Bear Lake 2023 Watershed Assessment

January 2024

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Introduction

Bear Lake (Muskegon County, MI) is a small, eutrophic/hypereutrophic (hereafter referred to as eutrophic) lake located within the Muskegon Lake Area of Concern (AOC). Because of elevated total phosphorus (TP) concentrations and excess algal growth, a Total Maximum Daily Load (TMDL) was issued for Bear Lake in 2008. Although the TMDL called for a 50% reduction in external phosphorus load and a 79% reduction in internal load (to attain a target total phosphorus concentration of 30 µg/L in Bear Lake), additional research revealed that the TMDL's internal loading estimate in Bear Lake was too high (Steinman and Ogdahl 2015). As a consequence, more effort was placed on external load reduction through the restoration of former celery fields to a flow-through marsh (Steinman and Ogdahl 2016). The restoration project has resulted in a significant decline in TP concentrations in the formerly flooded celery ponds (Hassett and Steinman 2022), although its positive impact on downstream Bear Lake nutrient concentrations will take time to be detected.

Phosphorus load reduction is needed in Bear Lake not only to meet water quality standards, but also to remove the eutrophication and undesirable algae beneficial use impairment (BUI) for the Muskegon Lake AOC, whose geographic boundary includes Bear Lake, ultimately resulting in this AOC being removed from EPA's list of Great Lakes Areas of Concern.

The Bear Lake - Lake Board contracted with GVSU's Annis Water Resources Institute to monitor water quality conditions in Bear Lake beginning in 2022 and again in 2023. Our 2022 report noted that Bear Lake was still experiencing excess nutrients and chlorophyll *a* (an indicator of algal abundance). We recommended monitoring of tributary nutrient concentrations in order to identify the major sources of nutrients entering Bear Lake, as well as more frequent monitoring of chlorophyll *a* and a survey of lake users to determine their priorities; in addition, the report included our support of the use of Phoslock® to help control phosphorus concentrations in the lake.

This report includes our second year of findings and recommendations for future monitoring activities.

Methods

Tributaries

The Bear Lake – Lake Board approved the addition of three new tributary sites for 2023 monitoring, which were sampled monthly: two inflowing tributaries (at Fenner's Ditch and the Bear Creek gazebo) and one outflowing tributary (from the upstream side of the Ruddiman Drive bridge that spans the Bear Creek channel; Figure 1). Tributary sites were sampled monthly at baseflow conditions on the same dates that we sampled the Bear Lake sites. Water transparency was measured as Secchi disk depth. General water quality parameters were measured using a YSI EXO2 sonde (YSI, Inc., Yellow Springs, OH), which included water temperature, dissolved oxygen (DO), pH, specific conductivity (SpCond), and turbidity. Water was collected via grab sampling at surface depth only and analyzed for TP and soluble reactive phosphorus (SRP: the bioavailable form of P) as described below. Additional tributary sampling for general water quality parameters, TP, and SRP, occurred during two storm flow events, defined as >0.25" of precipitation preceded by 72 hours of dry weather. Storm sampling water collection occurred via Van Dorn sampler from the Ruddiman Drive bridge or by cup-on-a-stick from the shoreline.

Bear Lake

Bear Lake water quality monitoring sites were the same as in prior years to facilitate comparisons of 2023 data with prior data. Due to budget constraints and the desire to sample earlier in the calendar year, sampling in 2023 occurred in April, June through August, and in October (skipping both May and

September 2023), in contrast to sampling in 2022 that occurred monthly from May through October. The four sites included two sites monitored by Restorative Lake Science (RLS) in 2017-2021 (Site 1 and Site 3) and two sites previously monitored by AWRI in 2011-2012 and 2022 (Site 2 and Site 4). Site locations are specified in Table 1 and Figure 1.

Lake samples were collected once monthly from a jonboat throughout the monitoring period, with sampling occurring usually between 9:00-11:30 AM. Water transparency was measured as Secchi disk depth. General water quality parameters were measured using a YSI EXO2 sonde (YSI, Inc., Yellow Springs, OH), which included water temperature, dissolved oxygen (DO), pH, specific conductivity (SpCond), and turbidity. Water was collected at surface depth via grab sampling and at middle and near-bottom depths via a Van Dorn water sampler. Samples for water chemistry analysis were collected in 500-mL bottles, stored on ice, and returned to the lab for nutrient analysis, usually within 4 hours.

Separately, an additional 1-L sample was collected in amber bottles at surface and near-bottom depths at each site for chlorophyll *a* (chl *a*) extraction. One 250-mL sample was collected for phytoplankton identification from the middle depth of each site, which was later composited with subsamples from surface and near-bottom chl *a* sample bottles from each site into a single integrated depth phytoplankton sample per site.

Additionally, we subsampled from surface and near-bottom chl *a* bottles for microcystin analysis. Microcystin is the most common toxin produced by cyanobacteria (blue-green algae). We used the ELISA QuantiPlate kit for Microcystins High Sensitivity, which serves as a useful screening tool if microcystin is present in the lake. Advisories for microcystin exposure have been developed by the World Health Organization (WHO) and U.S. EPA. For drinking water, the WHO advisory is >1 µg/L and EPA is >1.6 µg/L (0.3 µg/L for infants and pre-schoolers); for recreational use, WHO is >20 µg/L and EPA is >8 µg/L (WHO 2017; U.S. EPA 2019). Since Bear Lake is used only for recreation, we applied the latter two criteria.

We also collected water samples, using near-surface grabs only, to measure *E. coli* concentrations. One sample was collected from each site in addition to a field duplicate sample each month. These 100-mL aliquots were analyzed via the IDEXX Colilert-18® method. Briefly, substrate powder was added to aliquots and incubated in Colilert Quanti-Tray®/2000 at 35°C for 18 hours, then trays were exposed to long-wave ultraviolet light and blue tray wells were counted as positive. The number of positive wells was the most probable number (MPN) per 100 mL, and 300 colony-forming units (cfu) per 100 mL is a recognized upper limit as being safe for total body contact in the state of Michigan (MCL 323.1062 of 2006 *et seq.*).

After returning to the lab, water from each lake site was gently inverted and subsampled for analysis of 1) phosphorus (P) as both soluble reactive phosphorus (SRP) and total phosphorus (TP); and 2) nitrogen (N) as nitrate (NO_3^-), ammonia (NH_3), and total Kjeldahl nitrogen (TKN) species. Duplicate water quality samples were collected once a month for quality control. Water for SRP and NO_3^- analyses was syringe-filtered through acid-washed 0.45-µm membrane filters into scintillation vials; SRP was refrigerated at 4°C, and NO_3^- was frozen, until analysis. TKN was acidified with sulfuric acid; TP and TKN were kept at 4°C until analysis. SRP, TP, NO_3^-, NH_3, and TKN were analyzed on a SEAL AQ2 discrete automated analyzer (U.S. EPA 1993). Any values below detection were reported as ½ of their respective detection limits.

Chl *a* was subsampled for phytoplankton analysis by gently inverting and removing 250 mL from surface and near-bottom samples and combining them with the 250 mL middle depth sample. These integrated depth phytoplankton samples were preserved with 7.5 mL of Lugol's iodine to create a 1% final solution.

Phytoplankton were later identified to genus or species, and abundance was estimated via light microscopy as the respective sum of each species' biovolume present at each site on each sampling date.

For a historic comparison of water quality conditions between the current sampling year and recent years of monitoring by Restorative Lake Science (RLS), AWRI's 2022 and 2023 data were reformatted to match RLS's data summary methods based on their 2021 Bear Lake water quality report, using only lake sites 1 and 3. AWRI water quality depth profiles (measured at every meter) and nutrient data (near-surface and near-bottom) were averaged into single point values per site, and April 2023 and July 2023 data were compared to historic Spring and Summer data, respectively.

Water quality dashboards for TP, chl *a*, and Secchi depth were created using historic (Steinman and Ogdahl 2013) and current AWRI Bear Lake monitoring data in conjunction with historic RLS data (RLS 2022) and are attached in Appendix A. AWRI 2023 data are presented seasonally by separately averaging surface data into Spring (April and June), Summer (July and August), and Fall (October) seasons. Water quality goals for chl *a* and Secchi depth were established based on thresholds used in AWRI's annual Muskegon Lake water quality dashboard (www.gvsu.edu/wri/dashboard); the TP category's "Meeting Goal" threshold was created from the Bear Lake's TMDL goal of 30 µg/L and the "Desirable" threshold of 24 µg/L from the Muskegon Lake water quality dashboard.

Table 1. Tributary and Bear Lake site coordinates and maximum depth across 2023 sampling events.

Site	Latitude (°N)	Longitude (°W)	Depth (m)
Channel	43.243203	86.296022	2.3
Fenner	43.267375	86.278917	1.5
Gazebo	43.265553	86.267061	1.1
Lake 1	43.248856	86.290336	8.3
Lake 2	43.253489	86.286969	4.2
Lake 3	43.254906	86.284244	4.0
Lake 4	43.260489	86.273539	3.0

Figure 1. Map of Bear Lake (yellow triangles) and tributary (red circles) water quality monitoring sites. Fenner and Gazebo are inflows, Channel is an outflow.

Results

Tributary Water Quality

Water temperature followed expected seasonal trends at both Bear Lake inflowing tributaries and the outflow, ranging 11.6-25.5 ºC at baseflow (Table 2). Surface depth DO in tributaries was high at all sites and supersaturated in Fenner's Ditch, which averaged 11.7 mg/L (or 137%) throughout the study period (Table 2, Figure 2). All sites had alkaline pH ranging 8-9 (Table 2, Figure 3). Specific conductivity increased throughout the year, ranging 333-363 µS/cm in April and 418-466 µS/cm by October (Table 2, Figure 4); this increase (~100 µS/cm) is not trivial although levels are not high enough to suggest an ecological problem; conductivity also increased through the summer in 2022 but to a lesser degree, suggesting there may be leaking septic systems contributing ions to the lake. Turbidity was low overall and varied by location; the Gazebo site by Bear Creek was often less turbid than either Fenner's Ditch or the Channel outflow (Table 2, Figure 5). Secchi depth was generally uniform in April, with water clarity tending to decline (i.e., Secchi depth getting shallower) following clear water conditions in June-July (Table 2, Figure 6). Channel clarity tended to be better than the two inflow sites, possibly due to backflow from clearer Muskegon Lake water and/or the settling out of sediments in the lake from the inflowing tributaries.

There were relatively small differences in water quality between base flow and storm flow conditions. Increases in turbidity during storm events are commonly observed, as sediment gets washed off of land and into storm drains or directly into Bear Lake. However, specific conductivity (an indicator of dissolved ions) either increased slightly or decreased, indicating storm flow was not having a substantial impact on ions such as salt.

Table 2. Means (range) of tributary general water quality parameters. n = number of sampling events; Temp = water temperature; DO = dissolved oxygen; SpCond = specific conductivity; ND = no data (Secchi depth not measured during storm events).

Flow	Site	n	Temp (°C)	DO (mg/L)	DO (%)	pH	SpCond (µS/cm)	Turbidity (FNU)	Secchi Depth (m)
Base	Channel	5	20.8 (11.6-25.5)	8.8 (7.4-11.4)	96.8 (90-104.9)	8.4 (8.3-8.7)	387.1 (333.9-418.7)	3.9 (3.0-4.7)	1.09 (0.74-1.54)
	Fenner	5	21.7 (16.4-25.5)	10.6 (8.0-15.2)	119.1 (93-155.8)	8.6 (8.4-9.1)	403.8 (363-450.6)	2.3 (1.2-4.6)	0.81 (0.5-1.28)
	Gazebo	5	22.4 (14.7-27.5)	11.7 (9.9-15.8)	135.8 (97.7-195.9)	8.8 (8.0-9.2)	419.8 (347.7-466.4)	4.2 (2.2-5.7)	0.87 (0.4-1)
Storm	Channel	2	24.5 (23.7-25.3)	7.8 (7.1-8.6)	93.9 (86.7-101.1)	8.5 (8.3-8.8)	392.4 (388.1-396.6)	5.3 (4.3-6.4)	ND
	Fenner	2	22.9 (22.0- 23.9)	11.2 (10.2-12.2)	130.5 (121.2-139.8)	9.1 (9.0-9.2)	423.8 (403.5-444.1)	8.1 (6.7-9.4)	ND
	Gazebo	2	22.7 (21.9-23.6)	8.8 (8.5-9.1)	102.6 (100.7-104.4)	8.5 (8.4-8.6)	412.0 (409.8-414.2)	1.4 (0.9-1.9)	ND

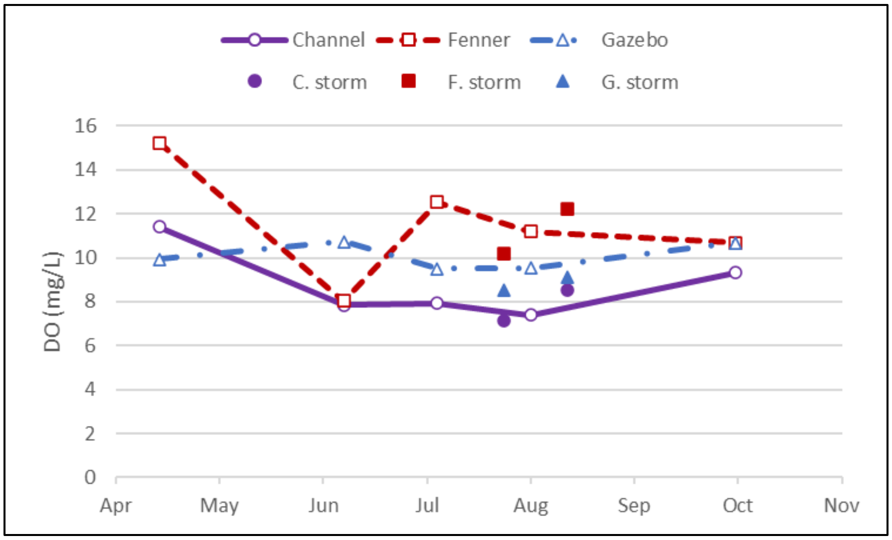

Figure 2. Tributary DO concentrations sampled April – October 2023 at baseflow (lines with white symbols) and storm flow events (filled symbols).

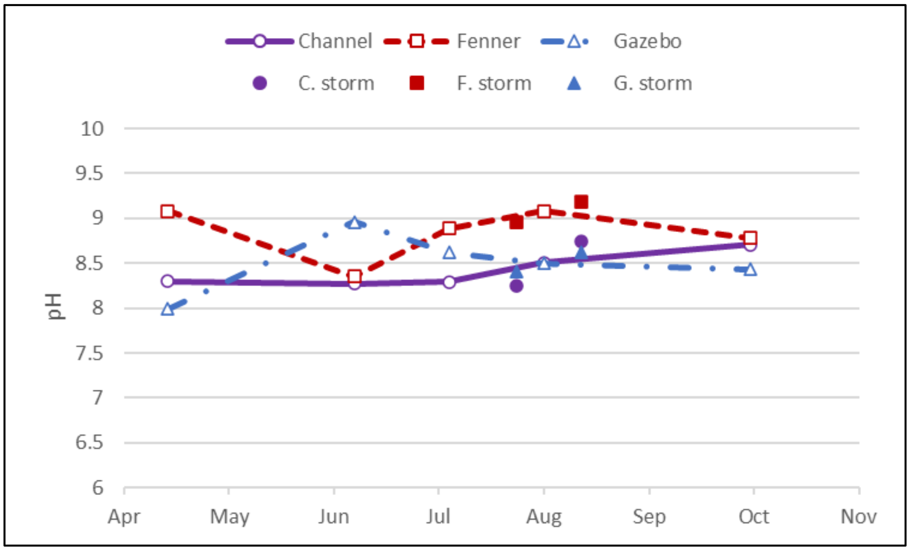

Figure 3. Tributary pH sampled April – October 2023 at baseflow (lines with white symbols) and storm flow events (filled symbols).

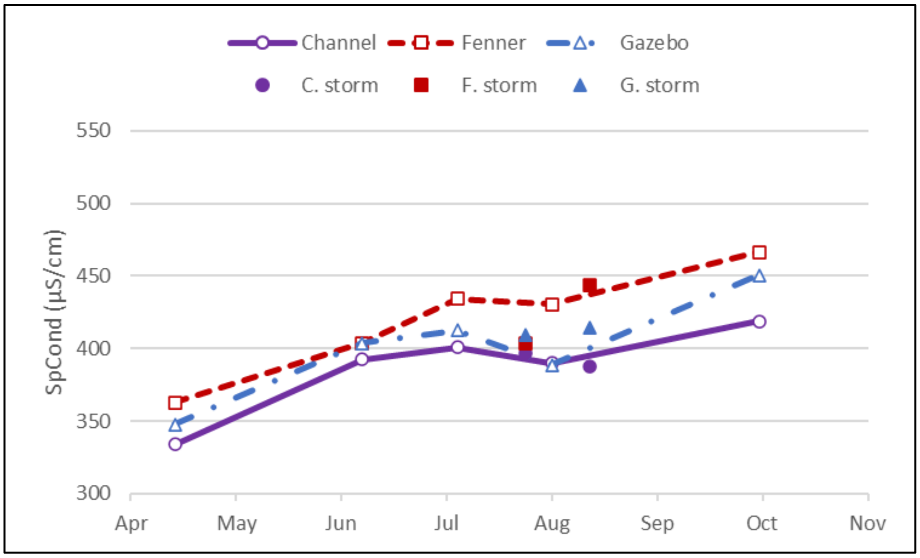

Figure 4. Tributary specific conductivity sampled April – October 2023 at baseflow (lines with white symbols) and storm flow events (filled symbols).

