with a 106-foot hydroelectric dam (the largest in Michigan). The location of the dam is in an area where the Muskegon River has its steepest drop in elevation (Alexander, 2006). The resulting bathymetry of the impoundment is characterized by relatively shallow depths in the artificially inundated areas along the edges, and then a deep, narrow valley where the historic river channel was. Because of the sharply contrasting bathymetry, the average depth of the impoundment is 34.5 feet; however, the maximum depth is 110 feet. Because of the unique nature of Hardy Dam Pond and its singular effect on the depth analysis, an additional evaluation was performed excluding that water body.

When Hardy Dam Pond was excluded from the ANOVA, there were significant depth differences between water body types (ANOVA: F = 3.4, df = 2, 79, p = 0.04; Table 2), with reservoirs being shallower than natural lakes with dams (Figure 7). There were also significant differences in SDFs between water body types with reservoirs having significantly greater SDFs than both natural and natural with dam lakes (ANOVA: F = 6.4, df = 2, 83, p < 0.01; Table 2; Figure 8).

A comparison of microcystin concentrations from side-by-side samples of cyanobacterial scum and nearby ambient water revealed that the scum contained more microcystin than the nearby ambient water (t = 2.08, df = 47, p = 0.04; Figure 9).

Table 2. Tukey's honestly significant differences between depths and shoreline development factors among lake types.

Depth				Shoreline development factor		
	Reservoir	Natural with dam			Reservoir	Natural with dam
Natural	0.15	0.56		Natural	**<0.01**	0.6
Natural with dam	**0.03**			Natural with dam	**0.04**	

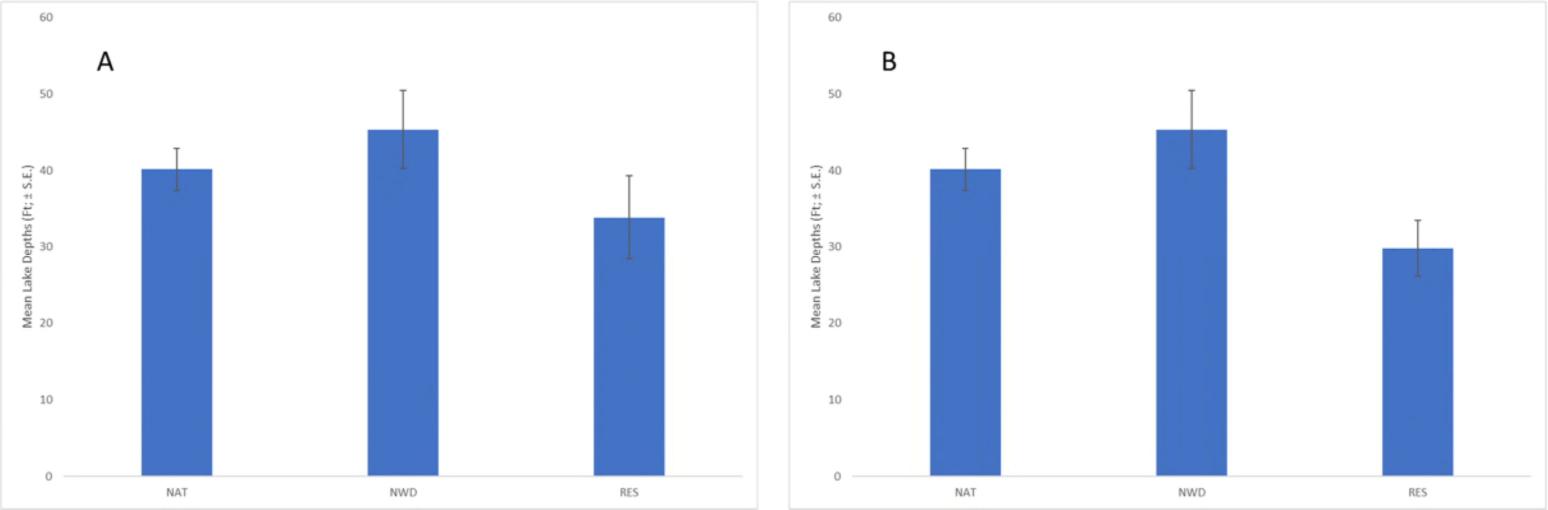

Figure 7. Mean depths (feet ± S.E.) among lake types. Graph A includes Hardy Dam Pond in the reservoir average, and Graph B excludes Hardy Dam Pond.

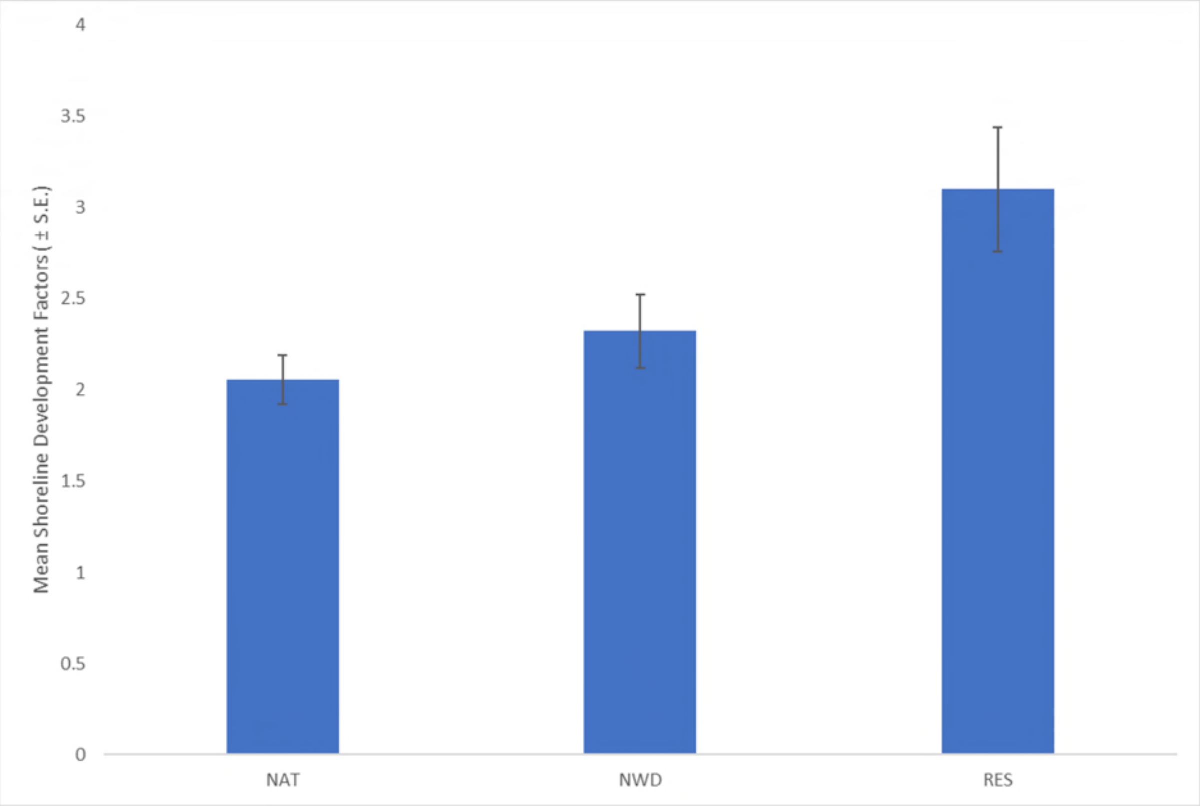

Figure 8. Mean shoreline development factors (± S.E.) among lake types.

