Bear Lake 2022 Watershed Assessment

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Alan D. Steinman* and Michael C. Hassett

Annis Water Resources Institute, Grand Valley State University

740 West Shoreline Drive, Muskegon, MI 49441

*Contact Information
Email: steinmaa@gvsu.edu
Voice: 616-331-3749

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 load and a 79% reduction in internal load (to attain a target total phosphorus [TP] 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 impact to downstream Bear Lake may 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 Bear Lake and ultimately delist the Muskegon Lake AOC.

The Bear Lake - Lake Board contracted with GVSU's Annis Water Resources Institute to monitor water quality conditions in Bear Lake from May through October 2022. This report includes our findings and recommendations for future monitoring activities.

Methods

Bear Lake water quality monitoring sites were selected based on where prior sampling occurred to enable comparisons of 2022 data with prior data. We used 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 (Site 2 and Site 4). Site locations are specified in Table 1 and Figure 1.

Samples were collected once monthly via jonboat from May – October 2022, with sampling usually occurring between 9:00-11:30 AM. Water was sampled at surface depth via grab sampling and at middle and near-bottom depths via a Van Dorn water sampler. Water samples were collected in 500-mL bottles, stored on ice, and returned to the lab for nutrient analysis, usually within 4 hours. General water quality parameters were measured via YSI EXO2 sonde (YSI, Inc., Yellow Springs, OH), including water temperature, dissolved oxygen (DO), pH, specific conductivity (SpCond), and turbidity. Water transparency was measured as Secchi disk depth.

Separately, an additional 1-L sample was collected in amber bottles at top and bottom depths at each site for chlorophyll *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 chlorophyll sample bottles from each site into a single integrated depth phytoplankton sample per site.

Additionally, we subsampled from surface and near-bottom chlorophyll 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 is not as sensitive an assay as using High-Performance Liquid Chromatography (HPLC) but serves as a useful screening tool if microcystin is present in the lake. This kit has a greater detection limit than the QuantiTubes that were used in 2017 but still ranks below the HPLC for sensitivity. Advisories for microcystin consumption have been developed by the World Health Organization (WHO) and US EPA. For drinking water, the WHO advisory is triggered when microcystin concentrations >1 µg/L and the EPA advisory is >1.6 µg/L for school children and adults (0.3 µg/L for infants and pre-schoolers); for recreational use, WHO is >20 µg/L and EPA is >8 µg/L. Since Bear Lake is used only for recreation, we applied the latter two criteria.

We also collected water samples, from 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 swimming in the state of Michigan.

After returning to the lab, water from each 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.

Chlorophyll was subsampled by gently inverting and removing 250 mL from surface and near-bottom samples and combining them with the 250 mL middle depth sample. 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 data were reformatted to match RLS's data summary methods based on their 2021 Bear Lake water quality report. 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 May 2022 and July 2022 data were compared to historic Spring and Summer data.

Water quality dashboards for TP, chlorophyll *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). AWRI data are presented seasonally by averaging surface data into Spring (May and June), Summer (July and August), and Fall (September and October) seasons. Water quality goals for chlorophyll 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. Bear Lake site coordinates and average depth across sampling event.

Site	Latitude (°N)	Longitude (°W)	Depth (m)
1	43.248856	86.290336	8.36
2	43.253489	86.286969	3.96
3	43.254906	86.284244	3.88
4	43.260489	86.273539	3.02

Figure 1. Map of Bear Lake water quality monitoring sites.

Results

2022 Bear Lake Water Quality

Bear Lake mean water quality was generally consistent among sampling sites throughout the sampling period with some expected variation due to depth and upstream-downstream orientation (Table 2). Secchi depth ranged ~1-1.5 m at all sites (Table 2, Figure 2). As expected, DO decreased with depth and the lowest values were observed at the deepest site (Site 1); seasonal variation occurred with low values of ~0.2 mg/L in July and August (Table 2, Figure 3). Site pH was slightly basic throughout sampling and ranged ~7.5-8.8 (Table 2, Figure 4). Specific conductivity was similar throughout the water column and among sites; seasonal trends saw a mean increase from ~360 to 400 µS/cm through the sampling period (Table 2, Figure 5). Turbidity was low at all sites and sampling events, ranging only ~3-11 NTU, but tended to be higher in bottom samples (Table 2, Figure 6), which is to be expected due to disturbance of the sediment and its resuspension.

Table 2. Means (±SD) of general water quality parameters recorded monthly. Temp = water temperature, DO = dissolved oxygen; SpCond = specific conductance.