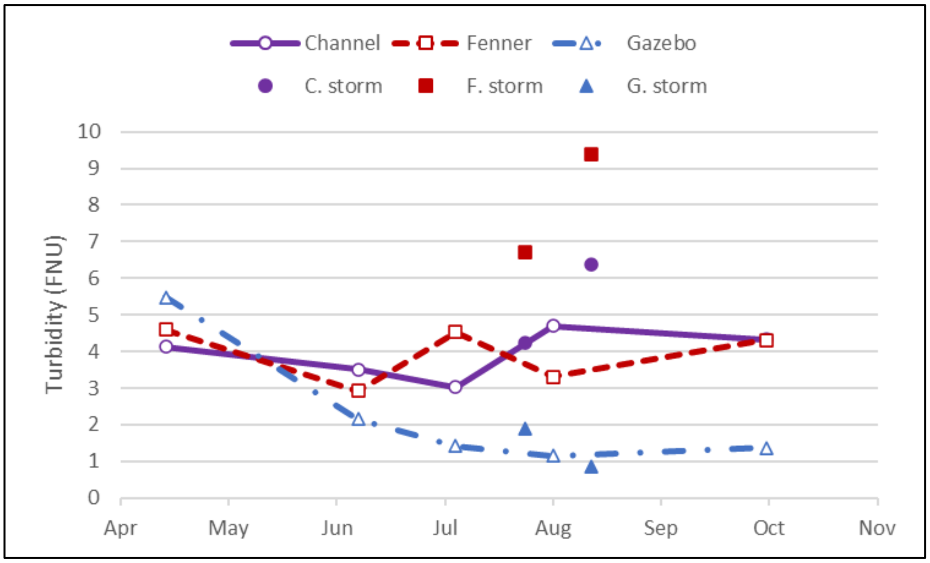

Figure 5. Tributary turbidity sampled April – October 2023 at baseflow (lines with white symbols) and storm flow events (filled symbols).

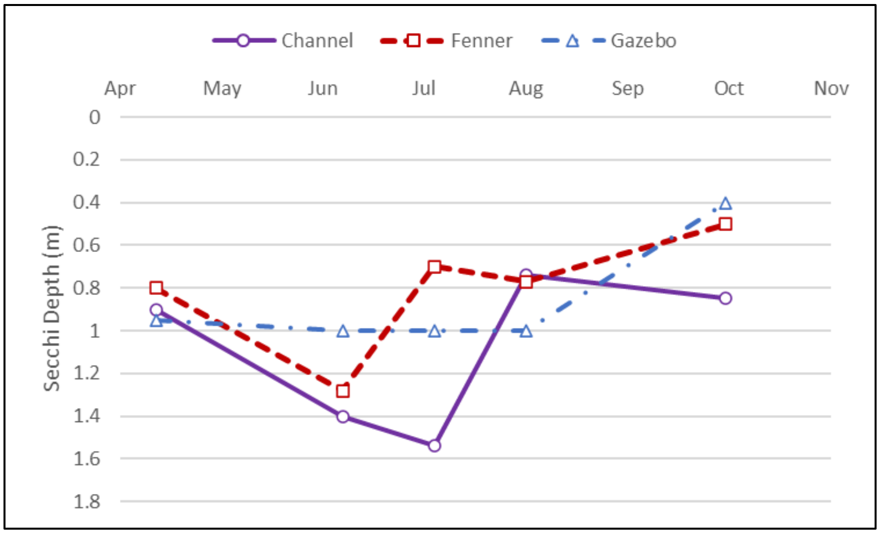

Figure 6. Tributary Secchi depth sampled at baseflow from April – October 2023. The higher the Secchi depth number, the greater the water clarity.

Tributary Nutrients

Mean TP was highest at Fenner's Ditch (58 µg/L) compared to other sites (19-31 µg/L), although this value is largely driven by a 122 µg/L TP spike in July (Table 3, Figure 7). TP concentrations were lowest at Gazebo (≤20 µg/L), indicating that the celery field restoration project continues to have a positive effect on phosphorus concentrations entering Bear Lake. SRP values were much lower, and samples collected at the Bear Creek Gazebo and Channel outflow were often below detection (Table 3, Figure 8).

TP and SRP likewise increased during storm events, and the highest P concentrations on each date were found at Fenner's Ditch (Table 4, Figures 7-8), although SRP concentrations remained relatively low (mean < 10 µg/L). We did not measure nitrogen species but it is possible that the increase in specific conductivity over time may be due to nitrate-nitrogen (NO_3^-), which is applied as a fertilizer (lawn and crop). Both nitrogen and phosphorus can contribute to algal blooms, and both should be controlled.

Table 3. Means (range) of tributary total phosphorus (TP) and soluble reactive phosphorus (SRP) for baseflow and storm event samplings. n = number of sampling events.

Flow	Site	n	TP (µg/L)	SRP (µg/L)
Base	Channel	5	30.8 (19.5 - 39)	2.5 (2.5 - 2.5)
	Fenner	5	57.6 (26.7 - 121.7)	3.5 (2.5 - 5.5)
	Gazebo	5	19.1 (10.1 - 28.9)	3.7 (2.5 - 8.3)
Storm	Channel	2	42.1 (40.3 - 43.9)	2.5 (2.5 - 2.5)
	Fenner	2	101.3 (87 - 115.5)	9.5 (6 - 12.9)
	Gazebo	2	13.7 (9.2 - 18.1)	3.8 (2.5 - 5)

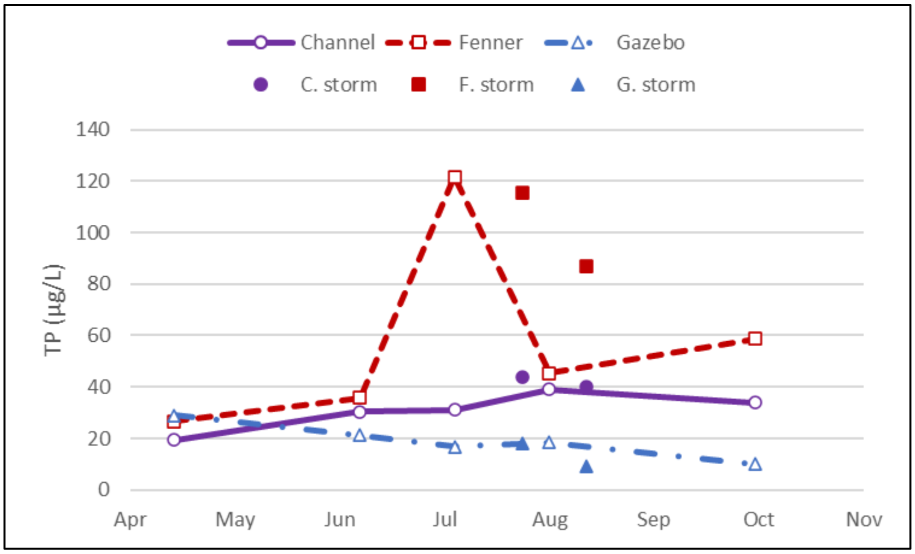

Figure 7. Tributary total phosphorus (TP) concentrations sampled April – October 2023 at baseflow (lines with white symbols) and storm flow events (filled symbols).

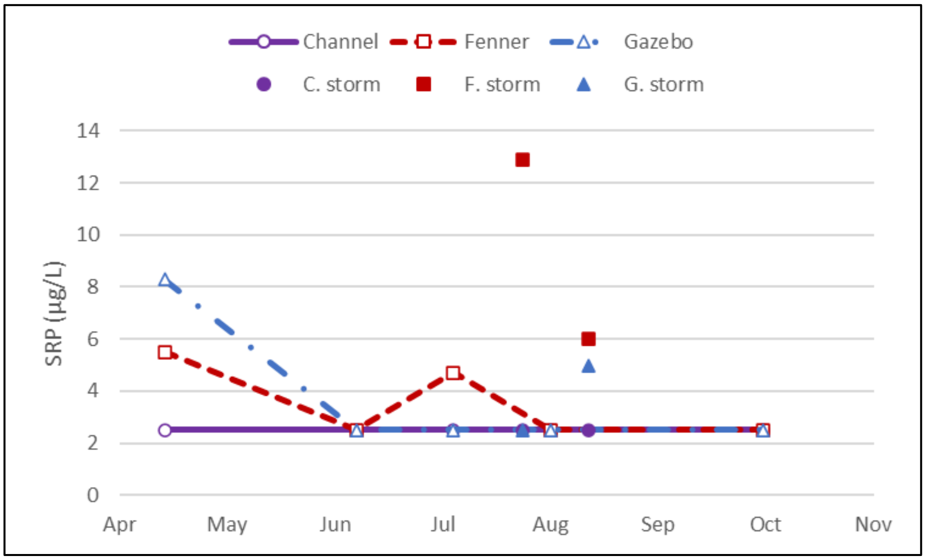

Figure 8. Tributary soluble reactive phosphorus (SRP) concentrations sampled April – October 2023 at baseflow (lines with white symbols) and storm flow events (filled symbols). Note that samples below analytical detection are reported graphically as 2.5 µg/L.

2023 Bear Lake Water Quality

Bear Lake water quality mean values (excluding phosphorus) showed variation with depth, but only limited variation across sites (Table 4). As observed last year, DO decreased with depth; site 1 was severely hypoxic at depth in July and August (0.13-0.14 mg/L; Figure 9). As seen in tributary sites, lake site pH was slightly alkaline; pH declined (i.e., became less alkaline) with depth at all sites, but especially as Site 1 (Table 4, Figure 10). Specific conductivity was similar throughout the lake at all depths except for elevated levels in July and August at Site 1 (Table 4, Figure 11). Turbidity was low and ranged ~3-8 FNU and tended to be greatest in the bottom sites where sediments are most easily disturbed and resuspended (Table 4, Figure 12).

Table 4. Means (±SD) of Bear Lake general water quality parameters across all months (n=5). Temp = water temperature, DO = dissolved oxygen; SpCond = specific conductivity.

Site	Depth	Temp (°C)	DO (mg/L)	DO (%)	pH	SpCond (µS/cm)	Turbidity (FNU)	Secchi Depth (m)
1	Surface	21.6 (13-26.1)	9.4 (7.4-13.2)	105.1 (85.4-125.7)	8.6 (8.3-8.8)	391.7 (331.3-418)	3.9 (3.4-5)	1.06 (0.75-1.44)
	Middle	21.1 (12.3-25.7)	8.5 (6.1-12.5)	93.6 (74.8-116.8)	8.4 (8.2-8.7)	388.9 (333.7-419)	4.3 (3.2-6.2)	
	Bottom	17.7 (11.2-22.2)	4 (0.1-9.2)	40.9 (1.4-83.7)	7.6 (7.3-8)	432 (343-517)	5.5 (4.1-7.1)	
2	Surface	22.0 (14.1-26.4)	9.7 (7.5-13.1)	109.2 (87.5-127.5)	8.6 (8.3-8.9)	391.9 (331.2-417.4)	3.7 (2.8-4.6)	1.01 (0.75-1.35)
	Middle	21.7 (13-26.3)	9.5 (7.3-12.9)	106.1 (83.9-122.4)	8.6 (8.3-8.9)	392 (332-417.8)	4 (2.9-4.6)	
	Bottom	21.0 (11.7-26.1)	7.8 (5.3-10.1)	85.8 (65-102.1)	8.3 (7.9-8.7)	393.6 (340.5-419.9)	6 (4.3-7.9)	
3	Surface	22.1 (13.9-26.4)	9.7 (7.8-13.4)	110.1 (90.7-129.7)	8.7 (8.4-8.9)	392.9 (331.8-420.5)	3.8 (3-4.7)	1.06 (0.85-1.25)
	Middle	21.9 (13.5-26.4)	9.5 (7.1-13.1)	107.2 (82.3-126.2)	8.6 (8.2-8.8)	392.5 (331-420.1)	3.9 (3.2-4.6)	
	Bottom	21.3 (12.6-26.2)	8.3 (6.1-12.3)	92.3 (75.2-115.5)	8.4 (8-8.7)	393 (332.9-422.1)	4.9 (4.1-5.9)	
4	Surface	21 (14.6-26.6)	10.1 (7.7-13.1)	111.3 (89.1-129.8)	8.6 (8.3-8.8)	384.5 (332.4-429.5)	4.3 (3.2-5)	1 (0.8-1.33)
	Middle	22.1 (14-26.6)	9.4 (7.7-13.3)	106.5 (88.8-129.2)	8.6 (8.3-8.9)	394.6 (332.1-429)	4.2 (3.4-5.2)	
	Bottom	21.5 (13.3-26.2)	7.5 (4.2-11.9)	83.6 (46.4-113.5)	8.3 (7.9-8.7)	395.3 (333.3-427.9)	6 (5.1-7.3)	
All Sites	Surface	21.7 (13-26.6)	9.7 (7.4-13.4)	108.9 (85.4-129.8)	8.6 (8.3-8.9)	390.2 (331.2-429.5)	3.9 (2.8-5)	1.03 (0.84-1.33)
	Middle	21.7 (12.3-26.6)	9.2 (6.1-13.3)	103.3 (74.8-129.2)	8.5 (8.2-8.9)	392 (331-429)	4.1 (2.9-6.2)	
	Bottom	20.4 (11.2-26.2)	6.9 (0.1-12.3)	75.7 (1.4-115.5)	8.2 (7.3-8.7)	403.5 (332.9-517)	5.6 (4.1-7.9)	

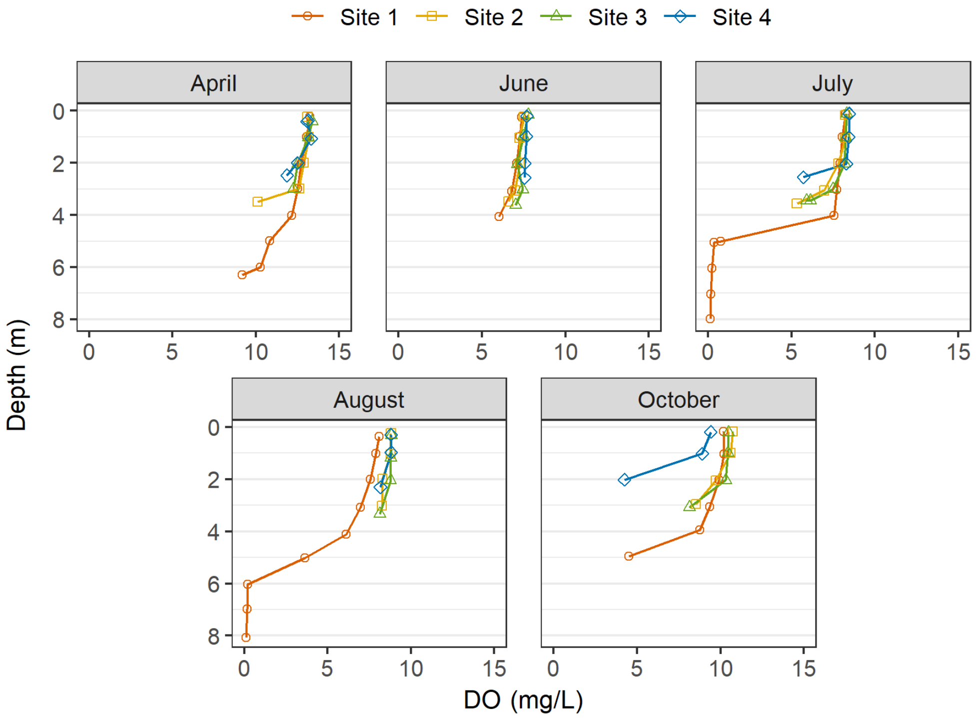

Figure 9. Bear Lake DO concentrations sampled April – October 2023.

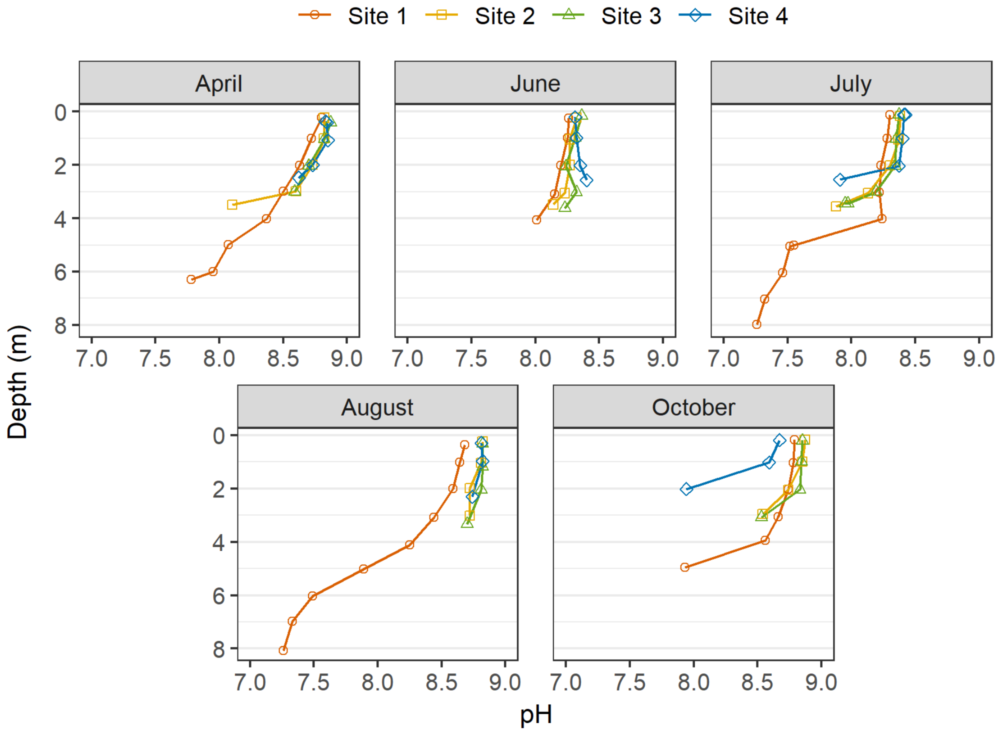

Figure 10. Bear Lake pH sampled April – October 2023.