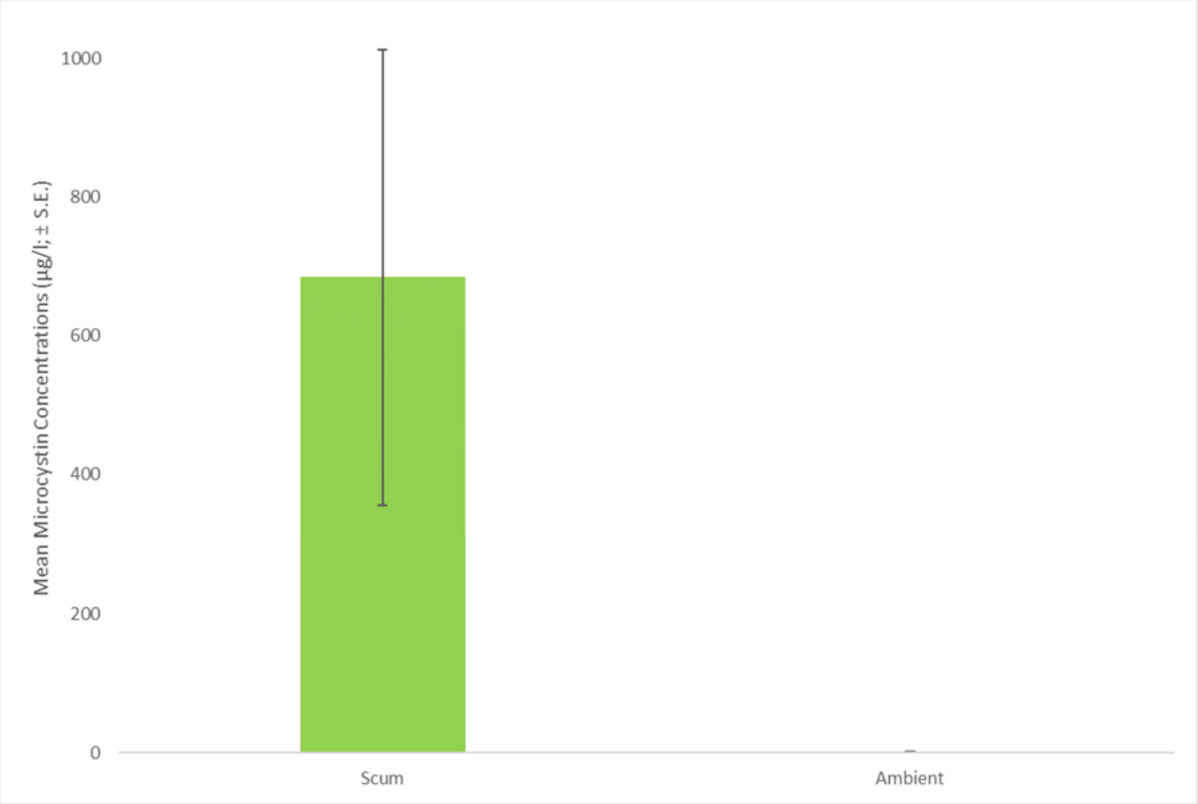

Figure 9. Mean microcystin concentrations (± S.E.) from scum and ambient water samples collected side by side.

Discussion

In the last few years, the number of complaints received by EGLE about nuisance cyanobacteria and algae have increased. EGLE (Parker, 2018b) and others (Cheung et al., 2013) have acknowledged that the increased awareness and attention that HABs have received recently may account for the increased reports. However, Cheung et al. (2013) maintained that the increasing number of reports is unlikely the sole result of increased attention. Recently, Ho et al. (2019) also found that cyanobacteria blooms are increasing globally after reviewing satellite images in 71 lakes over three decades. The consensus amongst most researchers is that the frequency, magnitude, and intensity of HABs is increasing worldwide, and that given future climate scenarios coupled with more intensive agricultural practices worldwide, HABs are only expected to get worse (Kosten et al., 2012; O'Neil et al., 2012; Paerl and Paul, 2012; Michalak et al., 2013; Scavia et al., 2014; Taranu et al., 2015; Scholz et al., 2017).

In the United States, after the 2019 recreational season, disentangling whether the increased number of complaints that year was a result of actual increases or increased media attention was especially difficult. Following canine deaths from cyanobacteria in several southern states, there was intense, nationwide media coverage of the cases. This led to numerous citizen inquiries to EGLE about water bodies throughout the state. In 2019, half of the water bodies that we received complaints about did contain cyanobacteria, as opposed to filamentous green algae or duckweed. In 2019, anatoxin-a was measured at the highest concentrations we have observed since monitoring began, in a private pond where several dogs died after consuming cyanobacteria (Parker, 2020). Finally, cylindrospermopsin was also detected for the first time by EGLE staff in an Oakland County lake in September 2019.

We have consistently found that, statewide, the vast majority of the randomly sampled lakes have not had active cyanobacteria blooms occurring and that typically, the only time we do find active blooms is if we target specific lakes that have had them in the past, or if we are alerted to a bloom by citizens. In general, confirmed cyanobacterial blooms were more prevalent in the southern Lower Peninsula of Michigan, which is the most populated area of the state and contains more agricultural areas. Using remote sensing, Torbick et al. (2013) also found that lakes in the southern Lower Peninsula were more productive and that cropland and urban land use was associated with more eutrophic lakes.

There is widespread consensus that water bodies with greater than 10 percent impervious cover in their watersheds will begin to exhibit water quality degradation (Schueler and Holland, 2000; Brabec et al., 2009; Carey et al., 2013). Urban and residential areas quickly convey nutrients and other pollutants to storm drains that then directly discharge to nearby water bodies (Steinman et al., 2006; Carey et al., 2013; Yang and Toor, 2016; Janke et al., 2017; Yang and Toor, 2017). Unlike streams, which will assimilate some nutrients in the sediment and plant biomass, pipes will direct all nutrients to a receiving water body (Steinman et al., 2006; Brabec et al., 2009). Lakes in more populated areas also tend to be largely developed along their immediate shoreline since lakefront property is highly desired. Residential land use along lake shorelines can contribute nutrients to the lake via lawn fertilizer application (Morton et al., 1988; Bierman et al., 2010; Carey et al., 2012; Steinman et al., 2015) and septic system leachate (Gilliom and Patmont, 1983; Tessier and Lauf, 1992; Swann, 2001; Brennan et al., 2016; Schellenger and Hellweger, 2019).

Agricultural nutrient runoff has been recognized as a contributing factor to cyanobacteria blooms, with much attention being focused on the re-eutrophication of western Lake Erie (Michalak et al., 2013; Scavia et al., 2014; Bullerjahn et al., 2016). However, on a smaller scale, agriculture has also been implicated as contributing to cyanobacteria blooms in inland lakes as well (Torbick et al., 2013; Taranu et al., 2015 and 2017; Clement and Steinman, 2017;

Marion et al., 2017). Increased dissolved reactive phosphorus loading via field tile drainage pipes has been cited as one of the main causes of cyanobacteria blooms in water bodies that are surrounded by agricultural land use (Bullerjahn et al., 2016; Clement and Steinman, 2017).