Site	Depth	Temp (°C)	DO (mg/L)	DO (%)	pH	SpCond (µS/cm)	Turbidity (NTU)	Secchi Depth (m)
1	Surface	20.2 (6)	8.6 (2)	92.9 (9.9)	8.4 (0.2)	384.8 (17.5)	4.6 (1.6)	1.13 (0.27)
	Middle	19.9 (6.1)	7.3 (2.8)	77.2 (19.2)	8.1 (0.4)	385.3 (17)	5 (1.7)	
	Bottom	18.8 (5.3)	5.1 (4.6)	50.6 (43.1)	7.9 (0.5)	399 (32.5)	7.9 (2.5)	
2	Surface	20.3 (5.9)	8.8 (1.9)	96 (8.8)	8.4 (0.2)	385.9 (15.5)	4.6 (1.7)	1.13 (0.16)
	Middle	20.2 (6)	8.5 (2)	92 (11)	8.4 (0.3)	387 (14.8)	5 (1.8)	
	Bottom	19.9 (5.9)	7.3 (3.3)	77.1 (28.4)	8.2 (0.4)	387.5 (15)	6.1 (1.6)	
3	Surface	20.4 (5.9)	9.1 (1.9)	98.7 (9.3)	8.5 (0.3)	386.3 (13.9)	4.6 (1.6)	1.12 (0.16)
	Middle	20.2 (5.9)	8.7 (2)	94.5 (11)	8.4 (0.3)	386.4 (14.4)	4.8 (1.6)	
	Bottom	19.9 (5.9)	7.5 (2.3)	80.4 (15.2)	8.2 (0.3)	387.2 (17.4)	6.3 (1.2)	
4	Surface	20.5 (5.8)	9.2 (2.2)	100.4 (14.9)	8.5 (0.3)	388.6 (14.8)	4.9 (1.7)	1.12 (0.17)
	Middle	20.4 (5.8)	9 (2.3)	97.5 (17.2)	8.5 (0.3)	388.7 (14.9)	5 (1.7)	
	Bottom	20 (5.8)	7.6 (3)	80.4 (22.7)	8.2 (0.4)	392 (15.5)	6.4 (2.1)	
Grand Mean	Surface	20.4 (0.1)	8.9 (0.3)	97 (3.3)	8.4 (0.1)	386.4 (1.6)	4.7 (0.1)	1.12 (0.00)
	Middle	20.1 (0.2)	8.4 (0.8)	90.3 (9)	8.3 (0.1)	386.9 (1.4)	4.9 (0.1)	
	Bottom	19.7 (0.6)	6.8 (1.2)	72.1 (14.4)	8.1 (0.1)	391.4 (5.5)	6.7 (0.8)	

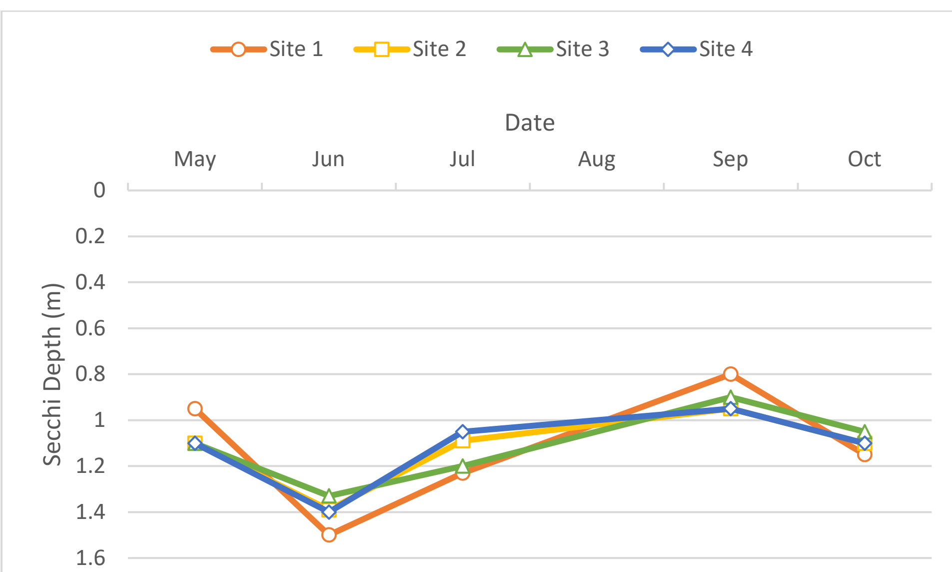

Figure 2. Bear Lake Secchi depth sampled May – October 2022.