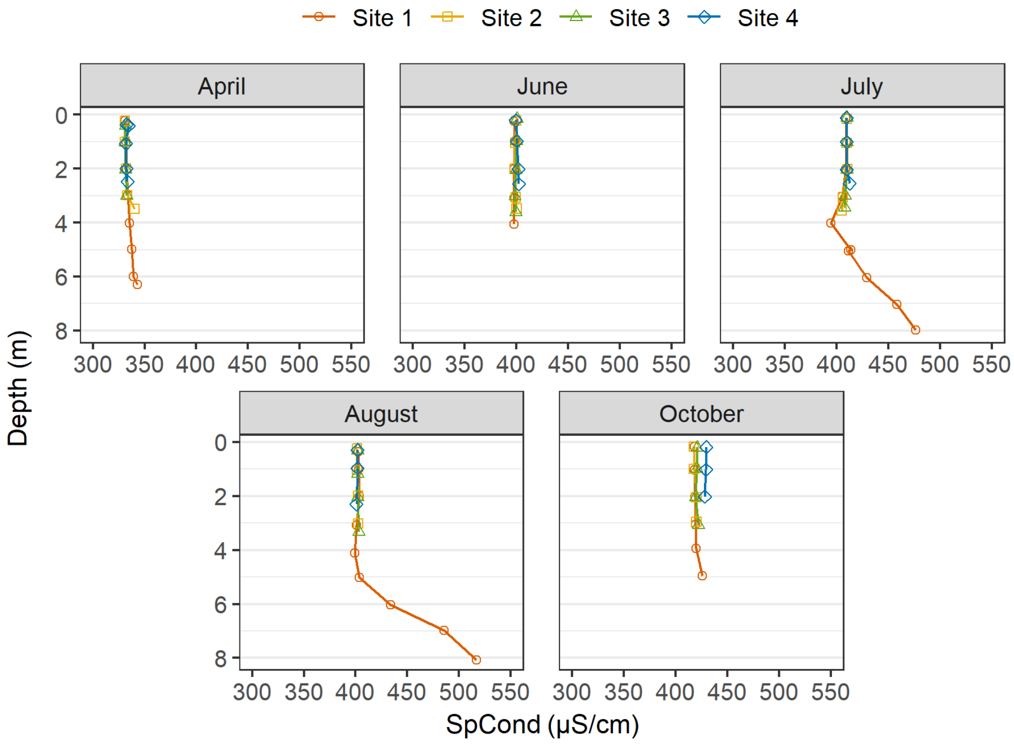

Figure 11. Bear Lake specific conductivity sampled April – October 2023.

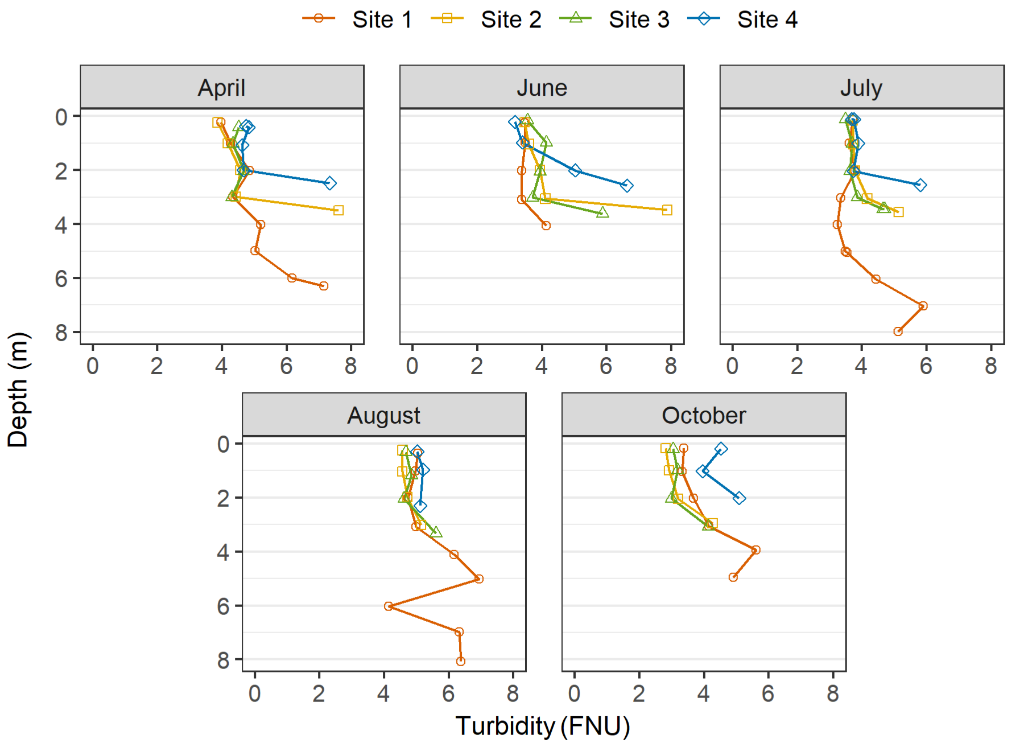

Figure 12. Bear Lake turbidity sampled April – October 2023.

Secchi depth measurements were similar across all sites, with highest clarity in June, and becoming more turbid thereafter (Fig. 13), presumably due to increased chlorophyll in the summer/fall (Figure 19).

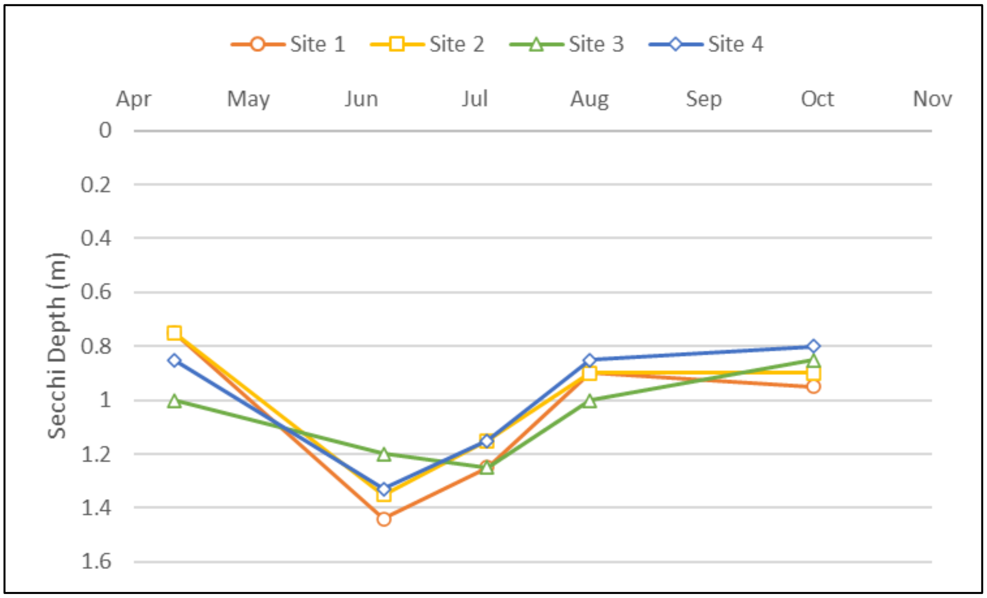

Figure 13. Bear Lake Secchi depth sampled April – October 2023. The greater the Secchi depth magnitude, the greater the water clarity.

Bear Lake Nutrients

Lake TP generally ranged 20-52 µg/L except for spikes of 422 and 745 µg/L in July and August at the bottom depth of site 1 (Table 5, Figure 14A-B). SRP followed the same pattern and was below detection (reported here as 2.5 µg/L, which is one-half our detection limit of 5 µg/L) at every site and depth except for the site 1 summer spikes, which were measured as 156 and 217 µg/L in July and August, respectively (Table 5, Figure 15). The bottom water spike is most likely due to release from the sediments (internal phosphorus loading) and appears to be limited to the deeper area of the lake, consistent with the findings of Steinman and Ogdahl (2015), although the amount of phosphorus measured in their study was much lower than what we measured in 2023. The grand mean for surface TP across all sites and months was 30.25 µg/L, very slightly above the target growing season TMDL of 30 µg/L (MDEQ 2008).

NO_3^- concentrations generally ranged below 0.05 mg/L in 2023 and were more spatially variable with a less discernable seasonal trend than in 2022 (Table 5, Figure 16; cf. Steinman and Hassett 2023). However, 2023 did see a strong return of spiking NH_3 and TKN concentrations in the bottom waters of Site 1 during July and August, which peaked at 3.4 mg NH_3-N/L and 4.8 mg TKN-N/L, respectively. This is consistent with the low DO concentrations at this deep site, and internal release of the chemically reduced form of nitrogen: ammonia (NH_3). Similar to the release of phosphorus from the sediments at this site in summer, the nitrogen and phosphorus concentrations are high enough to merit concern, but appear limited to this one deep site (Table 4, Figures 17-18).

Table 5. Means (range) of Bear Lake total phosphorus (TP), soluble reactive phosphorus (SRP), nitrate (NO_3^-), ammonia (NH_3), and total Kjeldahl nitrogen (TKN). BD = below detection.

Site	Depth	TP (µg/L)	SRP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
1	Surface	30.0 (19.5-38.8)	BD	0.03 (0.03-0.04)	0.03 (BD-0.07)	0.98 (0.77-1.12)
	Bottom	251.5 (26-745)	76.0 (BD-216.9)	0.04 (BD-0.08)	1.35 (0.02-3.42)	2.42 (0.75-4.83)
2	Surface	28.2 (20-39.6)	BD	0.03 (0.03-0.03)	0.02 (BD-0.06)	0.98 (0.61-1.18)
	Bottom	36.3 (21.7-51.5)	BD	0.03 (BD-0.05)	0.03 (BD-0.08)	0.81 (0.49-0.98)
3	Surface	31.3 (24.6-37.2)	BD	0.03 (BD-0.04)	0.02 (BD-0.06)	0.89 (0.48-1.1)
	Bottom	34.8 (21.8-44.4)	BD	0.03 (0.02-0.03)	0.04 (BD-0.09)	0.86 (0.63-1.09)
4	Surface	31.8 (27.1-36.4)	BD	0.03 (BD-0.05)	0.05 (BD-0.17)	0.76 (0.58-0.94)
	Bottom	39.8 (28.8-46.7)	BD	0.03 (BD-0.06)	0.06 (BD-0.2)	1.17 (0.73-1.63)

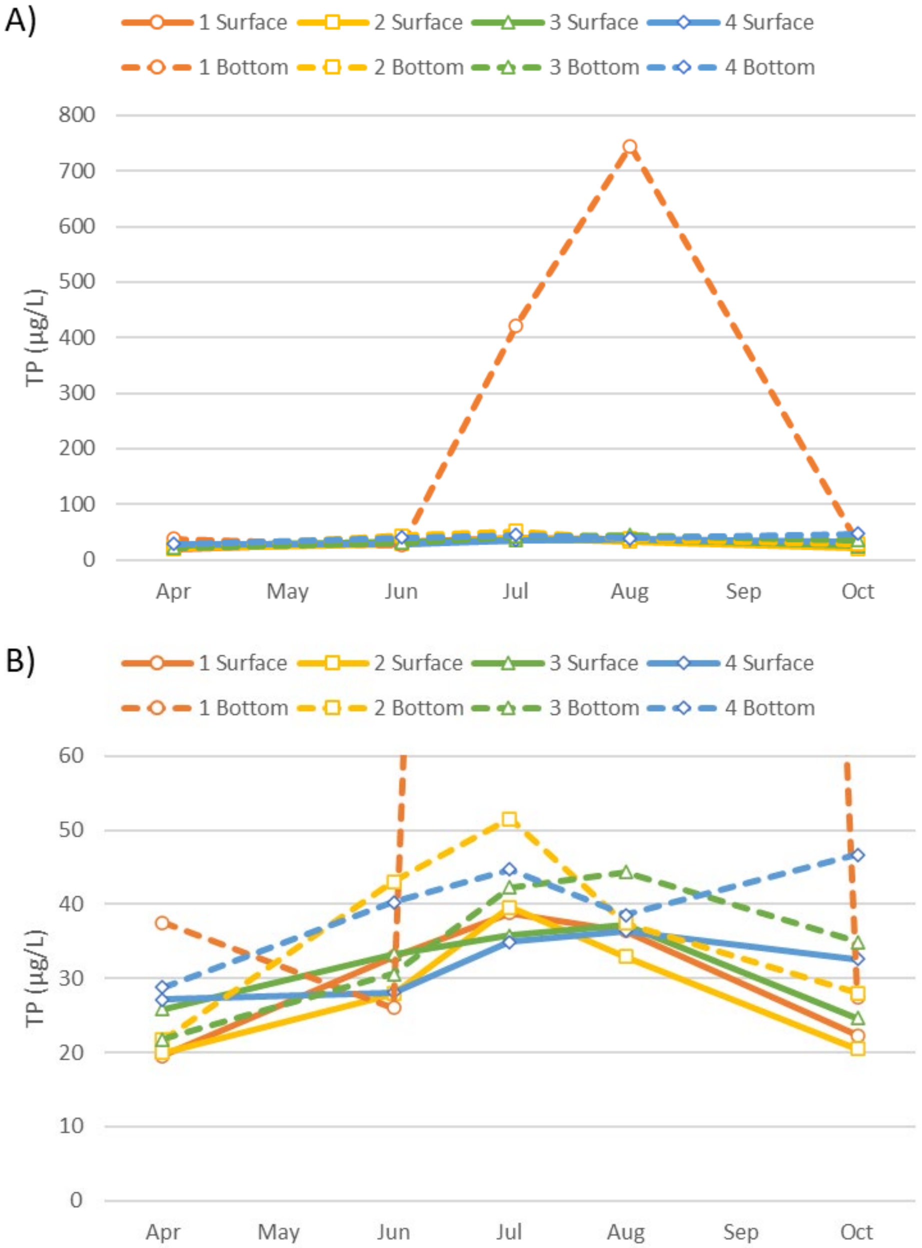

Figure 14. Bear Lake total phosphorus (TP) concentrations sampled April – October 2023 at near-surface (solid lines) and near-bottom depths (dashed lines). Panel B provides more detail of the lower range of panel A (i.e., between 20 and 50 µg/L).

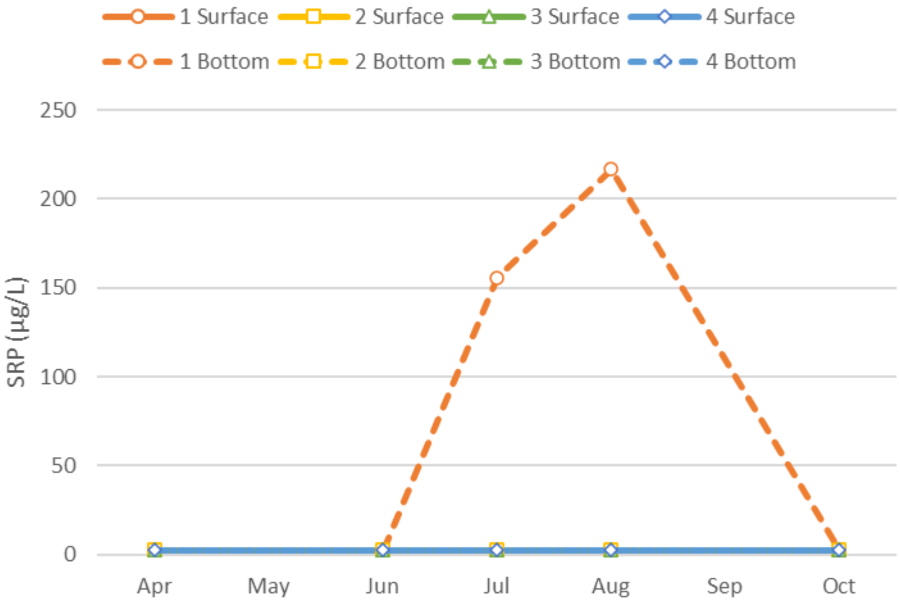

Figure 15. Bear Lake soluble reactive phosphorus (SRP) concentrations sampled April – October 2023 at near-surface (solid lines) and near-bottom depths (dashed lines). Note that samples below analytical detection are reported graphically as 2.5 µg/L.