Similar to other work (Taranu et al. 2017; Gina LaLiberte, Wisconsin Department of Natural Resources, personal communication) we found that the majority of cyanobacteria blooms occurred in lakes with some kind of an impoundment structure. Most of the lakes that had confirmed cyanobacteria blooms in the northern Lower Peninsula were either reservoirs or natural lakes with a lake-level control structure. This is significant since the majority of inland lakes in Michigan are natural. The most recent lake inventory by the Michigan Department of Natural Resources recognizes 10,759 inland lakes throughout the state that are greater than five acres (Michigan.gov/DNR/0,4570,7-350-79135_81276_82887-160092--,00.html). Based on conservative estimates, it is likely that only around 10 percent of those lakes are impoundments or natural lakes with a dam. However, approximately 53 percent of the lakes with confirmed cyanobacteria blooms from 2016-2019 were impounded in some way.

The reservoirs were the shallowest water bodies, had the highest shoreline development factors, and were the most productive systems that we sampled. In general, reservoir systems tend to age faster and are more productive than natural systems (Ryder, 1978; Kimmel and Groeger, 1986; Whittier et al., 2002; Knoll et al., 2015; Doubek and Carey, 2017). Reservoirs also typically have larger catchment-to-lake-area ratios than natural lakes (Knoll et al., 2015; Taranu et al., 2017). That is, they have larger watersheds draining into them from an upstream tributary than a typical, kettle lake will have. With larger watersheds, more nutrients are likely to flow into the receiving water bodies, thus increasing the chances for cyanobacteria blooms (Toporowska et al., 2018). Reservoir systems also tend to be created in either urban or agriculture-dominated areas (Kimmel and Groeger, 1986), which both contribute nutrients to water bodies as described above. Finally, some reservoirs were created for the sole purpose of developing residential communities around a water body (Nicholls and Crompton, 2018), in which case the majority of the shoreline is going to have residential land use along the immediate shoreline of the lake. Shallow lakes coupled with nutrient-rich sediment are prone to nutrient resuspension into the water column as a result of physical disturbances such as wind (Kristensen et al., 1992; Blottière et al., 2013), fish foraging (Havens, 1991), and boat traffic (Anthony and Downing, 2003).

We found that the shoreline development factors of reservoirs were higher than those of the natural and natural with dam lakes. This is not surprising since impoundments tend to flood historic tributary stream valleys and other low-lying areas. The resultant shoreline features of reservoirs, depending on the extent of impoundment and surrounding landscape features, are often numerous peninsulas, coves, canals, and islands throughout the water body. All of which extend the amount of shoreline. Given the inherent desirability of lakefront property and the fact that some reservoirs are created for the purpose of creating residential lake lots (Nicholls and Crompton, 2018), reservoirs tend to have a disproportionate number of residential dwellings along their entire shoreline compared to lakes of similar size, but with less shoreline. Each residential lake dwelling can then contribute nutrients to the water body via lawn fertilizer (Morton et al., 1988; Bierman et al., 2010; Carey et al., 2012; Steinman et al., 2015), pet waste (Schueller and Holland, 2000), loss of natural shoreline buffers (Woodard and Rock, 1995; Søndergaard and Jeppesen, 2007; Rosenberger et al., 2008), and septic systems (Gilliom and Patmont, 1983; Tessier and Lauf, 1992; Swann, 2001; Brennan et al., 2016; Schellenger and Hellweger, 2019). The shallow embayments that are characteristic of reservoir systems often offer calm areas of warm water that is conducive to cyanobacteria growth (Parker, 2018b).

Although the natural lakes with dams had similar depths and shoreline development factors as the natural lakes with no water level control structures, they were over-represented among the water bodies that experienced cyanobacteria blooms. Lake-level control structures are typically constructed at lake outlets to ensure that consistent water levels are maintained that can accommodate recreational activities. In fact, over half of the dams in Michigan on the National Inventory of Dams list have “recreation” as the primary purpose for the dam structure. Typically, lakes that have water-level control structures for recreational purposes are going to have a high number of residential units along the shoreline, which may contribute nutrients from lawns (Morton et al., 1988; Bierman et al., 2010; Carey et al., 2012; Steinman et al., 2015) and/or be near urban centers that can contribute nutrients (Steinman et al., 2006; Carey et al., 2013; Yang and Toor, 2016; Janke et al., 2017; Yang and Toor, 2017). However, if lake-level control structures are constructed in lake outlets for the purpose of artificially raising water levels, then this will also artificially raise groundwater levels around the immediate riparian shoreline. If septic systems were in place prior to the groundwater level rising, then the amount of non-saturated soil to filter nutrients from the septic leachate will decrease, which then increases the risk of septic pollution entering the lake via groundwater (Gilliom and Patmont, 1983; Swann, 2001; Lusk et al., 2017).

Some broad conclusions can be made about the occurrences of cyanobacteria blooms throughout Michigan and possible causes of them. Similar to other work (Kardinaal and Visser, 2005; Omidi et al., 2018), we found that microcystin production dynamics over a large geographic area are very unpredictable (Parker, 2019). For example, although cyanobacteria blooms are rare in the northern Lower Peninsula, one of the highest recorded total microcystin concentrations that we observed (13,000 µg/l) occurred in a lake in Iosco County. And while cyanobacteria blooms are typically associated with eutrophic and hypereutrophic lakes, we have observed high microcystin concentrations in oligotrophic and mesotrophic lakes, possibly as a result of selective feeding by Dreissenid mussels (Raikow et al., 2004; Sarnelle et al., 2005; Wilson et al., 2005; Knoll et al., 2008; Woller-Skar, 2009; Sarnelle et al., 2010; White et al., 2017; Gaskill and Woller-Skar, 2018). Finally, we have sampled obvious cyanobacteria scums in the southeastern Lower Peninsula that have not had any microcystin in them (Parker, 2019).

Whether a population of cyanobacteria produces microcystin is dependent on whether they possess the toxin-producing genotypes or not (Kardinaal and Visser, 2005). In Michigan, cyanobacterial populations are genetically diverse both between lakes, and within lake populations (Wilson et al., 2005). Even within a single lake, cyanobacteria species and genotypes will change throughout the year, meaning that toxins may only be found in a particular water body for part of the year (Kardinaal et al., 2007; Lehman, 2007; Lehman et al., 2009). Further complicating the understanding of microcystin dynamics is that the exact triggers for microcystin production by cyanobacteria are not fully understood (Sivonen and Jones, 1999; Kardinaal and Visser, 2005).

The factors that determine microcystin production by cyanobacteria are probably dependent on the particular genotypes and environmental conditions within individual water bodies (Kardinaal and Visser, 2005; Omidi et al., 2018). For some well-studied, individual lakes in Michigan, microcystin production can be predicted with some accuracy. For example, in Mona Lake, Muskegon County, microcystin concentrations have consistently been correlated with water column, total phosphorus concentrations (Xie et al., 2012; Parker, 2018b). In Ford Lake, Washtenaw County, and Belleville Lake, Wayne County, the cyanobacterial communities appear to exhibit predictable, seasonal shifts in species composition and toxicity (Lehman, 2007).