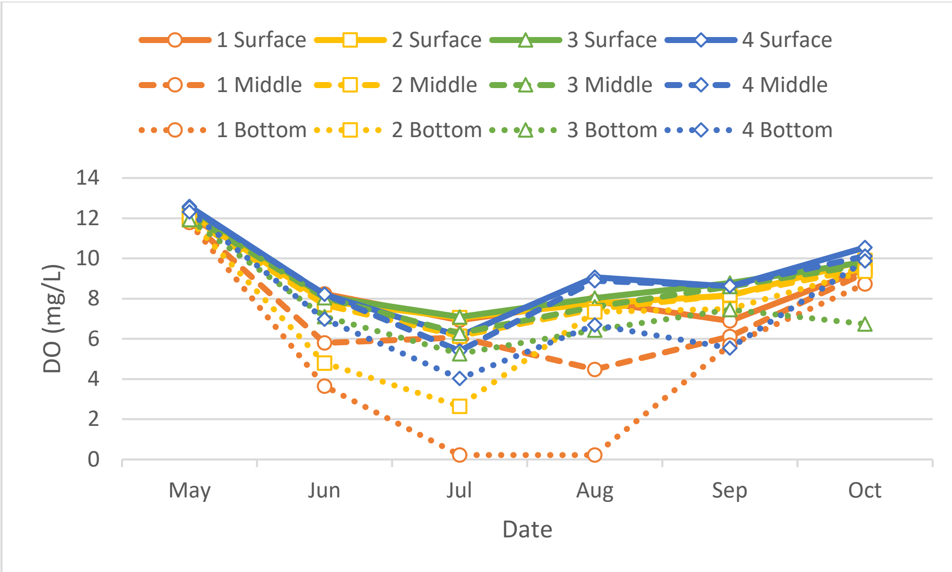

Figure 3. Bear Lake DO concentrations sampled May – October 2022 at near-surface (solid lines), middle depths (dashed lines), and near-bottom depths (dotted lines).

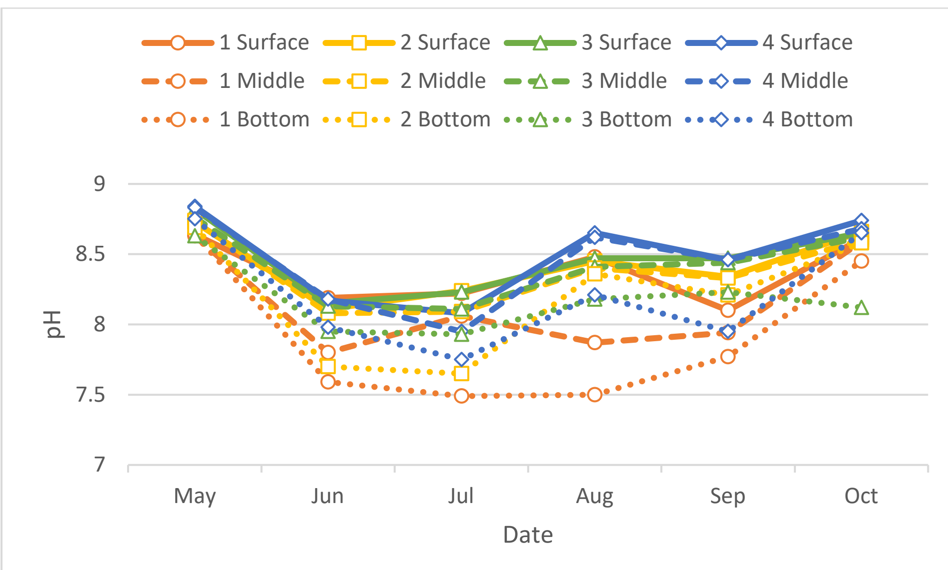

Figure 4. Bear Lake pH sampled May – October 2022 at near-surface (solid lines), middle depths (dashed lines), and near-bottom depths (dotted lines).