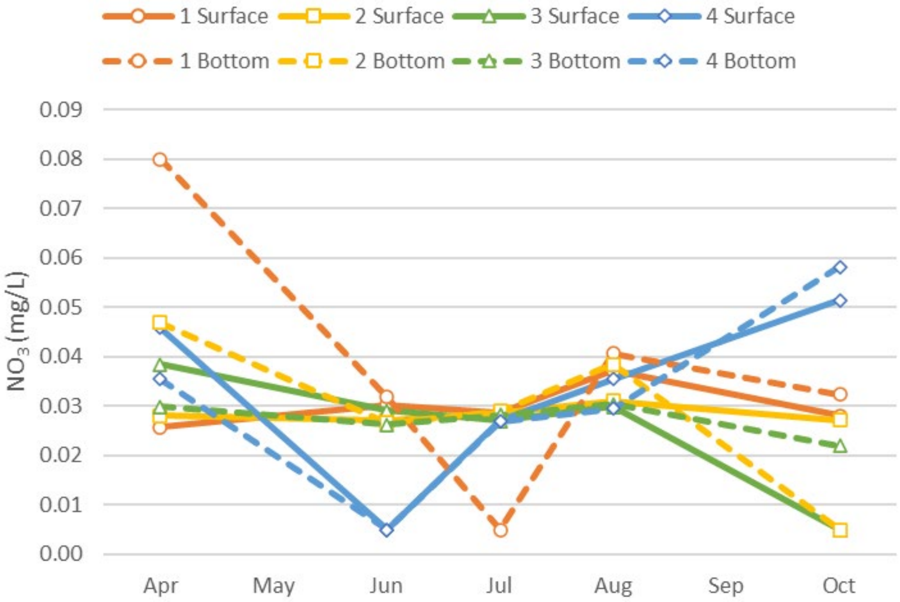

Figure 16. Bear Lake nitrate (NO_3^-) concentrations sampled April – October 2023 at near-surface (solid lines) and near-bottom depths (dashed lines).

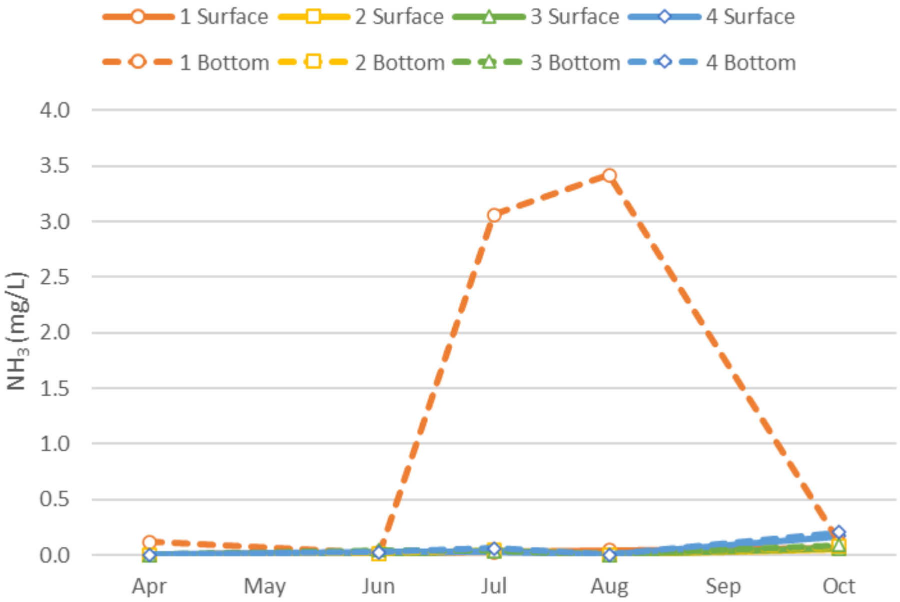

Figure 17. Bear Lake ammonia (NH_3) concentrations sampled April – October 2023 at near-surface (solid lines) and near-bottom depths (dashed lines).

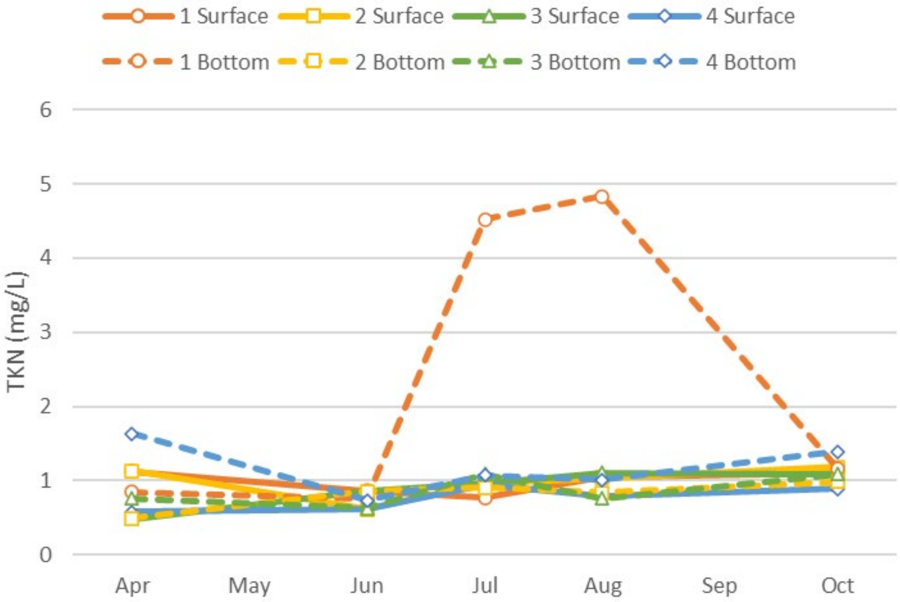

Figure 18. Bear Lake total Kjeldahl nitrogen (TKN) concentrations sampled April – October 2023 at near-surface (solid lines) and near-bottom depths (dashed lines).

Mean chl *a* concentrations, averaged across time, were similar among sites, ranging from the low to mid 20's (in µg/L; Table 6). This is a higher concentration than considered desirable; in Muskegon Lake, the target chl *a* concentration is 10 µg/L. Of course, these are grab samples and may not be representative of the intervening time periods that were not sampled (Table 6, Figure 19).

Microcystin was low throughout most of 2023 but spiked in August, averaging 1.77 µg/L across all sites and depths; however, this remains below the WHO and EPA guidelines for recreational contact (Table 6, Figure 20). *E. coli* concentrations were very low in 2023 and ranged below 5 cfu/100 mL (Table 6), remaining well below the 300 cfu/100 mL limit for Michigan waters.

Table 6. Means (range) of Bear Lake biological parameters of water quality. Chl = chlorophyll. NA = not applicable, as *E. coli* samples were not collected at bottom depth.

Site	Depth	Chl *a* (µg/L)	Microcystin (µg/L)	*E. coli* (cfu/100 mL)
1	Surface	24.4 (14.4-36.7)	0.4 (0.02-1.63)	1.6 (0.5-3)
	Bottom	22.1 (9.7-51.1)	0.4 (0-1.77)	NA
2	Surface	20.8 (15.9-32.9)	0.4 (0-1.85)	1.9 (0.5-3)
	Bottom	24.9 (10.7-37.1)	0.4 (0-1.82)	NA
3	Surface	24.0 (19.4-31.9)	0.4 (0.03-1.85)	0.6 (0.5-1)
	Bottom	25.4 (12.2-40.2)	0.4 (0.02-1.67)	NA
4	Surface	22.2 (12-31.7)	0.4 (0.03-1.81)	1.8 (0.5-3)
	Bottom	27.5 (18.6-35.7)	0.4 (0.02-1.74)	NA

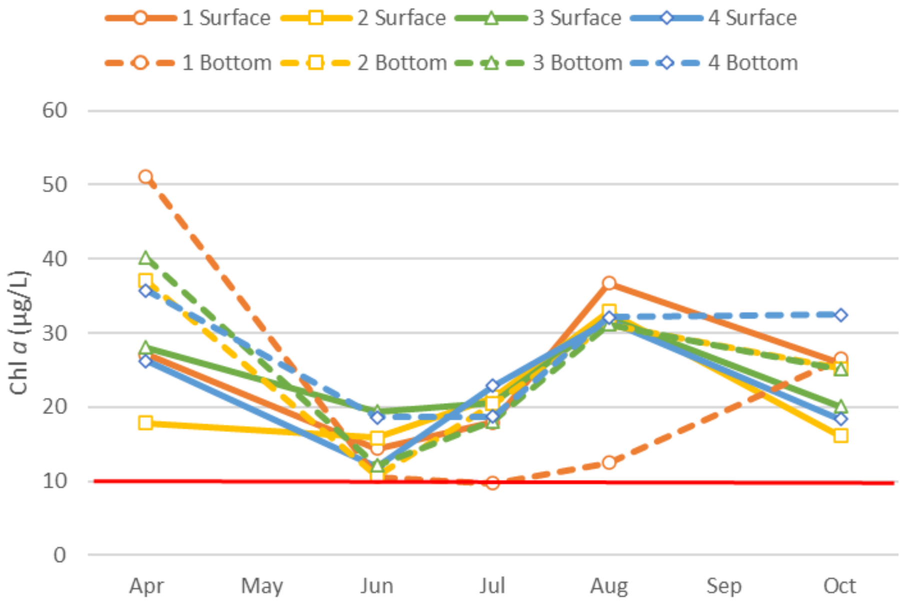

Figure 19. Bear Lake chlorophyll *a* concentrations sampled April – October 2023 at near-surface (solid lines) and near-bottom depths (dashed lines). Red line refers to restoration target of 10 µg/L for Muskegon Lake.

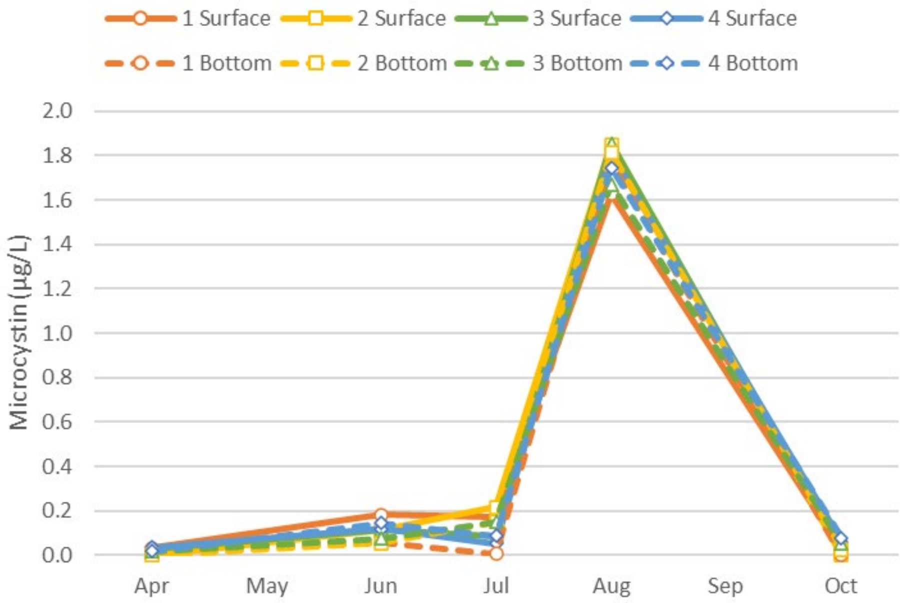

Figure 20. Bear Lake microcystin concentrations sampled April – October 2023 at near-surface (solid lines) and near-bottom depths (dashed lines).

Phytoplankton

The different taxonomic divisions of phytoplankton, including cyanobacteria, dominated in different times throughout the year, as commonly occurs in temperate lakes. Bacillariophyta (diatoms) dominated in April with 89% of total abundance by biovolume and decreased to 70% in June and 49% in July, finally plateauing at 10%-19% in August and October (Figure 21). Cyanobacteria exhibited an opposite trend with typical low abundance (9%-11%) through spring and early summer due to their preference for warmer temperatures and then bloomed to 79%-88% in later summer and fall (Table 5, Figure 22). Cyanobacteria abundance increased in 2023 compared to 2022, when it composed ~40-54% of all algae division biovolume during summer and fall (Steinman and Hassett 2023). Despite the high percentage of potentially toxin-forming cyanobacteria in Bear Lake in 2023 (Figure 23), the low microcystin levels indicate these taxa either lacked the toxin-forming gene or environmental conditions were not favorable for this gene to be expressed.

Several cyanobacteria taxa of interest were detected in Bear Lake samples. *Microcystis*, *Limnothrix*, *Planktothrix*, and *Oscillatoria* are all capable of producing microcystin (but may not necessarily be doing so all the time). *Aphanizomenon* and *Cylindrospermopsis* are likewise capable of producing a different cyanotoxin called cylindrospermopsin, and *Oscillatoria* is capable of producing both anatoxin-a and lyngbyatoxin-a. Bar-Yosef et al. (2010) suggested that *Aphanizomenon ovalisporum* production of cylindrospermopsin in Lake Kinneret, Israel, during times of phosphorus limitation caused other nearby phytoplankton to increase their alkaline phosphatase activity (releasing inorganic P [bioavailable form] from its organically bound form). This, in turn, results in increased bioavailable phosphorus concentrations in the water column, which is available to *Aphanizomenon*. Another unique biological adaptation allows *Anabaena* and *Aphanizomenon* to meet their nitrogen needs by fixing (using) atmospheric nitrogen. Distributions of cyanobacterial taxa across lake sites and sampling months are organized alphabetically in Appendix B (Figures B1-B10).

Table 7. Mean abundance of cyanobacteria (blue-green algae) biovolume compared to all algae divisions and mean abundances of observed cyanobacteria genera as respective biovolumes compared to all other cyanobacteria. Bold text indicates genera capable of producing cyanotoxins.

	% Abundance					
Genus	April	June	July	August	October	Grand Mean
Cyanobacteria	9%	2%	11%	85%	78%	37%
Anabaena	0%	51%	1%	2%	1%	11%
Aphanizomenon	58%	3%	75%	8%	39%	37%
Chroococcus	0%	14%	6%	0%	0%	4%
Coelosphaerium	0%	25%	2%	0%	0%	6%
Cylindrospermopsis	0%	0%	0%	3%	27%	6%
Limnothrix	42%	1%	2%	1%	9%	11%
Microcystis	0%	0%	13%	0%	0%	3%
Oscillatoria	0%	6%	0%	73%	0%	16%
Planktolyngbya	0%	0%	1%	5%	24%	6%
Planktothrix	0%	0%	0%	10%	0%	2%

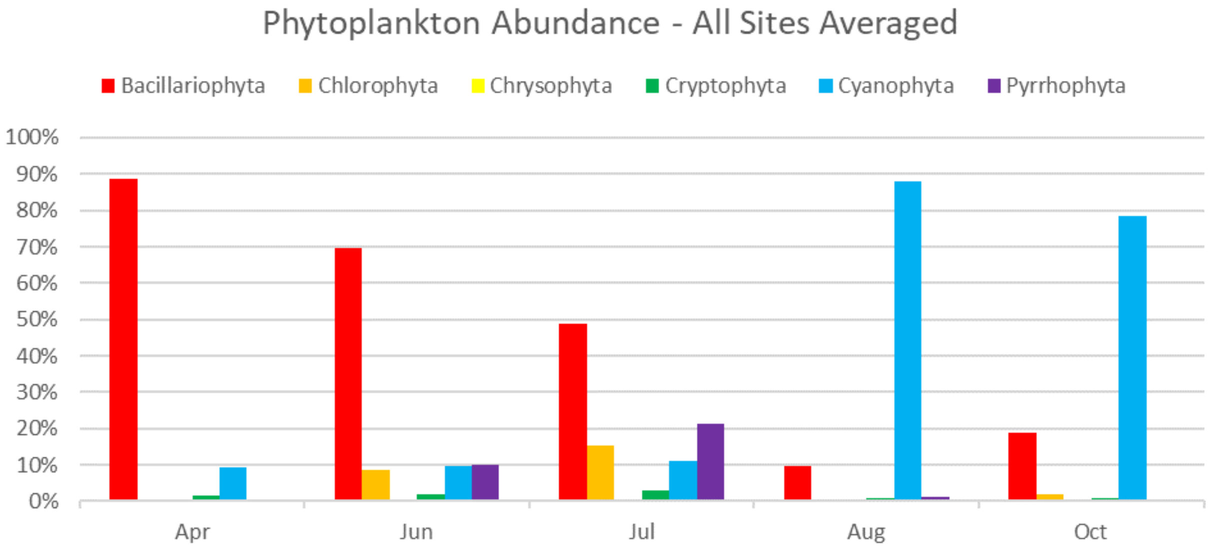

Figure 21. Relative abundance by biovolume of all observed phytoplankton taxonomic divisions.