Predicting microcystin production from lake to lake can be difficult. When we have found elevated concentrations in a water body, it is consistently in obvious cyanobacteria scum accumulations or obvious sheens on the water surface. Typically, when cyanobacteria are present in a lake, it is in a localized area that is protected from disturbance or along windswept shorelines. Only on rare occasions have we observed extensive, lake-wide blooms. Similar to others (Carmichael and Gorham, 1981; Bartram and Rees, 2000) we have found that microcystin concentrations are often much lower, or nondetectable in clear water that is within 10-15 feet of a cyanobacteria scum.

Conclusion

In general, cyanobacteria blooms do not appear to be a widespread problem in Michigan given how they are rarely observed when lakes are randomly sampled. Rather, we typically only observe cyanobacteria blooms and resultant toxin production in lakes that we either target because they have experienced blooms in the past, or because citizens have alerted us to them. Typically, the blooms that are observed occur in localized areas of a water body and any microcystin that is observed is typically found in obvious scums, whereas adjacent, clear water often has very little/no microcystin. The majority of the cyanobacteria blooms that we have observed in the last four years have been in the southern Lower Peninsula. The southern Lower Peninsula contains the most agricultural and urban areas in Michigan, which are known to contribute nutrients to water bodies. Despite only making up a small percentage of the total number of lakes in Michigan, lakes that were either reservoirs or natural, but with a lake-level control structure, made up the majority of the water bodies that experienced cyanobacteria blooms. These systems may have been over-represented since they are typically situated in populated areas and are usually heavily-developed along the riparian area. Reservoirs, in particular, tend to be shallow and have high shoreline development factors. Most experts agree that given future climate projections coupled with agricultural and urban land use scenarios, cyanobacteria blooms are expected to increase in occurrence and magnitude worldwide.

Report By: Aaron Parker, Aquatic Biologist
Surface Water Assessment Section
Water Resources Division

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Appendix 1: Raw lake data from 2019.

Lake	County	Site	Latitude	Longitude	Waterbody type	Month	Day	Year	Sample type (scum or ambient)	Algal Strip Result (Total MC ug/l)	Total microcystins (lab; ug/l)	Anatoxin (lab; ug/l)	detectrospermopsin (lab; ug/l)	Nodularin (lab; ug/l)	Comments
Geneva	Clinton	SW beach	42.830469	-84.585809	lake	6	18	2019	scum	all non-detect	non-detect	non-detect	non-detect	non-detect	
West Bloomfield	Oakland	lakewide	42.562046	-83.381923	lake	6	27	2019	scum	all non-detects	non-detect	non-detect	non-detect	non-detect	
Peach	Ogemaw	Dave's Beach	44.287347	-84.173707	lake	7	2	2019	scum	~5	16	non-detect	non-detect	non-detect	
.	Cheboygan	.	.	.	lake	7	3	2019	ambient	all non-detects	non-detect	non-detect	non-detect	non-detect	Canine illness complaints
Veteran's Park Pond	Washtenaw	Veteran's Park	42.322957	-84.021909	pond	7	9	2019	ambient	non-detect	.	.	.	.	duckweed bloom
.	Cheboygan	.	.	.	lake	7	10	2019	ambient	all non-detects	non-detect	non-detect	non-detect	non-detect	Canine illness complaints
Castell BLVD pond	Wayne	Castell and Ecorse intersection	42.249415	-83.465117	pond	7	11	2019	scum	2.5-5	non-detect	non-detect	non-detect	non-detect	red algae complaint
.	Osceola	.	.	.	pond	7	11	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	canine death and human illness
.	Allegan	.	.	.	lake	7	12	2019	ambient	all non-detects	non-detect	non-detect	non-detect	non-detect	canine illness, wildlife death
.	Montcalm	.	.	.	lake	8	6	2019	ambient	all non-detects	non-detect	non-detect	non-detect	non-detect	Canine death
Driskels	Cass		41.906343	-85.799748	lake	8	9	2019	ambient	all non-detects	.	.	.	.	
.	Hillsdale	.	.	.	lake	8	9	2019	ambient	both non-detects	non-detect	non-detect	non-detect	non-detect	Human illness
Van Auken	Van Buren	3 sites	42.260111	-86.181335	lake	8	13	2019	ambient	all non-detects	non-detect	non-detect	non-detect	non-detect	
Kent	Oakland/Livingston	6 sites	42.513549	-83.671412	lake	8	14	2019	ambient	all non-detects	non-detect	non-detect	non-detect	non-detect	
Kent	Oakland/Livingston	7 sites	42.513549	-83.671412	lake	8	14	2019	ambient	all non-detects	non-detect	non-detect	non-detect	non-detect	
Millpointe pond	Livingston	Chelsea Circle	42.629076	-83.75817	pond	8	14	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Squaw	Genesee	4190 Four Lakes Ave., Linden, MI	42.825168	-83.752408	lake	8	14	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Squaw	Genesee	4190 Four Lakes Ave., Linden, MI	42.825168	-83.752408	lake	8	14	2019	scum	non-detect	0.74	non-detect	non-detect	non-detect	
Big Twin	Kalkaska	private residence	44.827575	-84.971354	lake	8	16	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Lloyds Bayou	Ottawa	Boat launch	43.07271	-86.17219	lake	8	16	2019	ambient	non-detect	.	.	.	.	
Lloyds Bayou	Ottawa	Leonard RD	43.06953	-86.18414	lake	8	16	2019	ambient	non-detect	.	.	.	.	
Lloyds Bayou	Ottawa	M-104	43.07595	-86.16892	lake	8	16	2019	ambient	non-detect	.	.	.	.	
Lloyds Bayou	Ottawa	Oak Ridge	43.07215	-86.17487	lake	8	16	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
White	Muskegon	Boat launch	43.4114	-86.35706	lake	8	17	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
White	Muskegon	Crosswinds Marina	43.40631	-86.34974	lake	8	17	2019	scum	>10	4000	non-detect	non-detect	non-detect	
White	Muskegon	Dock A	43.40602	-86.35162	lake	8	17	2019	ambient	non-detect	0.58	non-detect	non-detect	non-detect	
White	Muskegon	Goodrich Park	43.40928	-86.35217	lake	8	17	2019	ambient	1-5	1.2	non-detect	non-detect	non-detect	
White	Muskegon	Municipal Marina dock	43.40987	-86.35171	lake	8	17	2019	scum	>10	28	non-detect	non-detect	non-detect	
White	Muskegon	Maple Beach	43.40137	-86.35872	lake	8	17	2019	ambient	5-10	2.7	non-detect	non-detect	non-detect	
White	Muskegon	Svensson Park	43.39697	-86.35485	lake	8	17	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Hamlin	Mason	Davis RD	44.0794	-86.43624	lake	8	19	2019	ambient	non-detect	.	non-detect	non-detect	non-detect	Gloeotrichia bloom
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	8	20	2019	ambient	>10	6.6	non-detect	non-detect	non-detect	
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	8	20	2019	scum	>10	3700	non-detect	non-detect	non-detect	
Bass	Mason	Boat launch	43.83957	-86.418	lake	8	20	2019	scum	>10	610	non-detect	non-detect	non-detect	
.	Osceola	.	.	.	pond	8	20	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
.	Osceola	.	.	.	pond	8	20	2019	scum	non-detect	non-detect	24	non-detect	non-detect	
.	Osceola	.	.	.	pond	8	20	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
.	Osceola	.	.	.	pond	8	20	2019	scum	non-detect	non-detect	43	non-detect	non-detect	
Hamlin	Mason	Davis RD	44.0794	-86.43624	lake	8	20	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	Gloeotrichia bloom
Hamlin	Mason	Duneview DR	44.04251	-86.45816	lake	8	20	2019	scum	5-10	0.98	non-detect	non-detect	non-detect	Gloeotrichia bloom
Hamlin	Mason	Middle Bayou	44.02804	-86.45657	lake	8	20	2019	scum	non-detect	.	non-detect	non-detect	non-detect	Gloeotrichia bloom
Hamlin	Mason	South Bayou	44.01552	-86.4574	lake	8	20	2019	scum	non-detect	.	non-detect	non-detect	non-detect	Gloeotrichia bloom
Hamlin	Mason	South canal	44.00887	-86.45853	lake	8	20	2019	ambient	non-detect	0.57	non-detect	non-detect	non-detect	Gloeotrichia bloom
Hamlin	Mason	South canal	44.00887	-86.45853	lake	8	20	2019	scum	>10	40	non-detect	non-detect	non-detect	Gloeotrichia bloom
Hamlin	Mason	State Park beach	44.03508	-86.49265	lake	8	20	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	clear
Lamberton	Kent		43.020403	-85.628929	lake	8	20	2019		ND	non-detect	non-detect	non-detect	non-detect	
Morrison	Ionia	9136 Ash LN	42.855858	-85.21666	lake	8	20	2019			0.58	non-detect	non-detect	non-detect	
Morrison	Ionia	Boat launch	42.862742	-85.213603	lake	8	20	2019			0.53	non-detect	non-detect	non-detect	