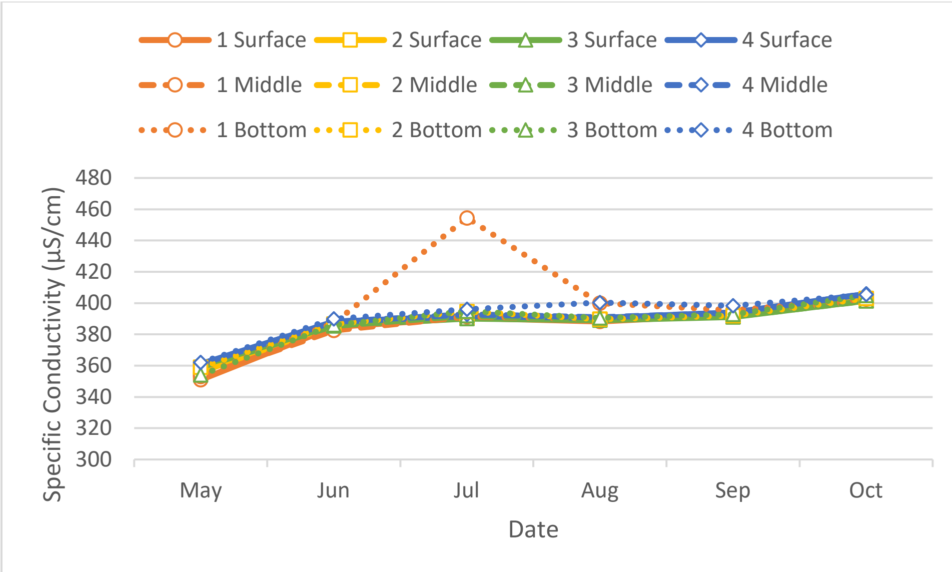

Figure 5. Bear Lake specific conductivity sampled May – October 2022 at near-surface (solid lines), middle depths (dashed lines), and near-bottom depths (dotted lines).

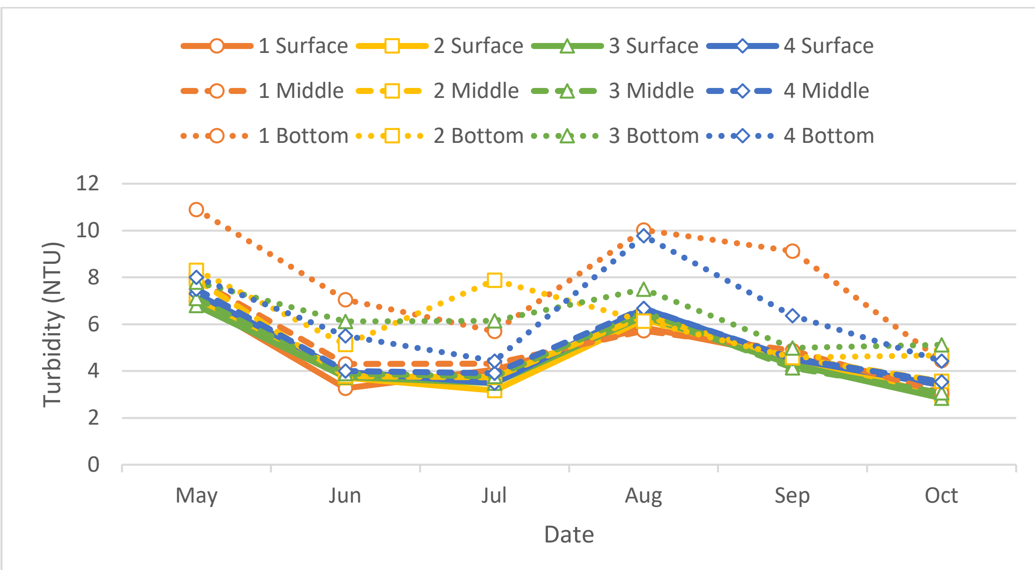

Figure 6. Bear Lake turbidity sampled May – October 2022 at near-surface (solid lines), middle depths (dashed lines), and near-bottom depths (dotted lines).

TP concentrations ranged 30-90 µg/L but site means across the sampling period were closer to 45-60 µg/L, considerably above the TMDL target. Near-bottom samples were greater than surface samples, especially at the deeper Site 1 (Table 3, Figure 7), suggesting the possibility of internal P loading at that location. SRP, the biologically available form of phosphorus, was below detection in all samples and is reported here as 2.5 µg/L, which is one-half our detection limit of 5 µg/L (Table 4, Figure 8). NO_3^- concentrations trended seasonally with higher values at the beginning of the monitoring period in May reaching lower values below detection in July and August with a spike at all sites in September, suggesting a runoff event, possibly due to storm flushing of a fertilizer application in the watershed (Table 4, Figure 9). We did not a similar September spike in NH_3 and TKN (the sum of ammonia and organic N) concentrations, consistent with nitrate runoff; indeed, NH_3 and TKN trended in an inverse manner from NO_3^-, starting low in May, peaking in July, and decreasing through the fall (Table 4, Figures 10-11).

Table 3. Means (±SD) of total phosphorus (TP), soluble reactive phosphorus (SRP), nitrate (NO_3^-), ammonia (NH_3), and total Kjeldahl nitrogen (TKN).