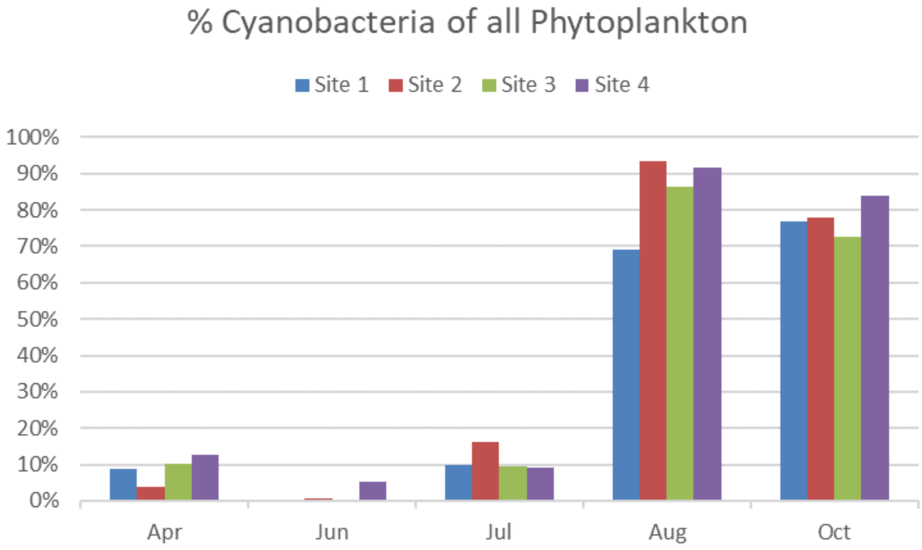

Figure 22. Relative abundance of cyanobacteria (blue-green algae) biovolume compared to all algae divisions in phytoplankton samples by site.

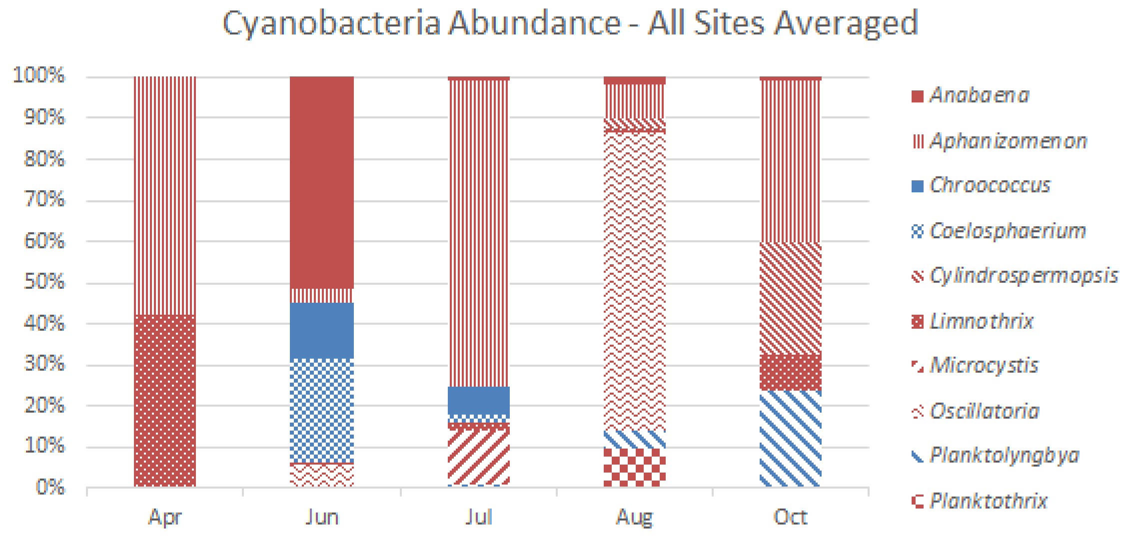

Figure 23. Summary of dominant cyanobacteria species biovolume relative abundance averaged across all sites by date. Cyanobacteria capable of producing toxins are red-patterned and non-toxin producing cyanobacteria are blue-patterned.

Of the total cyanobacteria observed in 2023 Bear Lake samples, *Anabaena* (Fig. B1), *Aphanizomenon* (Fig. B2), and *Oscillatoria* (Fig. B3) composed the largest percentage of the phytoplankton community, accounting for as much as ~51%-75% of biovolume in each month (Table 7). There was a clear seasonality in the cyanobacteria populations, with *Aphanizomenon and Limnothrix* dominating early in the growing season, followed by *Anabaena* (*Dolichospermum*) in June, *Aphanizomenon* again in July, *Oscillatoria* in August, and *Aphanizomenon, Cylindrospermopsis, and Planktolyngbya* in October (Figs. B2, 5, and 9, respectively). *Chroococcus*, *Coelosphaerium*, and *Planktolyngbya* are not widely known as cyanotoxin-producing algae taxa and composed as much as 14%-25% of cyanobacteria biovolume in different months of the monitoring period (Table 7, Figures B3-4, 9). *Microcystis* (Fig. B7) and *Planktothrix* (Fig. B10) were less commonly observed in 2023 than other cyanobacteria, with monthly biovolumes accounting for only as much as 10%-13% of total abundance (Table 7).

Historical Bear Lake Water Quality

Water quality parameters from 2017 through 2023 are presented in Tables 8 (spring) and 9 (summer) (Figures 24-30). The spring data reveal few consistent trends, which may reflect that parameters were measured on different spring dates by different groups over the 7 years (RLS: 2017-2021; AWRI: 2022-2023). Baseline monitoring is critical to determine trends, but sampling on just one date per season can result in anomalous results, so it is important to look at overall trends, not individual years.

There is a tendency in the spring data, especially since 2020, for pH to become more alkaline, TP and SRP to decline, and chl *a* to increase. Other parameters do not show any consistent trend (Table 8; Figures 24-30). Normally in lakes, there is a positive correlation between TP and chl *a*, so the inverse relationship in 3 out of the past 4 spring samples may be due to several reasons: 1) although lower, the TP concentration is still sufficient (25-30 µg/L) to stimulate blooms, especially with spring water temperatures warming earlier; 2) spring conditions are often dynamic, so the inverse relationship simply may be due to picking dates when short-lived blooms form in Bear Lake, and hence be totally random. Identifying if there is a mechanistic explanation for the spring blooms would require more extensive sampling (e.g., weekly) coupled with experiments (e.g., bioassays). Note that the low SRP concentrations (bioavailable form of phosphorus) are to be expected with increasing chlorophyll *a* because (unlike total phosphorus), the SRP is being taken up by the algae, so SRP in the water column declines as the chlorophyll concentrations increase.

In contrast to spring, summer environmental conditions in north temperate lakes tend to be more stable (except during storm events). In summer 2023 at the two deep sites (Table 9), there was a very significant spike of phosphorus and TKN at the July sampling date, accompanied by higher chlorophyll *a* and lower dissolved oxygen. This was a time between the two Phoslock applications by PLM at the deeper sites (June 14 and August 28). The high P levels are consistent with internal nutrient loading (Steinman and Spears 2020), whereby dissolved oxygen is being consumed at the deeper sites and the lake mixing fails to replenish atmospheric oxygen at those depths (Steinman and Ogdahl 2015); at that time, the iron in the sediment that previously was bound to phosphorus (forming a precipitate) becomes chemically reduced ($Fe^{3+} \rightarrow Fe^{2+}$). In the process, the bound phosphorus is released from iron, and diffuses from the sediment into the water column in the form of bioavailable phosphorus, and is taken up by the algae. The low oxygen conditions also can release ammonia, which is a major component of TKN. Hence, we end up at these deeper sites with low DO, elevated phosphorus, and elevated forms of chemically reduced nitrogen, such as ammonia. In shallow lakes such as Bear Lake, where mixing is frequent, it takes several days of calm conditions to allow the lake to stratify, and low DO levels to stimulate the internal nutrient loading. They are typically very short-lived, although there is concern this will become more frequent as lakes become warmer (Chen et al. 2020). We caution, as we did in the 2022 Bear Lake monitoring report, that comparisons of TKN with RLS-collected data is potentially problematic, due to how RLS defined TKN in a non-standard way as the sum of nitrate, nitrite, ammonia, and organic nitrogen – TKN should not include nitrate or nitrite (Steinman and Hassett 2023).

Table 8. Long-term trends of Bear Lake deep basin mean (±SD) spring water quality parameters.

Year	DO (mg/L)	pH	SpCond (µS/cm)	TP (mg/L)	SRP (mg/L)	TKN (mg/L)	Chl *a* (µg/L)	Secchi Depth (m)
2017	4.9 (2.7)	8.2 (0.1)	329 (6)	0.040 (0)	0.010 (0)	1.1 (0.2)	9.1 (2.0)	1.2 (0)
2018	5.2 (3.6)	7.9 (0.4)	370 (8)	0.045 (0)	0.016 (0)	1.0 (0.4)	0.7 (0.3)	1.2 (0.1)
2019	11.0 (0.2)	8.2 (0.1)	314 (35)	0.044 (0.1)	0.010 (0)	0.6 (0.1)	6.2 (3.6)	1.7 (0.1)
2020	6.5 (3.2)	8.4 (0)	376 (57)	0.038 (0)	0.019 (0)	0.9 (0.2)	20.0 (2.8)	0.4 (0)
2021	10.0 (1.4)	8.4 (0.2)	407 (15)	0.034 (0)	0.010 (0)	0.6 (0.1)	0.5 (0.8)	1.6 (0.1)
2022	12.0 (0.2)	8.7 (0.1)	354 (3)	0.032 (0)	0.003 (0)	0.7 (0.1)	24.0 (2.8)	1.0 (0.1)
2023	12.1 (1.3)	8.5 (0.4)	334 (4)	0.026 (0)	0.003 (0)	0.8 (0.3)	36.6 (11.4)	0.9 (0.2)

Table 9. Long-term trends of Bear Lake deep basin mean (±SD) summer water quality parameters.

Year	DO (mg/L)	pH	SpCond (µS/cm)	TP (mg/L)	SRP (mg/L)	TKN (mg/L)	Chl *a* (µg/L)	Secchi Depth (m)
2017	7.5 (1.9)	8.4 (0.4)	365 (4)	0.061 (0)	0.01 (0)	1.8 (0.4)	7.8 (1.5)	0.7 (0.1)
2018	6.5 (2.8)	8.2 (0.3)	366 (4)	0.043 (0)	0.016 (0)	1.1 (0.5)	8.0 (2.8)	1.0 (0.2)
2019	8.1 (2.3)	8.1 (0.1)	411 (79)	0.036 (0)	0.011 (0)	1.9 (1.5)	0.5 (0.6)	0.8 (0.1)
2020	7.1 (0.3)	8.2 (0.1)	726 (223)	0.045 (0)	0.023 (0)	0.8 (0.3)	12.5 (0.7)	1.2 (0.2)
2021	7.5 (1.6)	8.2 (0.3)	406 (6)	0.041 (0)	0.010 (0)	0.7 (0.2)	2.7 (3.4)	1.4 (0.1)
2022	4.6 (3.0)	7.9 (0.3)	403 (21)	0.041 (0)	0.003 (0)	1.5 (0.4)	18.3 (3.7)	1.2 (0)
2023	5.3 (3.6)	8.0 (0.4)	417 (21)	0.175 (0.1)	0.048 (0.011)	1.9 (0.1)	22.3 (8.1)	1.3 (0)

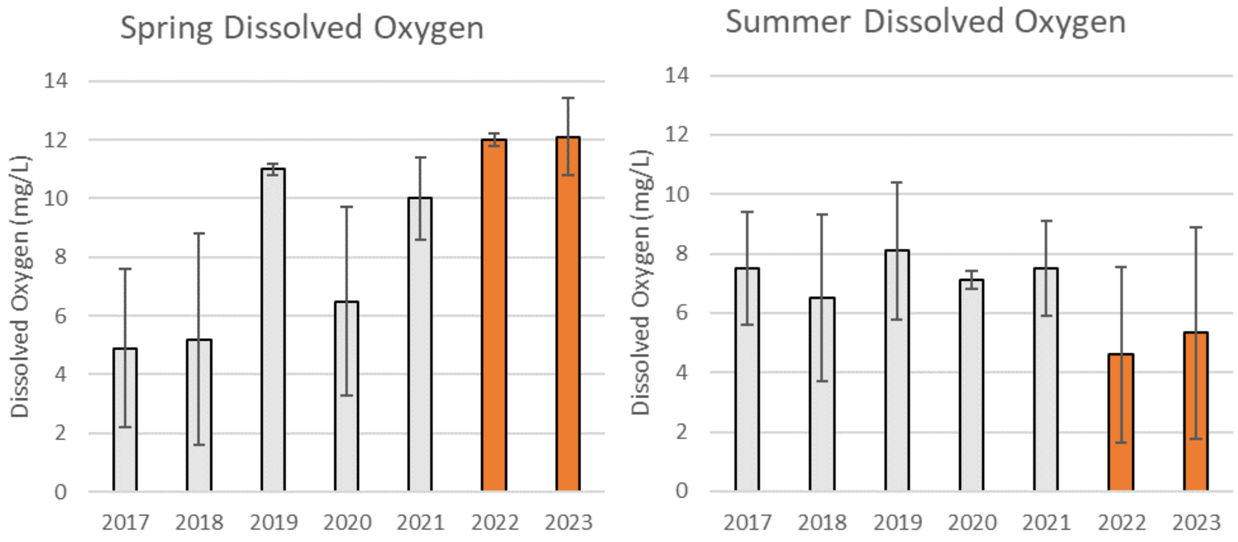

Figure 24. Lake grand mean (±SD) DO across water column depths at the two deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022-2023 (AWRI).

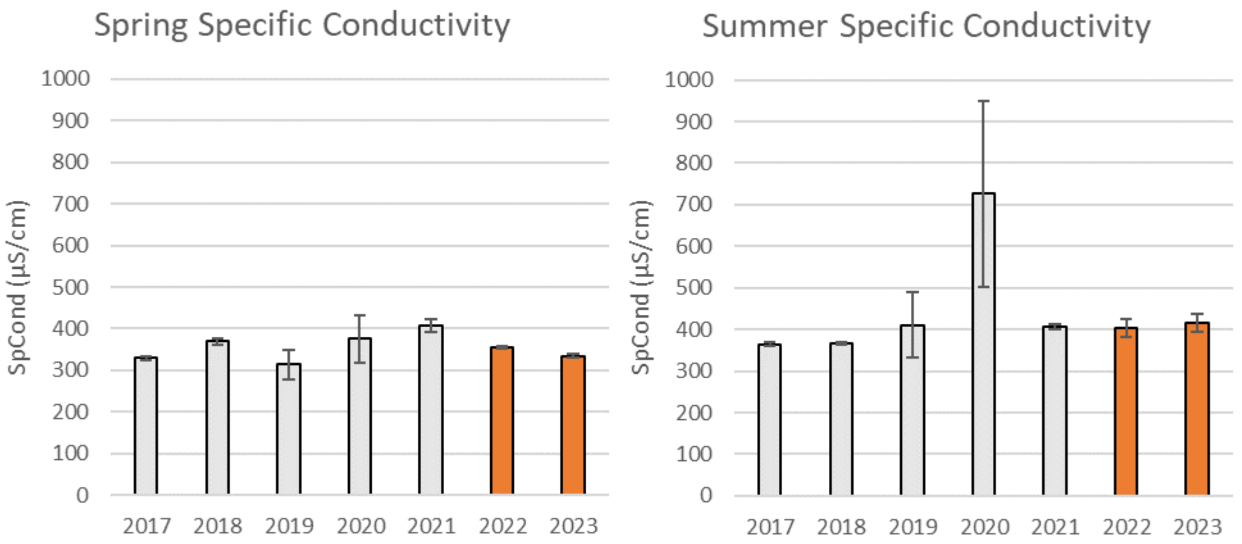

Figure 25. Lake grand mean (±SD) specific conductivity across water column depths at the two deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022-2023 (AWRI, in orange).

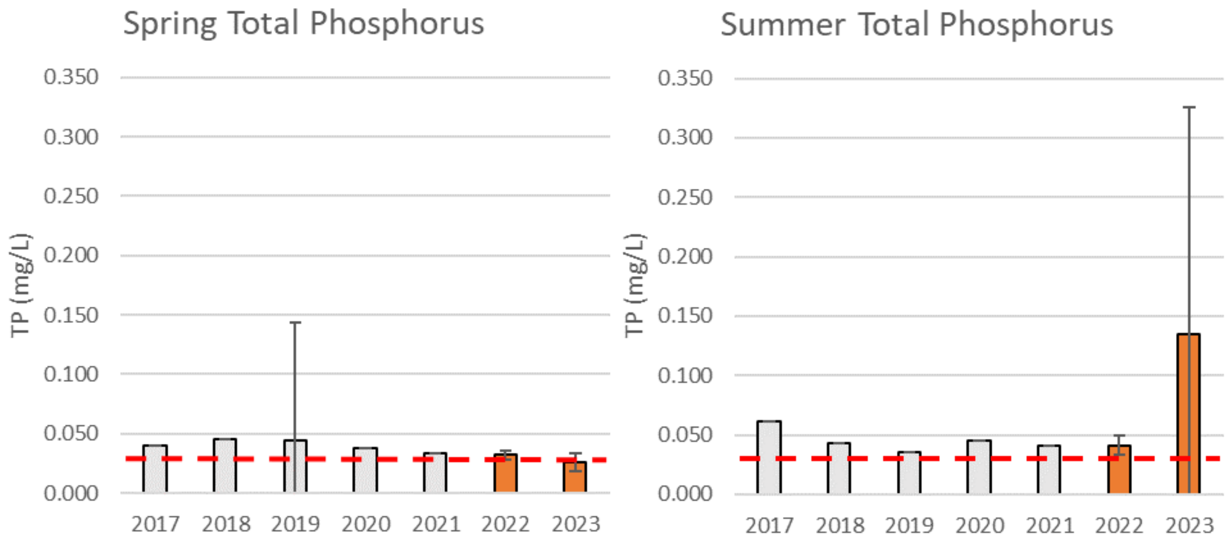

Figure 26. Lake grand mean (±SD) total phosphorus (TP) concentrations across water column depths at the two deep sites during May (left panel) and July (right panel) of each sampling year. Red dashed lines indicate Bear Lake's TMDL for TP: 0.030 mg/L. Data: 2017-2021 (RLS); 2022-2023 (AWRI, in orange).