Appendix 1 cont.

Lake	County	Site	Latitude	Longitude	Waterbody type	Month	Day	Year	Sample type (scum or ambient)	Algal Strip Result (Total MC ug/l)	Total microcystins (lab; ug/l)	Anatoxin (lab; ug/l)	Cylinon-detectrospermopsin (lab; ug/l)	Nodularin (lab; ug/l)	Comments
.	Newaygo	.	.	.	pond	8	20	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	canine death
.	Newaygo	.	.	.	pond	8	20	2019	ambient	non-detect	.	.	.	.	canine death
Chemung	Livingston	Red Oaks	42.58765	-83.84095	canal	8	21	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Chemung	Livingston	Boat launch	42.57849	-83.83517	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Chemung	Livingston	Park	42.57924	-83.85034	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Knoblock	Oakland	Knobby View DR	42.69614	-83.61859	lake	8	21	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Lake Oakland	Oakland	Rutherford CT	42.69356	-83.36557	lake	8	21	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Lake Oakland	Oakland	American Legion beach	42.70668	-83.36569	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Lake Oakland	Oakland	Boat launch	42.69862	-83.36316	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Pontiac	Oakland	Boat launch	42.66339	-83.44242	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Pontiac	Oakland	State Park beach	42.66809	-83.44731	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Pontiac	Oakland	Tackles DR boat launch	42.67098	-83.45863	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Pontiac	Oakland	Kingston	42.66475	-83.46125	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Pontiac	Oakland	Bonnie Briar	42.66851	-83.47015	lake	8	21	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
Upper Long	Oakland	Oakway DR	42.60039	-83.32726	canal	8	21	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
West Bloomfield	Oakland	Park	42.56122	-83.38134	lake	8	21	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect	
West Bloomfield	Oakland	Lake Bluff DR	42.56284	-83.38235	lake	8	21	2019	ambient	non-detect	.	.	.	.	
Bass	Mason	Marrison Park	43.83407	-86.40604	lake	8	22	2019	ambient	5-10	1.6	non-detect	non-detect	non-detect	
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	8	22	2019	ambient	>10	16	non-detect	non-detect	non-detect	
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	8	22	2019	scum	>10	21	non-detect	non-detect	non-detect	
Bass	Mason	Boat launch	43.83891	-86.41787	lake	8	22	2019	scum	>10	7900	non-detect	non-detect	non-detect	
Bass	Mason	Boat launch	43.83892	-86.41759	lake	8	22	2019	ambient	1-5	6.6	non-detect	non-detect	non-detect	
Hamlin	Mason	Davis RD	44.0794	-86.43624	lake	8	22	2019	scum	non-detect	non-detect	.	.	.	Thin layer of cyanobacteria
Hamlin	Mason	Upper lake boat launch	44.08539	-86.37343	lake	8	22	2019	ambient	non-detect	.	.	.	.	
Hamlin	Mason	Wilson Park	44.07134	-86.42713	lake	8	22	2019	ambient	non-detect	non-detect	.	.	.	
Hamlin	Mason	Duneview DR	44.04256	-86.45819	lake	8	22	2019	ambient	test fail	non-detect	.	.	.	
Hamlin	Mason	Middle Bayou	44.02804	-86.45657	lake	8	22	2019	ambient	non-detect	.	.	.	.	
Hamlin	Mason	South Bayou	44.01552	-86.4574	lake	8	22	2019	ambient	non-detect	.	.	.	.	
Hamlin	Mason	South canal	44.00887	-86.45853	lake	8	22	2019	ambient	non-detect	non-detect	.	.	.	
Hamlin	Mason	State Park beach	44.03508	-86.49265	lake	8	22	2019	ambient	non-detect	.	.	.	.	
.	Washtenaw	.	.	.	lake	8	22	2019	ambient	ND	non-detect	non-detect	non-detect	non-detect	canine death
.	Washtenaw	.	.	.	lake	8	22	2019	ambient	ND	non-detect	non-detect	non-detect	non-detect	
White	Muskegon	Lau RD boat launch	43.37604	-86.42112	lake	8	22	2019	ambient	non-detect	.	.	.	.	
White	Muskegon	Maple Beach	43.40136	-86.35872	lake	8	22	2019	ambient	1-5	.	.	.	.	
White	Muskegon	Montague boat launch	43.41141	-86.35709	lake	8	22	2019	ambient	non-detect	.	.	.	.	
White	Muskegon	Goodrich Park	43.40929	-86.35223	lake	8	22	2019	ambient	~1	non-detect	non-detect	non-detect	non-detect	
White	Muskegon	Municipal Marina dock	43.40994	-86.35176	lake	8	22	2019	scum	>10	21	non-detect	non-detect	non-detect	
White	Muskegon	Crosswinds Dock A	43.40604	-86.35162	lake	8	22	2019	ambient	~1	non-detect	non-detect	non-detect	non-detect	
White	Muskegon	Crosswinds Marina	43.40606	-86.34996	lake	8	22	2019	scum	>10	130	non-detect	non-detect	non-detect	
White	Muskegon	Svensson Park	43.39678	-86.35487	lake	8	22	2019	ambient	non-detect	.	.	.	.	
White	Muskegon	Mill Pond	43.39014	-86.35513	lake	8	22	2019	ambient	>10	3.5	non-detect	non-detect	non-detect	
White	Muskegon	Scenic DR boat launch	43.36309	-86.41199	lake	8	22	2019	ambient	1-5	.	.	.	.	
White	Muskegon	Sylvan Beach	43.36963	-86.42027	lake	8	22	2019	ambient	non-detect	0.55	non-detect	non-detect	non-detect	
Townsend Pond	Eaton	Townsend on the Park Apartments	42.740243	-84.709384	pond	8	23	2019	ambient	ND	.	.	.	.	
Bass	Mason	Marrison Park	43.83407	-86.40604	lake	8	29	2019	scum	>10	12	non-detect	non-detect	non-detect	
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	8	29	2019	scum	>10	180	non-detect	non-detect	non-detect	
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	8	29	2019	scum	>10	190	non-detect	non-detect	non-detect	
Bass	Mason	Boat launch	43.83891	-86.41787	lake	8	29	2019	scum	>10	240	non-detect	non-detect	non-detect	
White	Muskegon	Goodrich Park	43.40929	-86.35223	lake	8	29	2019	ambient	>10	0.5	non-detect	non-detect	non-detect	