Site	Depth	TP (µg/L)	SRP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
1	Surface	47.9 (11)	2.5 (0)	0.05 (0.06)	0.08 (0.12)	1.1 (0.36)
	Bottom	60.2 (21.3)	2.5 (0)	0.05 (0.05)	0.24 (0.29)	1.21 (0.62)
2	Surface	44.1 (13)	2.5 (0)	0.05 (0.04)	0.08 (0.1)	1.02 (0.34)
	Bottom	47.9 (10.9)	2.5 (0)	0.05 (0.04)	0.08 (0.1)	1.1 (0.33)
3	Surface	45.3 (12.9)	2.5 (0)	0.06 (0.03)	0.07 (0.1)	1 (0.34)
	Bottom	48.5 (11.7)	2.5 (0)	0.06 (0.04)	0.11 (0.18)	1.12 (0.29)
4	Surface	45.9 (14.2)	2.5 (0)	0.05 (0.04)	0.06 (0.08)	1.13 (0.4)
	Bottom	48.3 (12.2)	2.5 (0)	0.04 (0.04)	0.09 (0.09)	1.12 (0.26)
Grand Mean	Surface	45.8 (1.6)	2.5 (0)	0.05 (0.01)	0.07 (0.01)	1.06 (0.06)
	Bottom	51.2 (6)	2.5 (0)	0.05 (0.01)	0.13 (0.08)	1.14 (0.05)

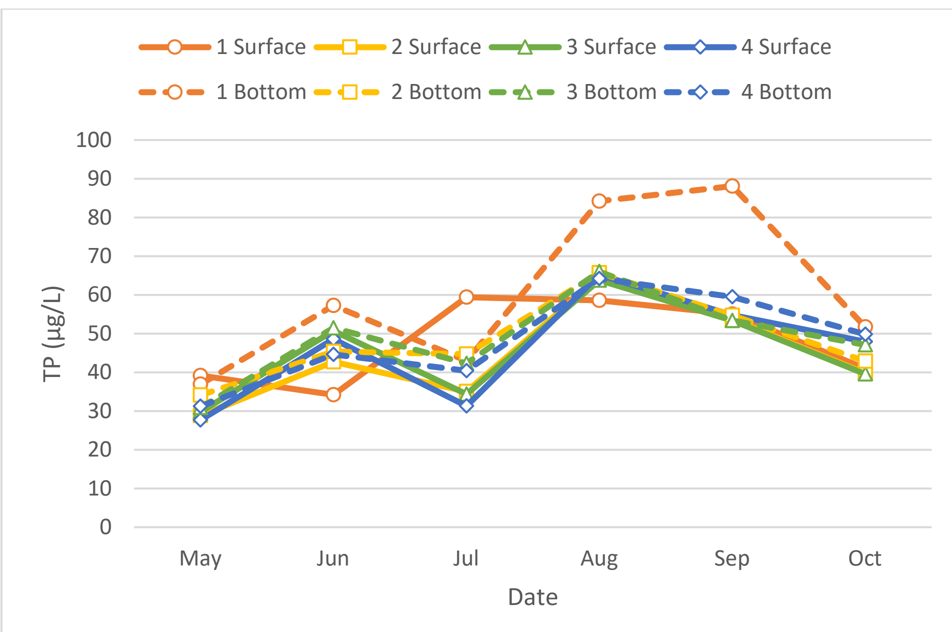

Figure 7. Bear Lake total phosphorus (TP) concentrations sampled May – October 2022 at near-surface (solid lines) and near-bottom depths (dashed lines).