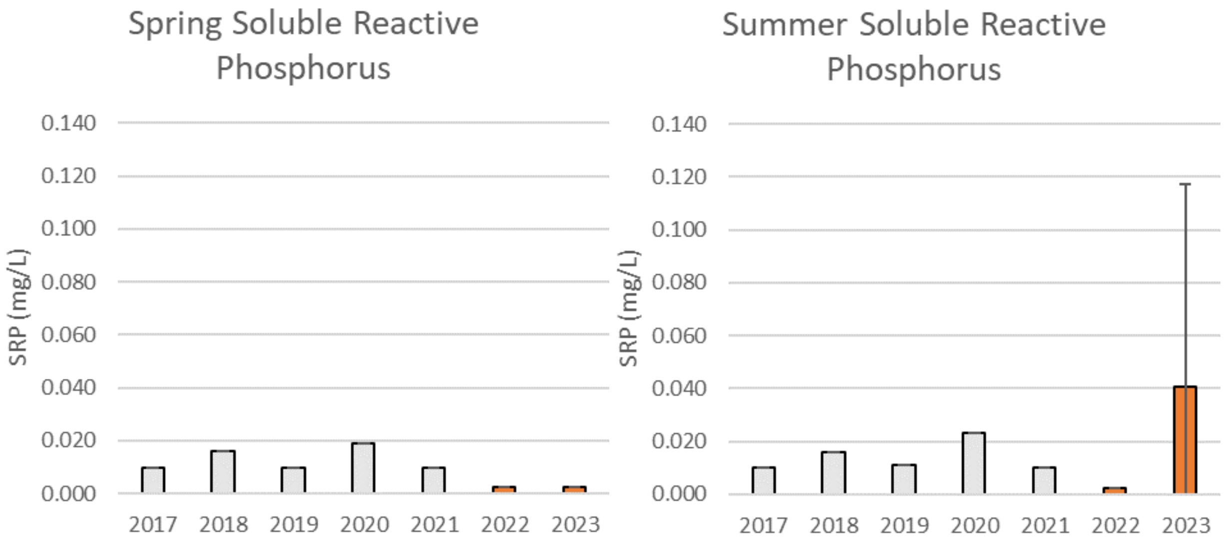

Figure 27. Lake grand mean (±SD) soluble reactive phosphorus (SRP) concentrations across water column depths at the two deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022-2023 (AWRI, in orange).

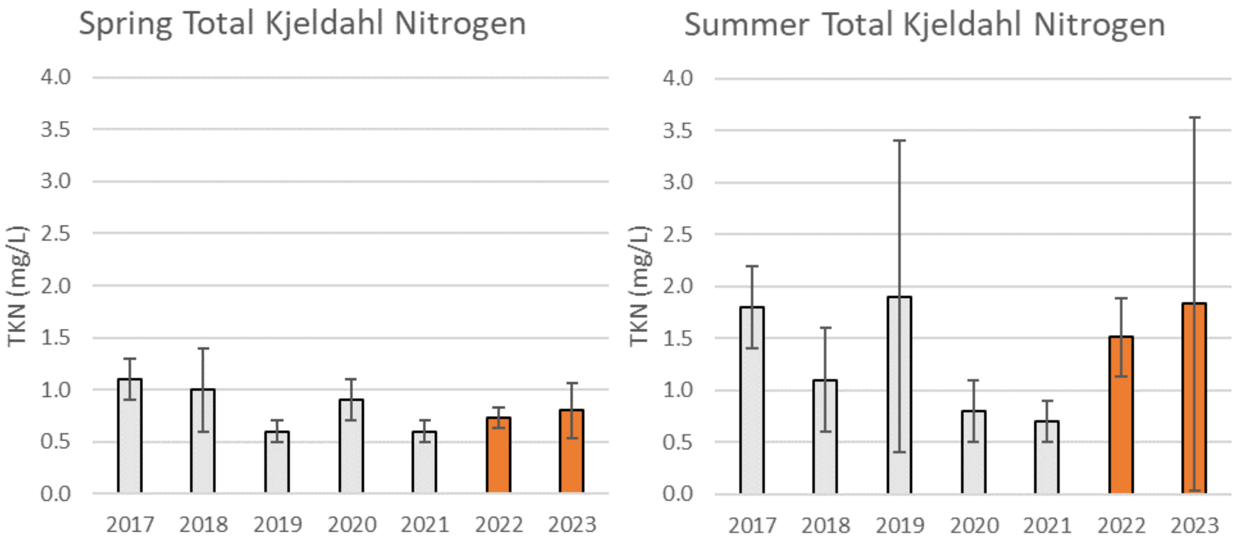

Figure 28. Lake grand mean (±SD) total Kjeldahl nitrogen concentrations across water column depths at the two deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022-2023 (AWRI, in orange).

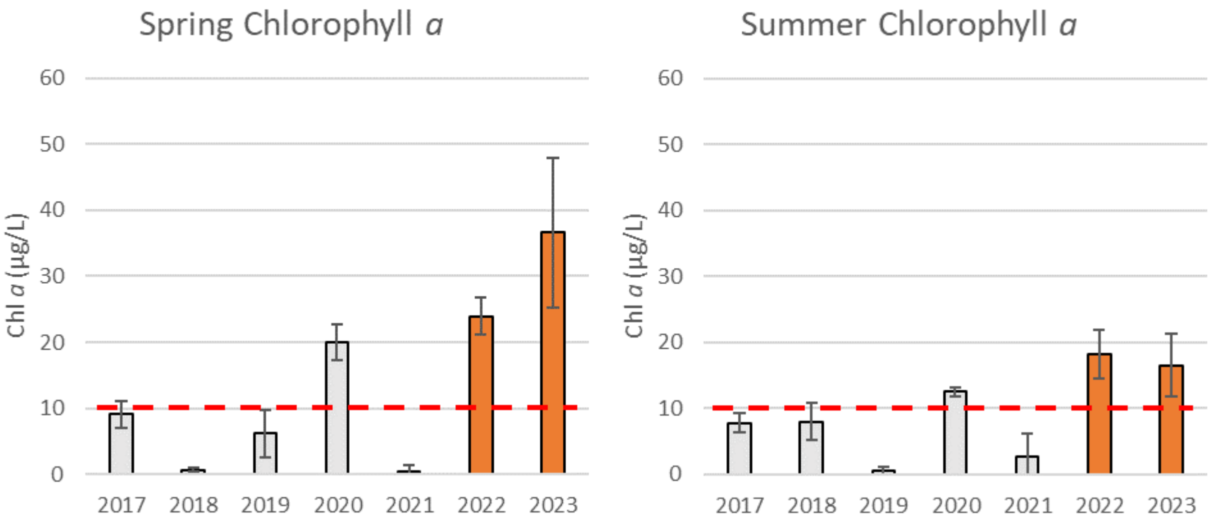

Figure 29. Lake grand mean (±SD) chlorophyll *a* concentrations across water column depths at the two deep sites during May (left panel) and July (right panel) of each sampling year. Red dashed lines indicate Muskegon Lake's restoration goal for chl *a*: 10 µg/L. Data: 2017-2021 (RLS); 2022-2023 (AWRI, in orange).

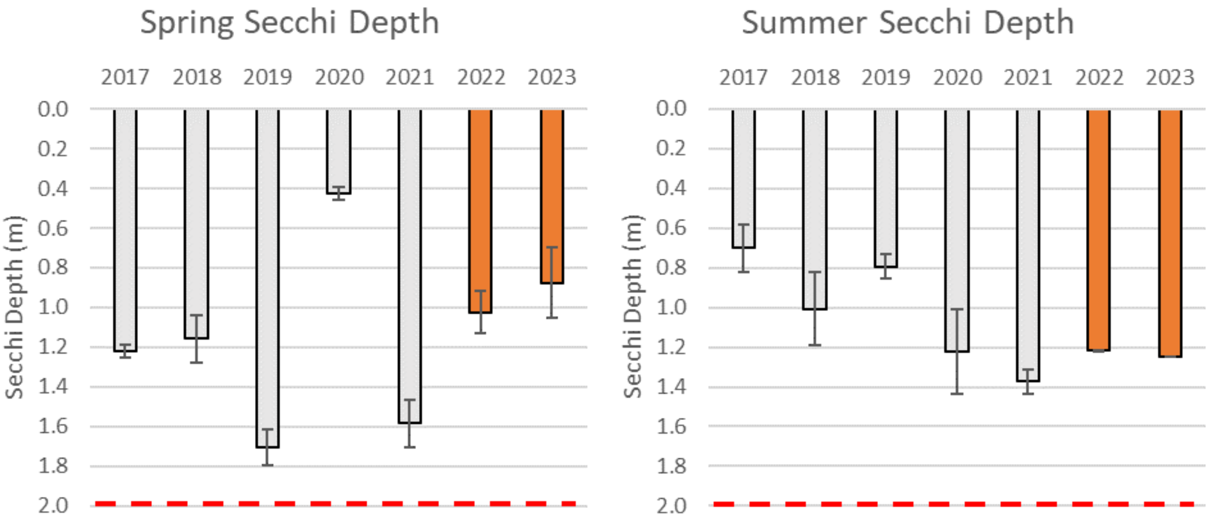

Figure 30. Lake grand mean (±SD) Secchi depth across water column depths at the two deep sites during May (left panel) and July (right panel) of each sampling year. Note that the y-axes are inverted so that data indicate the depth from the lake's surface. Red dashed lines indicate Muskegon Lake's restoration goal for Secchi depth: 2 m (~6.5 ft). Data: 2017-2021 (RLS); 2022-2023 (AWRI, in orange).

Summary and Recommendations

Our assessment of Bear Lake's spring and summer environmental condition reflects a mix of good and bad. Overall, when all the 2023 sampling dates and sites are considered, the mean TP concentration was just slightly above 30 µg/L. Indeed, the spring TP concentration was below the 30 µg/L threshold established in the TMDL. However, the summer TP concentration at the deep sites was extremely high, reflecting an episodic internal nutrient release event. Internal nutrient release was shown in the past not to be a significant source of phosphorus to Bear Lake, but as external loading from Bear Creek and the former celery ponds continues to be reduced, and warming water temperatures result in periods of lake stratification and low dissolved oxygen concentrations, nutrients from the sediments may be increasing in relative importance.

This year we assessed the role of the two major tributaries to Bear Lake as nutrient sources. The data indicate that inflows from Bear Creek actually serve to dilute the phosphorus concentration in Bear Lake, whereas inflows from Fenner's Ditch contribute phosphorus, both during baseflow and especially during storm flow. The very high baseflow concentration in July was between the two Phoslock treatment dates (14 June and 28 August) by PLM, suggesting 1) the Phoslock treatment is having a beneficial effect by keeping P concentrations lower than they would be otherwise, and 2) there is a significant source(s) "resupplying" phosphorus to Fenner's Ditch, which is amplified during storm events.

The algal community, as reflected both in terms of biomass (chlorophyll *a*) and species composition, reflect potential issues. Chlorophyll was greater than desired, and cyanobacteria (blue-green algae) continue to dominate in the summer months. As noted previously, this lower TP concentration is accompanied by an increase in chlorophyll *a*. We cannot be certain if the high chlorophyll concentrations are due to nutrients, the natural variability associated with algal growth (e.g., sampling after a few warm, calm days when blooms will form vs. days after algicide has been applied), or some other factor. Only more consistent and regular sampling will resolve this question (see recommendations).

Despite the abundance of cyanobacteria, the microcystin levels in Bear Lake remain low, and well below the thresholds developed by EPA for recreational lake usage. In addition, the *E. coli* levels measured indicate that fecal coliform concentrations are not currently a problem in Bear Lake.

The phytoplankton composition continues to vary in Bear Lake. Last year, the filamentous cyanobacteria genera *Planktothrix* and *Limnothrix* dominated in summer/fall, but this year the dominant genera in summer/fall were *Oscillatoria, Aphanizomenon, Planktolyngbya,* and *Cylindrospermopsis.* All these genera have species that are capable of producing cyanotoxins but as was the case in 2022, they were not doing so at levels of concern in 2023.

In summary, Bear Lake is improving with respect to phosphorus concentrations, but specific sources (isolated sediment locations and Fenner's Ditch) require more attention. In addition, additional efforts may be necessary to address algal abundance.

Recommendations:

1) **Expanded monitoring**: As noted in 2022, the snapshot samples taken monthly or bimonthly can result in misleading conclusions. It is unclear if the isolated high TP and chlorophyll concentrations were anomalies or part of a trend of higher values. The only way to parse out this question is through continued monitoring. For nutrients, we recommend continuing the 4 in-lake sites, dropping the sampling from the major inflows to Bear Lake now that we know Fenner's is more of a problem than Bear Creek, and focusing additional sampling around Fenner's Ditch.

    a. Alternate P sources: Examine possible sources of P accounting for high concentrations from this site (e.g., septage, yard runoff);
    b. Chlorophyll: The high chlorophyll concentrations may be a function of infrequent sampling, when low chlorophyll conditions are missed. While no additional sites are recommended for sampling, there are several ways to increase observations without collecting water samples and processing them in the lab.
        i. For example, citizens can get involved in doing qualitative surveys of lake color and bloom conditions to provide daily data. This would involve a training session to ensure data quality but involving citizens in the data collection is a great way for them to feel included and invested in lake health.
        ii. Alternatively, new lower-cost water quality sensors can be purchased and deployed in the lake to provide near real-time data. These need to be maintained and there is an upfront cost to purchase them, but it is an alternative the Lake Board may want to consider. More information is available at this website: https://www.nexsens.com/.

2) **Phoslock:** The application of Phoslock to strip P from the water column and create a benthic cap to limit internal loading appears to be working well. We recognize this is treating the symptom and not the disease, but until the source(s) of the disease is found, this is a reasonable approach. The Lake Board may want to expand the Phoslock application dates to 3 low-dose applications at their current sites (to avoid the July spikes we measured from Fenner's and the deep holes).

3) **Watershed Survey**: Finally, we recommend conducting a watershed survey to determine lake user priorities (targeting future monitoring around priorities). While including one in a mailing to residents is certainly cost-effective, it is not scientifically valid and based on our experience, interpretation of the data can be confounded. Hence, we recommend using a professional who is well-versed in watershed surveys (such as Dr. Amanda Buday at GVSU).

Acknowledgments

Thank you to Bear Lake - Lake Board members Doug Brown, Craig Howell, Brenda Moore, Paul Pek, and Darrell VanFossan for providing funding for this project.

We thank Brian Scull and Lexy Porter at AWRI for analyzing water chemistry and assistance with measuring *E. coli* concentrations, and Mark Luttenton for phytoplankton identifications. Additional thanks to Paris Velasquez, Kate Lucas, Jacquie Molloseau, Allison Passejna, and Allie Romanski in the Steinman Lab at AWRI for their assistance in the laboratory and field.

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Appendix A

Bear Lake 2023 Dashboards

As shown in the main report, Bear Lake TP concentrations in 2023 were in excess in the summer and qualify for the Undesirable category; however, spring and fall TP concentrations both decreased from 2022 and qualify for the Meeting Goal category (Figure A2). This may be due in part to changing the sampling regime between monitoring years, as 2023 spring sampling shifted earlier from May to April and 2023 fall sampling included only October rather than averaging both September and October. TP concentrations are often highly dependent on precipitation records: wet years usually result in greater concentrations due to runoff, and conversely for dry years, resulting in considerable variability. In 2023, Bear Lake followed the expected positive relationship between precipitation and TP. However, our data show two bottom depth samples that show a large difference in TP compared to other lower-TP samples at the same relative amounts of precipitation, resulting in a low R^2 value; as explained in the main report, these elevated concentrations are consistent with internal nutrient loading from the sediment, which would operate independently of precipitation (Figure A1).

Chlorophyll *a* concentrations in 2023 remain far in excess of the desired 10 µg/L threshold, and slightly less than 2022's historical high year (Figure A3). Chlorophyll concentrations are extremely variable, and can change dramatically within hours of sampling depending on environmental conditions. Hence, while the 2022 and 2023 numbers are disconcerting, they are based on only one sampling date per month. More frequent sampling would result in a more realistic portrayal of chlorophyll levels in Bear Lake.

Secchi disk depth as currently classified continues last year's trend of being Undesirable and is slightly worse than 2022 (Figure A4). The change in clarity is not consistent with the observed decrease in chlorophyll, suggesting that other materials, such as particulate and/or dissolved organic matter also may have been responsible for low water clarity.