Appendix 1 cont.

Lake	County	Site	Latitude	Longitude	Waterbody type	Month	Day	Year	Sample type (scum or ambient)	Algal Strip Result (Total MC ug/l)	Total microcystins (lab; ug/l)	Anatoxin (lab; ug/l)	Cylinon-detectrospermopsin (lab; ug/l)	Nodularin (lab; ug/l)	Comments	
White	Muskegon	Municipal Marina dock	43.40994	-86.35176	lake	8	29	2019	ambient	7.5	2.5	non-detect	non-detect	non-detect		
White	Muskegon	Mill Pond	43.39014	-86.35513	lake	8	29	2019	ambient	2.5	non-detect	non-detect	non-detect	non-detect		
White	Muskegon	Crosswinds scum	43.40631	-86.34974	lake	8	29	2019	scum	>10	180	non-detect	non-detect	non-detect		
White	Muskegon	2nd municipal marina	43.40994	-86.35176	lake	8	29	2019	ambient	7.5	10	non-detect	non-detect	non-detect		
Fish	Van Buren		42.323053	-85.807122	lake	9	2	2019		ND	.	.	.	.		
.	Antrim	.	.	.	lake	9	3	2019	ambient	ND	.	.	.	.	itching skin complaint	
Belleville	Wayne	Harmony LN cove	42.21731	-83.47219	lake	9	4	2019	scum	>10	13.1	non-detect	non-detect	non-detect		
Belleville	Wayne	Alba CT cove	42.21924	-83.45785	lake	9	4	2019	scum	>10	17.7	non-detect	non-detect	non-detect		
Belleville	Wayne	Dora CT	42.20678	-83.51161	lake	9	4	2019	ambient	ND	.	.	.	.		
Belleville	Wayne	Van Buren Park	42.212731	-83.537278	lake	9	4	2019	ambient	ND	.	.	.	.		
Columbia	Jackson	Cannes Circle	42.085439	-84.293553	lake	9	6	2019	scum	>10	370	non-detect	non-detect	non-detect		
Morrison	Ionia	Boat launch	42.862742	-85.213603	lake	9	6	2019	scum		2.9	non-detect	non-detect	non-detect		
Bass	Mason	Marrison Park	43.83407	-86.40604	lake	9	10	2019	ambient	1	0.94	non-detect	non-detect	non-detect		
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	9	10	2019	scum	>10	51	non-detect	non-detect	non-detect		
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	9	10	2019	scum	>10	20	non-detect	non-detect	non-detect		
Bass	Mason	Boat launch	43.83891	-86.41787	lake	9	10	2019	scum	>10	6300	non-detect	non-detect	non-detect		
Bass	Mason	Boat launch	43.83891	-86.41787	lake	9	10	2019	light scum	5-10	**9**	non-detect	non-detect	non-detect		
Columbia	Jackson	Stud Bay			lake	9	10	2019	scum	>10	260	non-detect	non-detect	non-detect		
Columbia	Jackson	W. Shore Bay			lake	9	10	2019	scum	>10	non-detect	non-detect	non-detect	non-detect		
Columbia	Jackson	Back Bedford			lake	9	10	2019		test fail	36	non-detect	non-detect	non-detect		
Mill Pond	Muskegon	Mill Pond RD	43.388148	-86.353147	pond	9	10	2019	ambient	ND	non-detect	non-detect	non-detect	non-detect		
Morrison	Ionia	Boat launch	42.862742	-85.213603	lake	9	10	2019	scum	>10	6.5	non-detect	non-detect	non-detect		
White	Muskegon	Lau RD boat launch	43.37604	-86.42112	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Maple Beach	43.40136	-86.35872	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Montague boat launch	43.41141	-86.35709	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Goodrich Park	43.40929	-86.35223	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Municipal Marina dock	43.40994	-86.35176	lake	9	10	2019	ambient	ND	0.52	non-detect	non-detect	non-detect		
White	Muskegon	Crosswinds Dock A	43.40604	-86.35162	lake	9	10	2019	ambient	ND	non-detect	non-detect	non-detect	non-detect		
White	Muskegon	Crosswinds Marina	43.40606	-86.34996	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Svensson Park	43.39678	-86.35487	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Mill Pond	43.39014	-86.35513	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Scenic DR boat launch	43.36309	-86.41199	lake	9	10	2019	ambient	ND	.	.	.	.		
White	Muskegon	Sylvan Beach	43.36963	-86.42027	lake	9	10	2019	ambient	ND	.	.	.	.		
Sherwood Forest	Macomb		42.694938	-82.983189	lake	9	11	2019		5-10	non-detect	non-detect	non-detect	non-detect		
Thornapple	Barry	Charleton Park	42.619623	-85.193754	lake	9	11	2019	scum	>10	40	non-detect	non-detect	non-detect		
Belleville	Wayne	West launch	42.20985	-83.53946	lake	9	12	2019	ambient	non-detect	.	.	.	.		
Belleville	Wayne	Van Buren Park	42.21256	-83.52494	lake	9	12	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect		
Belleville	Wayne	Middle DNR launch	42.21388	-83.4732	lake	9	12	2019	ambient	non-detect	.	.	.	.		
Belleville	Wayne	Edison Lake RD	42.21275	-83.44298	lake	9	12	2019	ambient	5-10	3.4	non-detect	non-detect	non-detect		
Belleville	Wayne	Belleville/Denton RD	42.20978	-83.49347	lake	9	12	2019	ambient	non-detect	.	.	.	.		
Budd	Clare	north				9	12	2019	scum	non-detect	non-detect	non-detect	non-detect	non-detect		
Budd	Clare	north				9	12	2019	scum	non-detect	non-detect	non-detect	non-detect	non-detect		
Budd	Clare	north end	44.031522	-84.80316	lake	9	12	2019	.	non-detect	.	.	.	.		
Ford	Washtenaw	North Bay Park	42.23015	-83.60725	lake	9	12	2019	ambient	non-detect	.	.	.	.		
Ford	Washtenaw	Ford Lake Park	42.21099	-83.57291	lake	9	12	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect		
Ford	Washtenaw	Lakeside Park	42.2047	-83.56217	lake	9	12	2019	ambient	non-detect	.	.	.	.		
Ausable	Ogemaw	Alcott	44.42667	-83.92129	lake	9	18	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect		
Ausable	Ogemaw	Boat launch	44.42632	-83.91886	lake	9	18	2019	ambient	1-5	1.2	non-detect	non-detect	non-detect		
Ausable	Ogemaw	Canal	44.43116	-83.90782	canal	9	18	2019	ambient	non-detect	.	.	.	.		