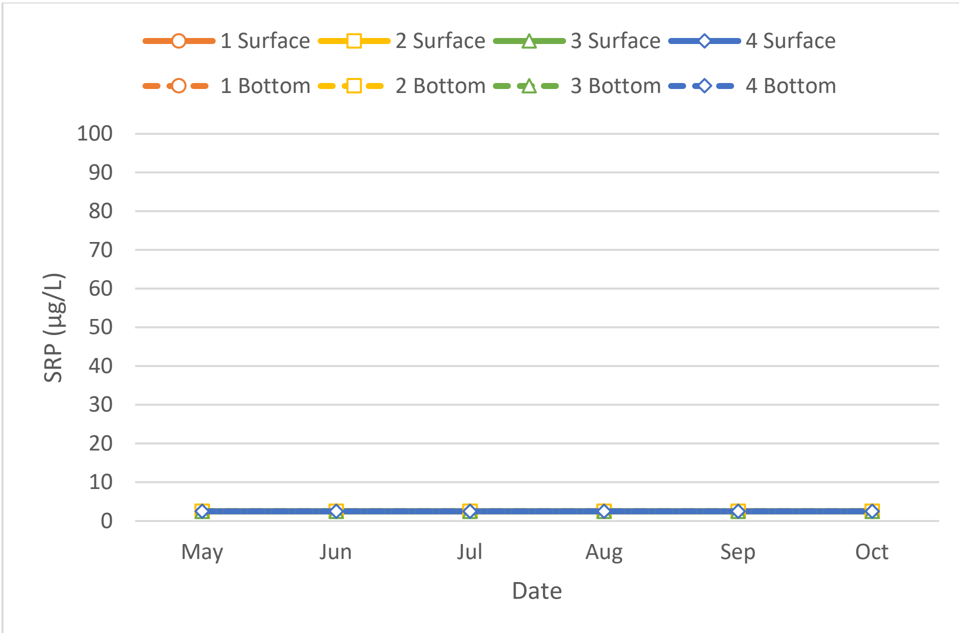

Figure 8. Bear Lake soluble reactive phosphorus (SRP) concentrations sampled May – October 2022 at near-surface (solid lines) and near-bottom depths (dashed lines).

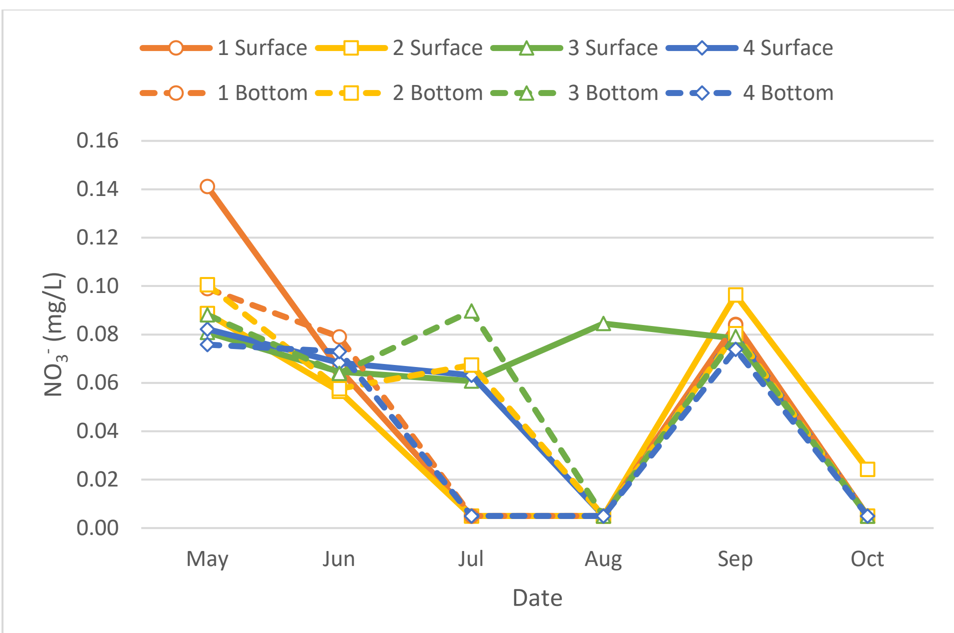

Figure 9. Bear Lake nitrate (NO_3^-) concentrations sampled May – October 2022 at near-surface (solid lines) and near-bottom depths (dashed lines).

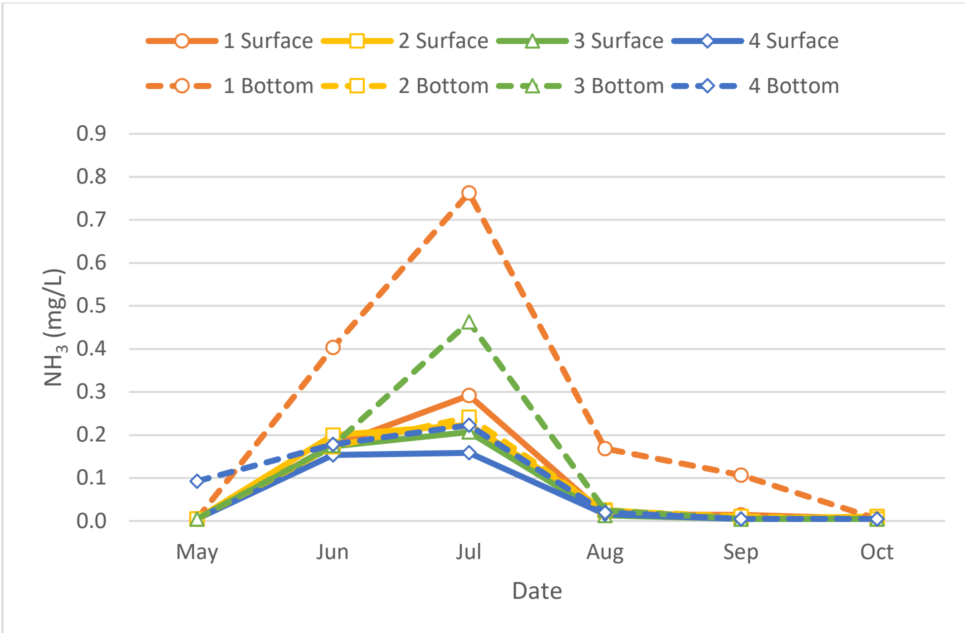

Figure 10. Bear Lake ammonia (NH_3) concentrations sampled May – October 2022 at near-surface (solid lines) and near-bottom depths (dashed lines).