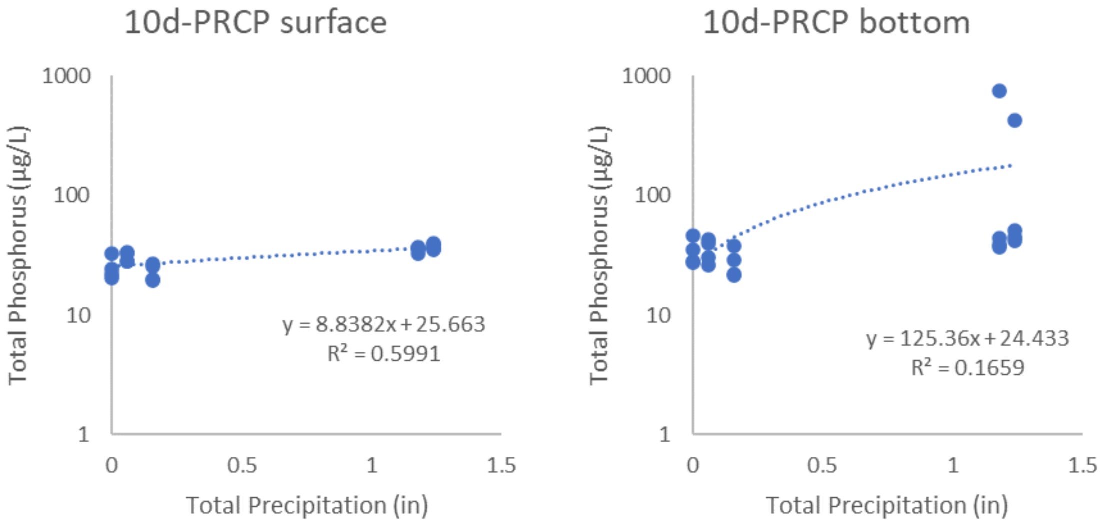
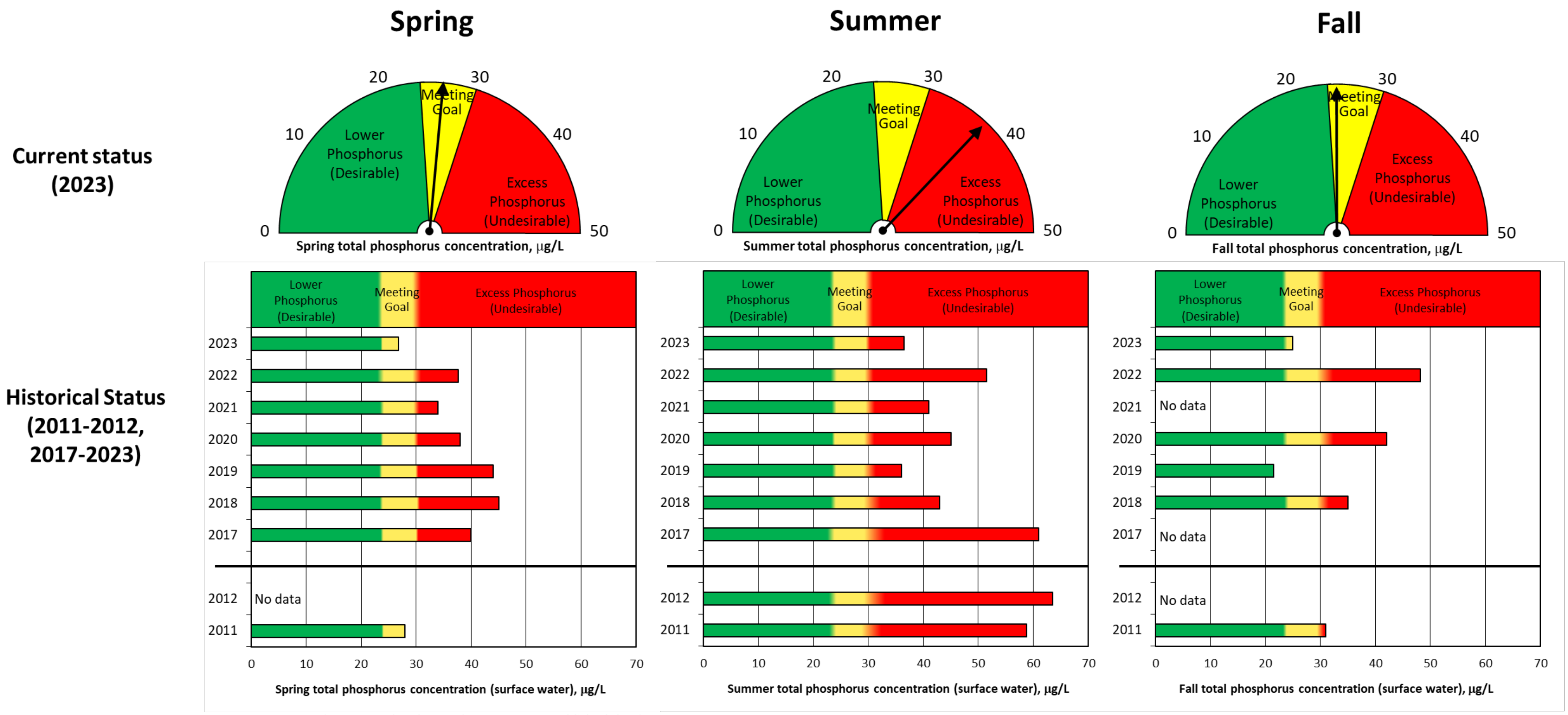
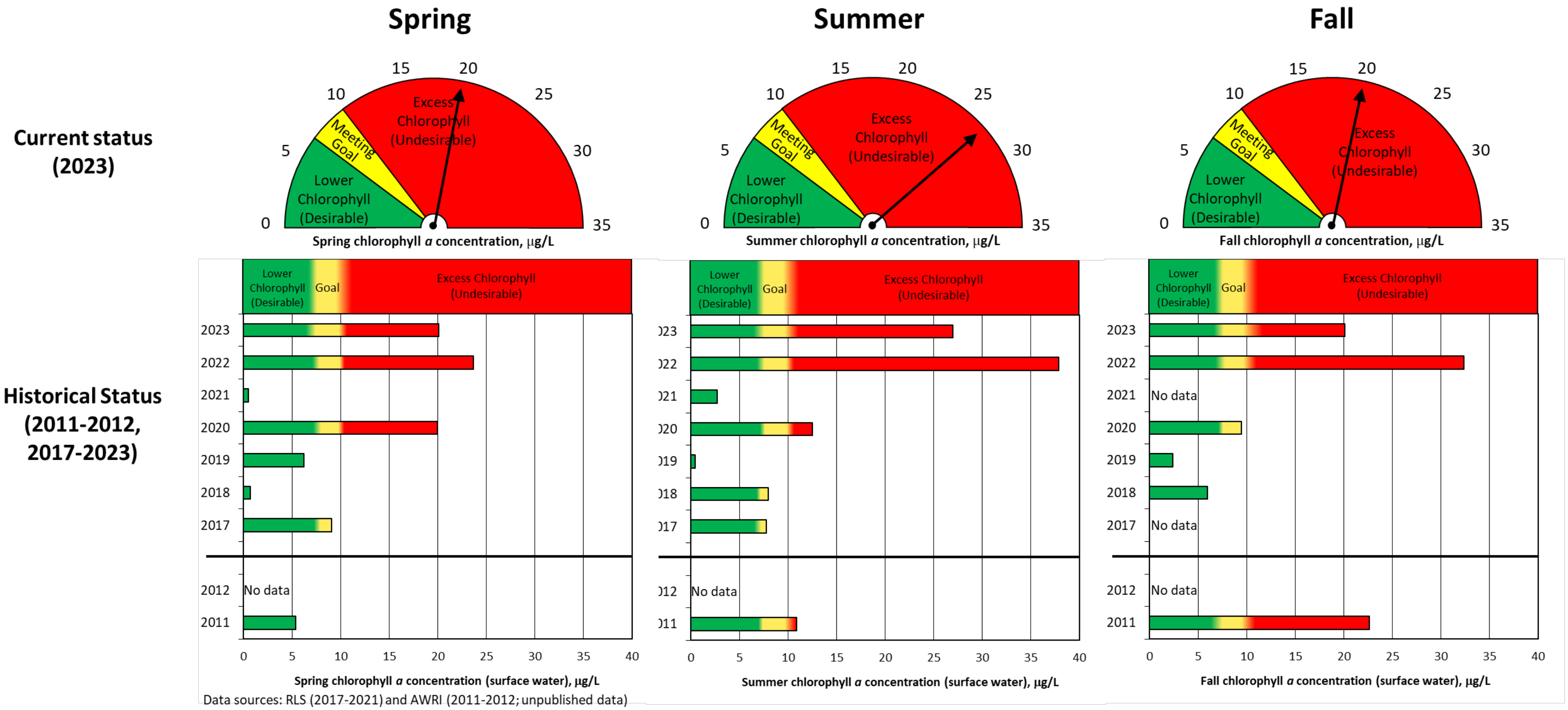


Figure A1. Linear regression of total phosphorus at the 4 lake sites vs. precipitation for 2023. Left panel: surface water; right panel: bottom water. Precipitation data are summed for the 10 days prior to sampling TP to account for the lag in rainfall in the watershed reaching Bear Lake. Note log scale on y-axes.



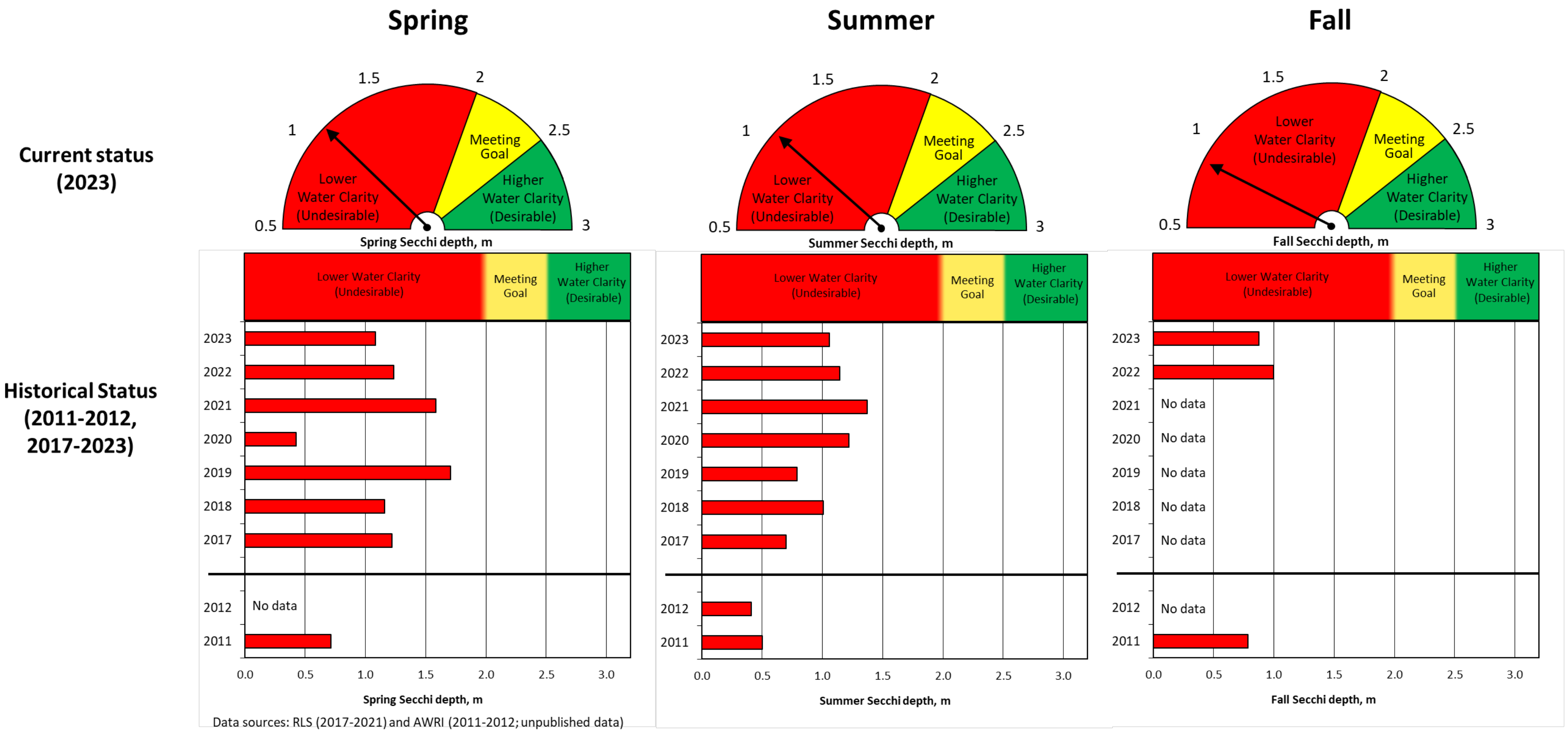
Data sources: RLS (2017-2021) and AWRI (2011-2012; unpublished data)

Figure A2. Bear Lake 2023 total phosphorus seasonal dashboard. Classifications are based on >30 µg/L “undesirable” threshold of Bear Lake TMDL, and the <30 µg/L “meeting goal” threshold and <24 µg/L “desirable” threshold of the Muskegon Lake long-term monitoring dashboard.



Data sources: RLS (2017-2021) and AWRI (2011-2012; unpublished data)

Figure A3. Bear Lake 2023 chlorophyll *a* seasonal dashboard. Classifications are based on >10 µg/L “undesirable” threshold, <10 µg/L “meeting goal” threshold, and <7.3 µg/L “desirable” threshold of the Muskegon Lake long-term monitoring dashboard.



Data sources: RLS (2017-2021) and AWRI (2011-2012; unpublished data)

Figure A4. Bear Lake 2023 Secchi disk depth seasonal dashboard. Classifications are based on >2 m “undesirable” threshold, <2 m “meeting goal” threshold, and <2.5 m “desirable” threshold of the Muskegon Lake long-term monitoring dashboard.

Appendix B

Phytoplankton Abundance

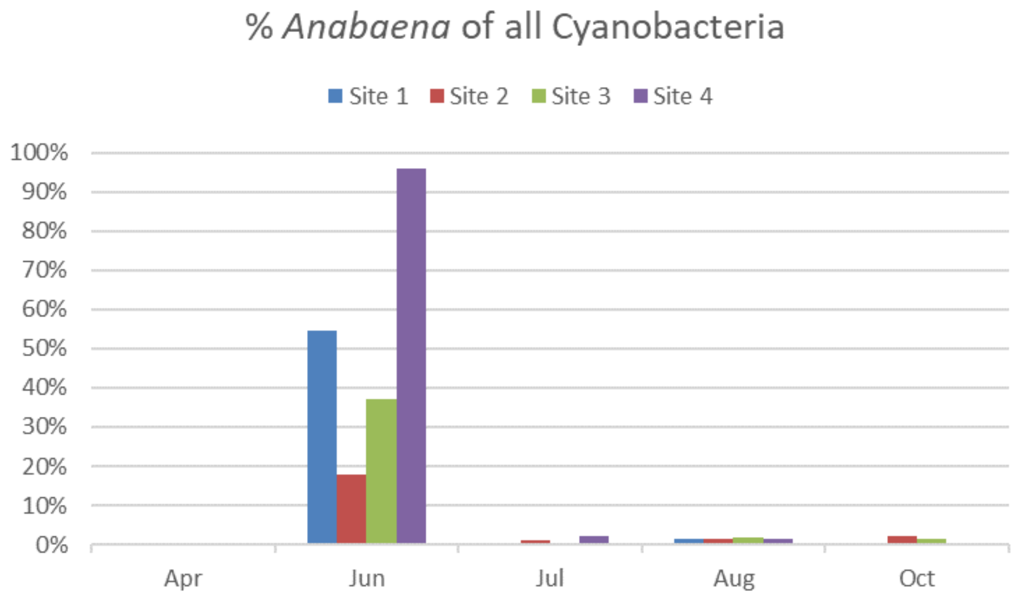


Fig. B1. Relative abundance of *Anabaena* biovolume compared to all cyanobacteria in phytoplankton samples by site.

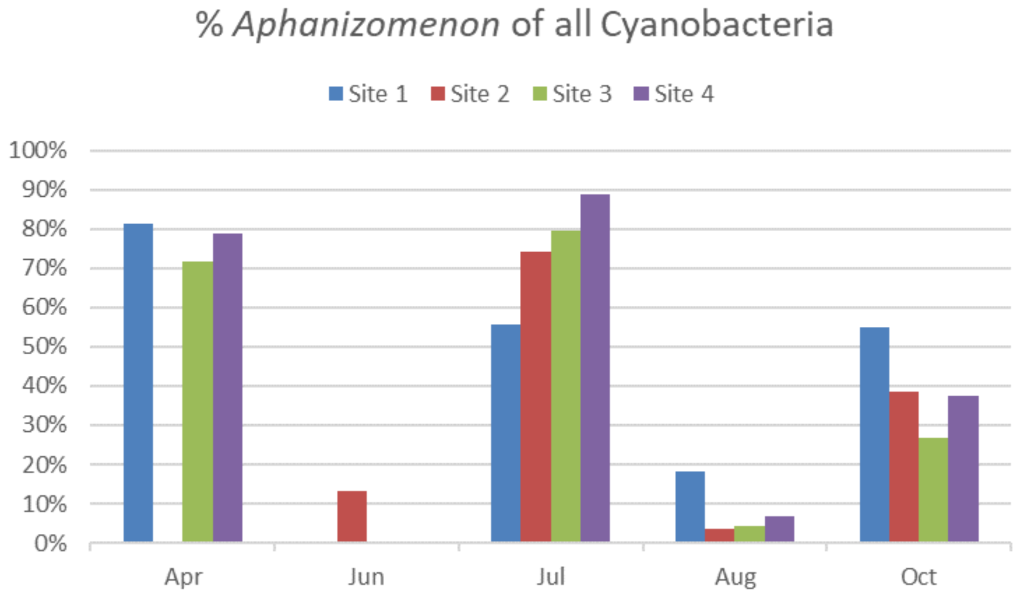


Figure B2. Relative abundance of *Aphanizomenon* biovolume compared to all cyanobacteria in phytoplankton samples by site.