Appendix 1 cont.

Lake	County	Site	Latitude	Longitude	Waterbody type	Month	Day	Year	Sample type (scum or ambient)	Algal Strip Result (Total MC ug/l)	Total microcystins (lab; ug/l)	Anatoxin (lab; ug/l)	Cylinon-detectrospermopsin (lab; ug/l)	Nodularin (lab; ug/l)
Bass	Mason	Marrison Park	43.83407	-86.40604	lake	9	18	2019	ambient	non-detect	.	.	.	.
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	9	18	2019	ambient	~1	non-detect	non-detect	non-detect	non-detect
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	9	18	2019	ambient	1-5	0.94	non-detect	non-detect	non-detect
Bass	Mason	Boat launch	43.83891	-86.41787	lake	9	18	2019	scum	>10	8.5	non-detect	non-detect	non-detect
Budd	Clare	Wilson State Park beach	44.02818	-84.80171	lake	9	18	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Budd	Clare	Townline Lake RD	44.03175	-84.80379	lake	9	18	2019	scum	non-detect	non-detect	non-detect	non-detect	non-detect
Budd	Clare	Boat launch	44.01608	-84.78818	lake	9	18	2019	ambient	non-detect	.	.	.	.
Budd	Clare	Saxton Park	44.02119	-84.79673	lake	9	18	2019	ambient	non-detect	.	.	.	.
Goodemoot Drain	Ionia	Goodemoot RD	42.85719	-85.20482	County drain	9	18	2019	ambient	non-detect	.	.	.	.
Jackson RD Drain	Ionia	Jackson RD	42.8693	-85.19344	County drain	9	18	2019	ambient	non-detect	.	.	.	.
Morrison	Ionia	Boat launch	42.862742	-85.213603	lake	9	18	2019	ambient	non-detect	0.54	non-detect	non-detect	non-detect
Rush Drain	Ionia	Rush st	42.85306	-85.21984	County drain	9	18	2019	ambient	non-detect	.	.	.	.
Tiffany LN Drain	Ionia	Tiffany Lane	42.86203	-85.19391	County drain	9	18	2019	ambient	non-detect	.	.	.	.
Bass	Mason	Marrison Park	43.83407	-86.40604	lake	9	22	2019	ambient	non-detect	.	.	.	.
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	9	22	2019	ambient	>10	34	non-detect	non-detect	non-detect
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	9	22	2019	ambient	1-5	.	.	.	.
Bass	Mason	Boat launch	43.83891	-86.41787	lake	9	22	2019	scum	>10	12	non-detect	non-detect	non-detect
Swan	Allegan	Beach	42.468285	-85.964365	lake	9	23	2019	ambient	1-5	1.5	non-detect	non-detect	non-detect
Swan	Allegan	Pauline	42.463632	-85.965052	lake	9	23	2019	ambient	1-5	1.9	non-detect	non-detect	non-detect
Swan	Allegan	boat launch	42.466349	-85.954209	lake	9	23	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Budd	Clare	Wilson State Park beach	44.02818	-84.80171	lake	9	24	2019	light scum	non-detect	.	.	.	.
Budd	Clare	Townline Lake RD	44.03175	-84.80379	lake	9	24	2019	ambient	non-detect	.	.	.	.
Budd	Clare	Boat launch	44.01608	-84.78818	lake	9	24	2019	light scum	non-detect	.	.	.	.
Budd	Clare	Saxton Park	44.02119	-84.79673	lake	9	24	2019	light scum	non-detect	non-detect	non-detect	non-detect	non-detect
Earl	Livingston	west canal	42.602398	-83.89996	lake	9	24	2019	scum	non-detect	non-detect	non-detect	non-detect	non-detect
Intermediate	Antrim	Campground boat launch	45.06815	-85.25997	lake	9	24	2019	ambient	non-detect	.	.	.	.
Intermediate	Antrim	Thurston Park beach	45.06993	-85.25932	lake	9	24	2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Intermediate	Antrim	E. State ST park	45.07001	-85.25846	lake	9	24	2019	ambient	non-detect	.	.	.	.
Intermediate	Antrim	Center Lake launch	45.05097	-85.25807	lake	9	24	2019	ambient	non-detect	.	.	.	.
Intermediate	Antrim	Gorham launch	45.02114	-85.22559	lake	9	24	2019	ambient	non-detect	.	.	.	.
Intermediate	Antrim	Bellaire park beach	44.97936	-85.20896	river	9	24	2019	ambient	non-detect	.	.	.	.
Intermediate	Antrim	Openo launch	45.01952	-85.20502	lake	9	24	2019	ambient	non-detect	.	.	.	.
Intermediate	Antrim	N. Intermediate Lake RD	45.03893	-85.24207	lake	9	24	2019	ambient	non-detect	.	.	.	.
Thornapple	Barry	Charleton Park	42.619623	-85.193754	lake	9	24	2019	scum	>10	31	non-detect	non-detect	non-detect
Sherwood	Oakland	Ledgewood DR docks	42.59534	-83.53905	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Winewood LN scum	42.59088	-83.53022	lake	9	25	2019	scum	test fail	19	non-detect	27	non-detect
Sherwood	Oakland	Winewood LN ambient	42.59104	-83.53013	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Driftwood docks	42.59356	-83.55486	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Driftwood DR residence	42.59056	-83.55232	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Trentwood/Surfwood	42.59438	-83.54713	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Wavewood DR	42.59444	-83.54545	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Ravinewood DR	42.58704	-83.54657	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Ravinewood DR E	42.59092	-83.53114	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Windwood CT	42.59245	-83.53147	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	E Commerce RD	42.5962	-83.53261	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	E Commerce RD/Winewood	42.59632	-83.53149	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Gulfwood	42.59883	-83.54696	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Inverrary CT	42.60209	-83.55523	lake	9	25	2019	ambient	non-detect	.	.	.	.
Sherwood	Oakland	Pikewood scum	42.5921	-83.53693	lake	9	25	2019	scum	5-10	2	non-detect	6.1	non-detect

Appendix 1 cont.