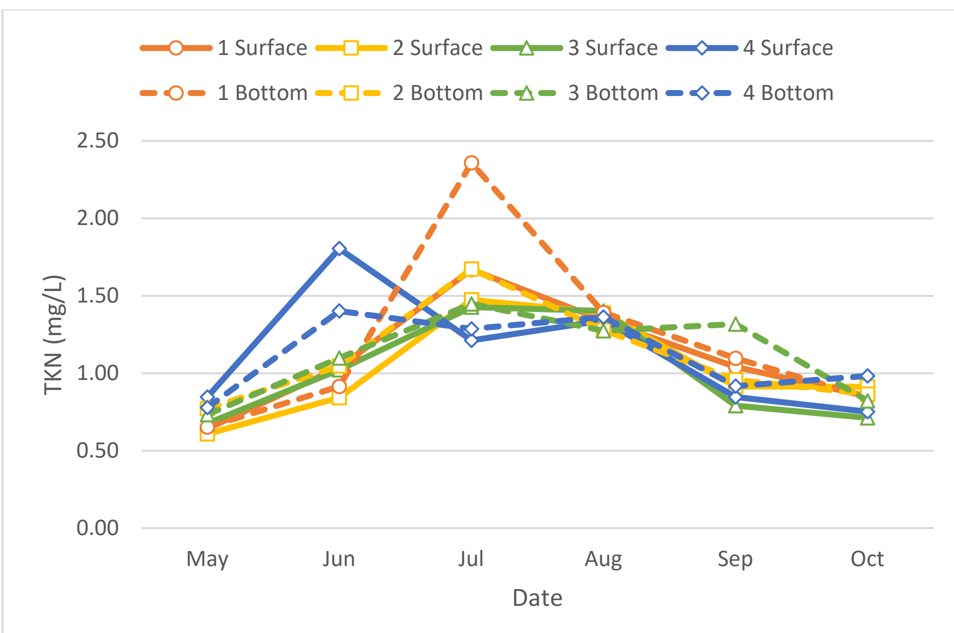

Figure 11. Bear Lake total Kjeldahl nitrogen (TKN) concentrations sampled May – October 2022 at near-surface (solid lines) and near-bottom depths (dashed lines).

Chlorophyll *a* concentrations followed normal seasonal and depth trends. Mean chl *a* concentrations at both depths from May-July averaged 21 µg/L, spiked to 47 µg/L in August-September, and decreased to 21 µg/L once again in October (Table 4, Figure 12). These levels are much higher than the restoration target of 10 µg/L for Muskegon Lake. Microcystin was detected at least once on all sampling events and concentrations were all under 0.09 µg/L, well below the WHO and EPA guidelines for recreational contact (Table 4, Figure 13). *E. coli* was measured in low concentrations and never exceeded 10 cfu/100 mL in any single sample (Table 4), well below the 300 cfu/100 mL limit for MI waters.

Table 4. Mean (±SD) biological parameters of water quality. Chl = chlorophyll.

Site	Depth	Lab-Extracted Chl *a* (µg/L)	ELISA Microcystin (µg/L)	*E. coli* (cfu/100 mL)
1	Surface	30.4 (13.3)	0.011 (0.022)	4.3 (4.5)
	Bottom	25.1 (17.2)	0.005 (0.026)	
2	Surface	31.1 (14.8)	0.027 (0.032)	2.8 (2.6)
	Bottom	30.2 (15.1)	0.037 (0.035)	
3	Surface	33.5 (16.1)	0.001 (0.026)	1.7 (1.2)
	Bottom	29.7 (11.6)	0.015 (0.02)	
4	Surface	32.6 (15.6)	0.041 (0.029)	1.7 (1.6)
	Bottom	28.6 (11.4)	0.026 (0.027)	
Grand Mean	Surface	31.9 (1.4)	0.02 (0.018)	2.6 (1.3)
	Bottom	28.4 (2.3)	0.021 (0.014)	