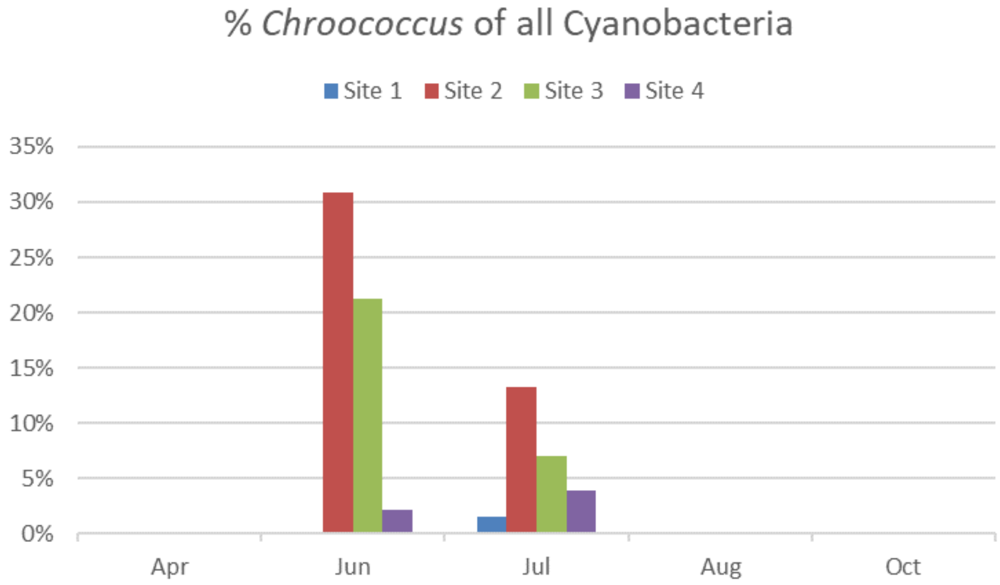


Figure B3. Relative abundance of *Chroococcus* biovolume compared to all cyanobacteria in phytoplankton samples by site.

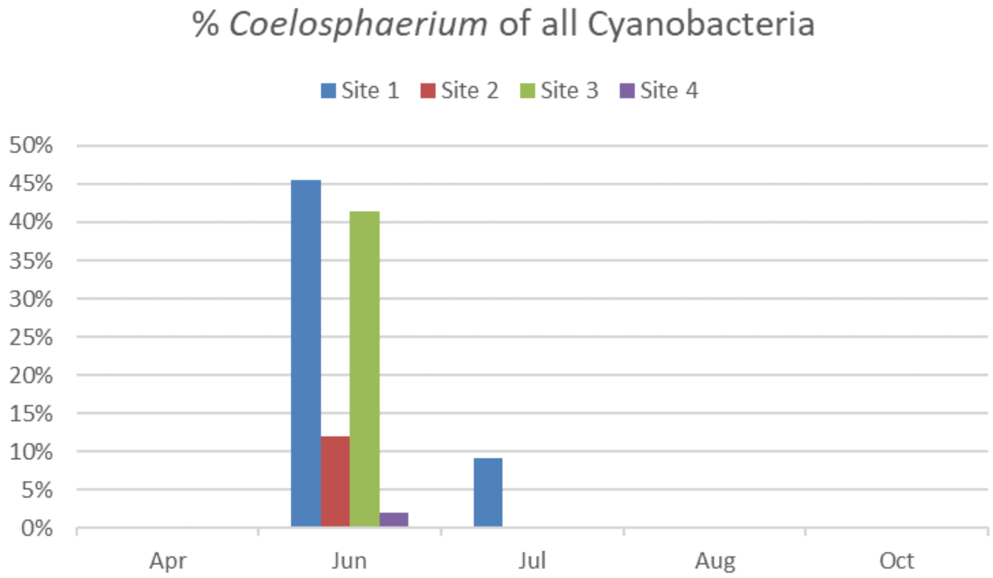


Figure B4. Relative abundance of *Coelosphaerium* biovolume compared to all cyanobacteria in phytoplankton samples by site.

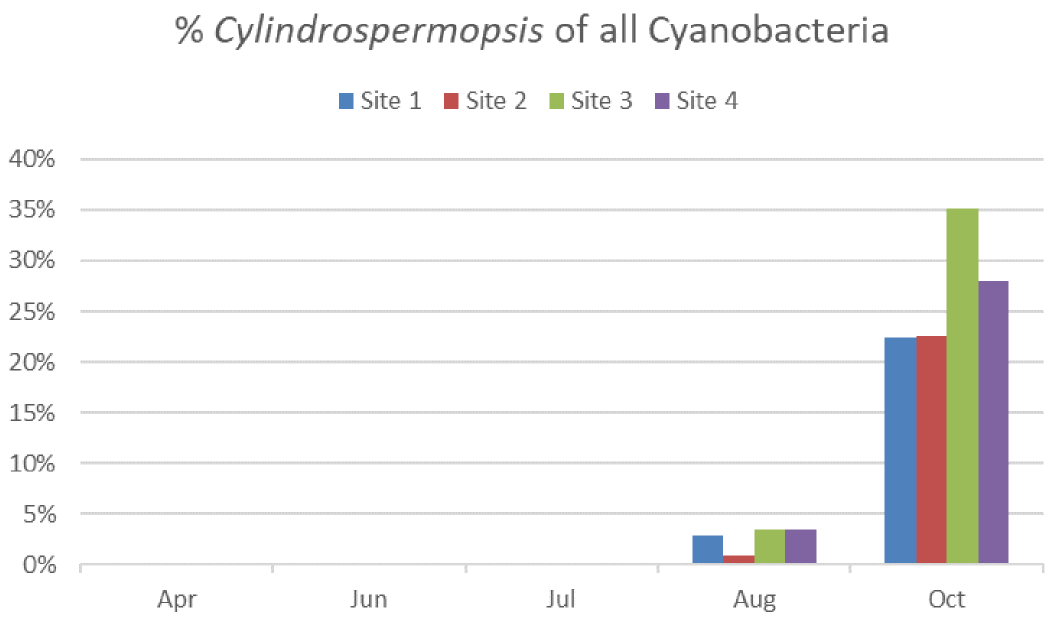


Figure B5. Relative abundance of *Cylindrospermopsis* biovolume compared to all cyanobacteria in phytoplankton samples by site.

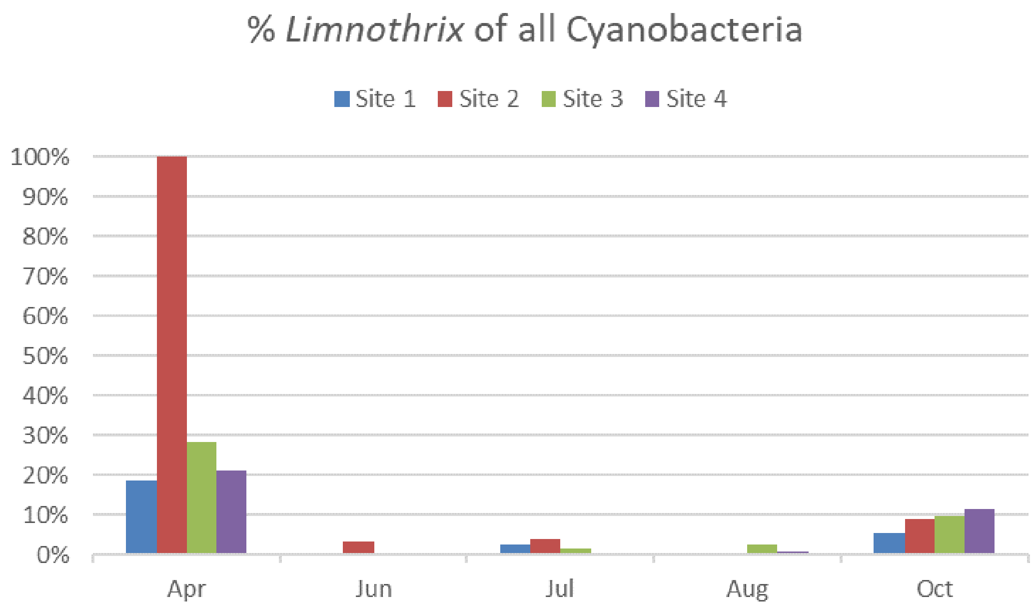


Figure B6. Relative abundance of *Limnothrix* biovolume compared to all cyanobacteria in phytoplankton samples by site.

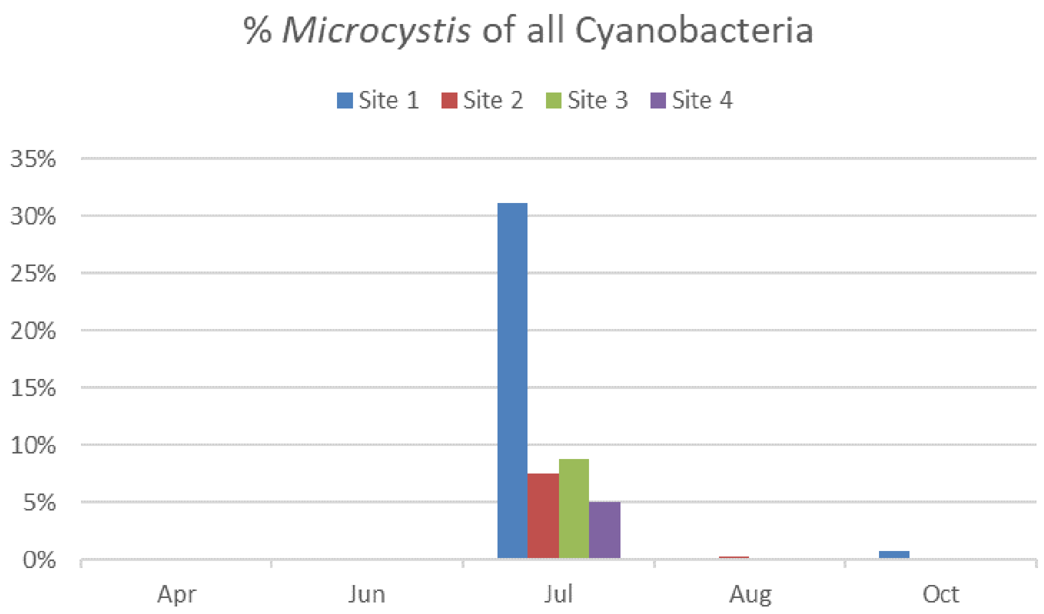


Figure B7. Relative abundance of *Microcystis* biovolume compared to all cyanobacteria in phytoplankton samples by site.

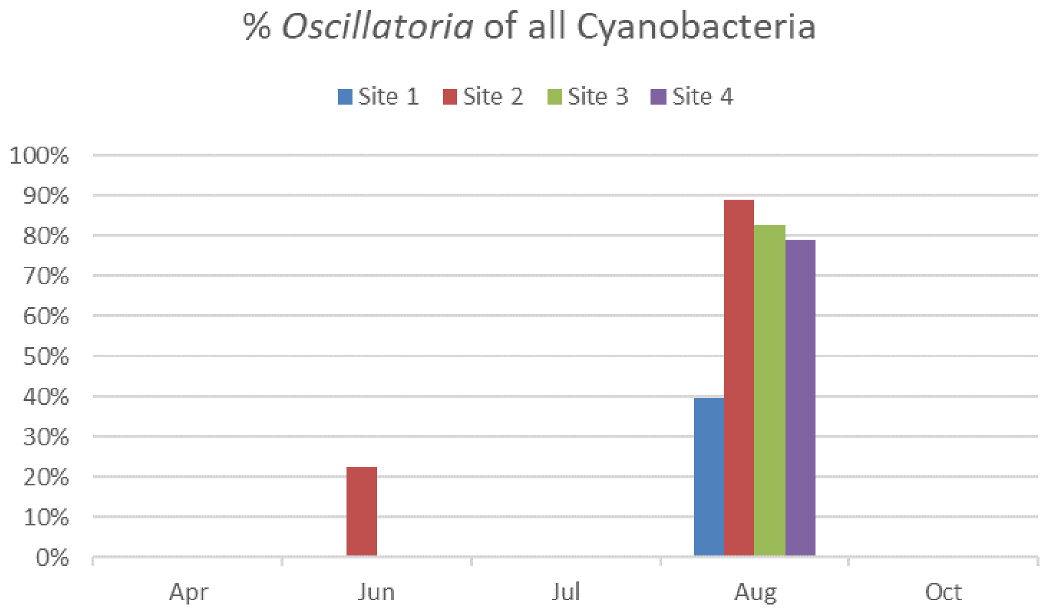


Figure B8. Relative abundance of *Oscillatoria* biovolume compared to all cyanobacteria in phytoplankton samples by site.

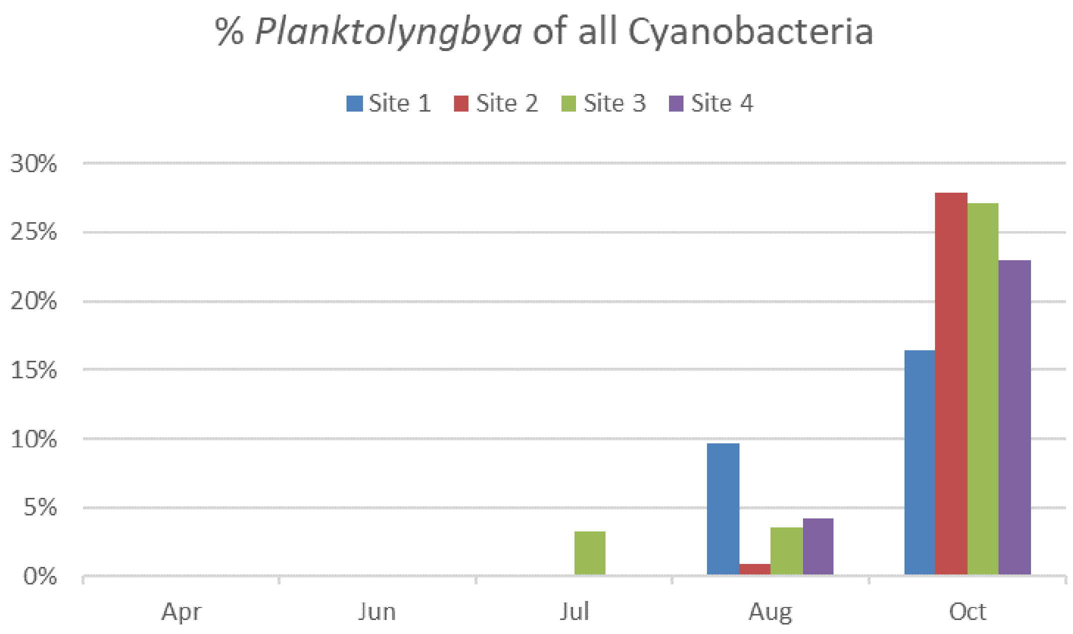


Figure B9. Relative abundance of *Planktolyngbya* biovolume compared to all cyanobacteria in phytoplankton samples by site.

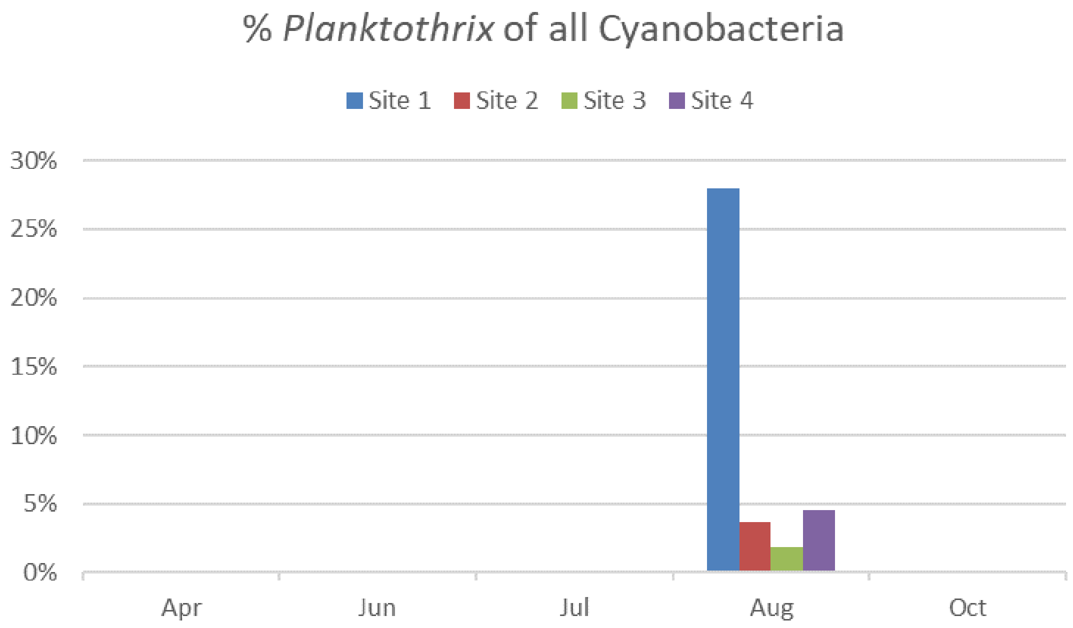


Figure B10. Relative abundance of *Planktothrix* biovolume compared to all cyanobacteria in phytoplankton samples by site.