Lake	County	Site	Latitude	Longitude	Waterbody type	Month	Day	Year	Sample type (scum or ambient)	Algal Strip Result (Total MC ug/l)	Total microcystins (lab; ug/l)	Anatoxin (lab; ug/l)	Cylinon-detectrospermopsin (lab; ug/l)	Nodularin (lab; ug/l)
Sherwood	Oakland	Pikewood ambient	42.59201	-83.53675	lake	9	25	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	Davis RD	44.0794	-86.43624	lake	10	2	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	Upper lake boat launch	44.08539	-86.37343	lake	10	2	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	Wilson Park	44.07134	-86.42713	lake	10	2	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	Duneview DR	44.04256	-86.45819	lake	10	2	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	Middle Bayou	44.02804	-86.45657	lake	10	2	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	South Bayou	44.01552	-86.4574	lake	10	2	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	South canal	44.00887	-86.45853	lake	10	2	2019	ambient	non-detect	.	.	.	.
Hamlin	Mason	State Park beach	44.03508	-86.49265	lake	10	2	2019	ambient	non-detect	.	.	.	.
Bass	Mason	Marrison Park	43.83407	-86.40604	lake	10	2	2019	ambient	non-detect	.	.	.	.
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	10	2	2019	ambient	non-detect	.	.	.	.
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	10	2	2019	ambient	non-detect	.	.	.	.
Bass	Mason	Boat launch	43.83891	-86.41787	lake	10	2	2019	scum	1-5	.	.	.	.
Bass	Mason	Marrison Park	43.83407	-86.40604	lake	10	7	2019	ambient	non-detect	.	.	.	.
Bass	Mason	S. Lakeshore DR	43.82897	-86.41901	lake	10	7	2019	ambient	non-detect	.	.	.	.
Bass	Mason	Bass Lake BLVD	43.8358	-86.41982	lake	10	7	2019	ambient	non-detect	.	.	.	.
Bass	Mason	Boat launch	43.83891	-86.41787	lake	10	7	2019	scum	>10	.	.	.	.
Sherwood	Oakland	Winewood LN scum	42.59088	-83.53022	lake	10	7	2019	scum	.	5.4	non-detect	2.74	.
LeAnn	Hillsdale					10	7	2019	scum	>10	55	non-detect	non-detect	non-detect
Croton	Newaygo	Croton Township Campground	43.44728	-85.65867	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Croton	Newaygo	DuChemine Park	43.43996	-85.6667	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Hardy	Mecosta	Pierce RD scum	43.57655	-85.51686	river impoundment	10	7	2019	scum	>10	510	.	.	.
Hardy	Mecosta	Pierce RD ambient	43.57657	-85.51688	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Hardy	Mecosta	River Ridge	43.58362	-85.52732	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Hardy	Mecosta	Elder/Pierce	43.57628	-85.53178	river impoundment	10	7	2019	scum	>10	5500	.	.	.
Hardy	Newaygo	Big Bend docks	43.52613	-85.58161	river impoundment	10	7	2019	scum	>10	910	.	.	.
Hardy	Newaygo	Breezy Knoll Beach	43.5158	-85.62081	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Hardy	Newaygo	Sandy Beach boat launch	43.49518	-85.62982	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Hardy	Newaygo	Hardy Dam launch	43.49128	-85.63675	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Hardy	Newaygo	Oxbow Park launch	43.5055	-85.61069	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Hardy	Newaygo	Newaygo State Park launch	43.50435	-85.58624	river impoundment	10	7	2019	scum	>10	56	.	.	.
Hardy	Mecosta	Brower Park launch	43.55957	-85.54907	river impoundment	10	7	2019	scum	>10	11000	.	.	.
Hardy	Mecosta	Brower Park launch	43.55954	-85.54901	river impoundment	10	7	2019	ambient	non-detect	.	.	.	.
Croton	Newaygo	Croton Township Campground	43.44728	-85.65867	river impoundment	10	16	2019	ambient	non-detect	.	.	.	.
Croton	Newaygo	DuChemine Park	43.43996	-85.6667	river impoundment	10	16	2019	ambient	non-detect	.	.	.	.
Hardy	Mecosta	Pierce RD scum	43.57655	-85.51686	river impoundment	10	16	2019	scum	>10	15000	.	.	.
Hardy	Mecosta	Pierce RD ambient	43.57657	-85.51688	river impoundment	10	16	2019	ambient	non-detect	.	.	.	.
Hardy	Mecosta	River Ridge	43.58362	-85.52732	river impoundment	10	16	2019	ambient	non-detect	.	.	.	.
Hardy	Mecosta	Elder/Pierce	43.57628	-85.53178	river impoundment	10	16	2019	scum	>10	8100	.	.	.
Hardy	Newaygo	Big Bend docks	43.52613	-85.58161	river impoundment	10	16	2019	scum	>10	3800	.	.	.
Hardy	Newaygo	Big Bend docks	43.52613	-85.58161	river impoundment	10	16	2019	ambient	>10	.	.	.	.
Hardy	Newaygo	Breezy Knoll Beach	43.5158	-85.62081	river impoundment	10	16	2019	light scum	>10	39	.	.	.
Hardy	Newaygo	Hardy Dam launch	43.49128	-85.63675	river impoundment	10	16	2019	scum	>10	1500	.	.	.
Hardy	Newaygo	Hardy Dam launch	43.49128	-85.63675	river impoundment	10	16	2019	ambient	non-detect	.	.	.	.
Hardy	Newaygo	Oxbow Park launch	43.5055	-85.61069	river impoundment	10	16	2019	ambient	non-detect	.	.	.	.
Hardy	Newaygo	Newaygo State Park launch	43.50435	-85.58624	river impoundment	10	16	2019	ambient	non-detect	.	.	.	.
Crooked Lake	Emmett	.	45.413963	-84.7980891	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Guthrie Lake	Otsego	.	44.857026	-84.6096769	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Long Lake	Iosco	.	44.420639	-83.834719	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect

Appendix 1 cont.

Lake	County	Site	Latitude	Longitude	Waterbody type	Month	Day	Year	Sample type (scum or ambient)	Algal Strip Result (Total MC ug/l)	Total microcystins (lab; ug/l)	Anatoxin (lab; ug/l)	Cylinon-detectrospermopsin (lab; ug/l)	Nodularin (lab; ug/l)
Sand Lake	Iosco	.	44.31973	-83.681392	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Peach Lake	Ogemaw	.	44.295004	-84.164735	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Hardwood Lake	Ogemaw	.	44.243735	-84.000542	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Bush Lake	Ogemaw		44.192891	-84.037132	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Five Lakes	Clare	.	43.872663	-84.798162	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Bennett Lake	Livingston	.	42.786143	-83.840685	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Wycamp Lake	Emmet	.	45.653211	-84.983139	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
White Cloud Pond	Newaygo	.	43.547107	-85.767489	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Winnewana Impoundment	Washtenaw	.	42.354662	-84.1129996	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Belle Lake 2	Luce	.	46.483349	-85.816124	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Kaks Lake	Luce	.	46.303501	-85.5690655	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Sixteenmile	Alger	.	46.300687	-86.758691	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Fortune, Third	Iron	.	46.089779	-88.4272853	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Fortune, Fourth	Iron	.	46.089779	-88.4272853	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Ford Dam (Kingsford Flowag	Dickinson	.	45.876727	-88.083629	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Rice Lake, Little	Houghton	.	45.653211	-84.983139	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Big Lake	Baraga	.	46.612157	-88.5724222	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Steusser	Ontanagon	.	46.4508	-89.248293	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
McClure Basin	Marquette	.	46.559455	-87.5448666	lake	8		2019	ambient	non-detect	non-detect	non-detect	non-detect	non-detect
Gulliver Lake		3	45.982504	-86.027025	lake	8		2019	.	non-detect	0.86	non-detect	non-detect	non-detect
Gulliver Lake		C	45.982504	-86.027025	lake	8		2019	.	non-detect	0.81	non-detect	non-detect	non-detect