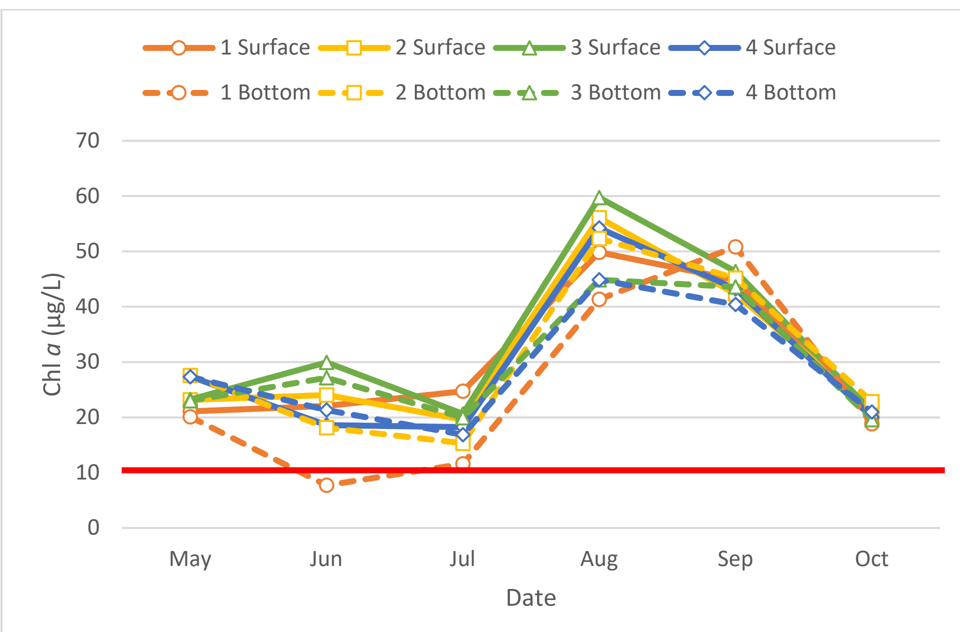

Figure 12. Bear Lake chlorophyll *a* concentrations sampled May – October 2022 at near-surface (solid lines) and near-bottom depths (dashed lines). Red line refers to restoration target of 10 µg/L for Muskegon Lake.

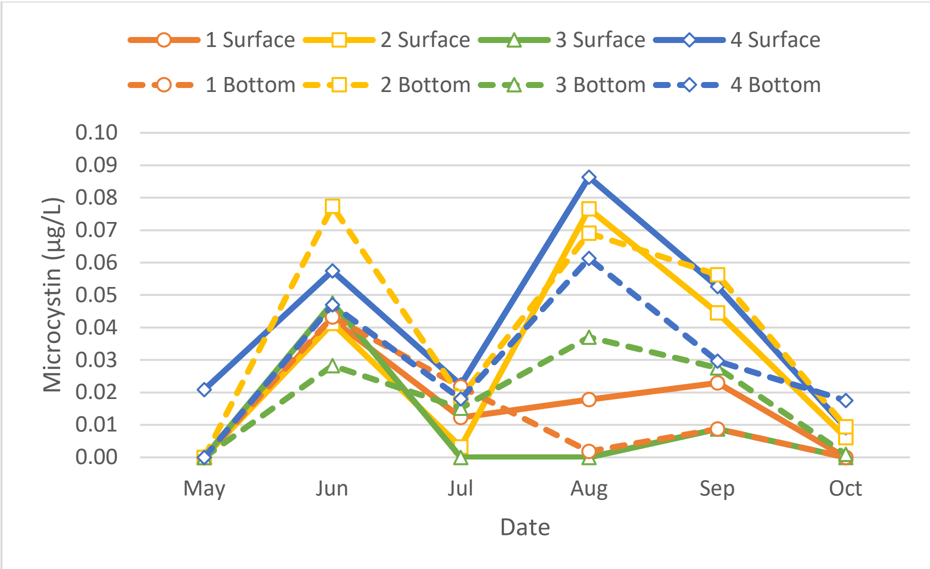

Figure 13. Bear Lake microcystin concentrations sampled May – October 2022 at near-surface (solid lines) and near-bottom depths (dashed lines).

The different taxonomic divisions of phytoplankton, including cyanobacteria, are known to flourish at different times throughout the year. In Bear Lake, cyanobacteria had typically low abundance during May-June sampling (they prefer warmer temperatures) and represented 0-9% of all phytoplankton biovolume (Table 5, Figures 14-15). Cyanobacteria abundance increased to 18% in July and plateaued at 40-54% in August-October (Table 5, Figure 14). In many MI inland lakes, cyanobacterial blooms are lasting longer in to the Fall, consistent with these data (https://www.mlive.com/news/muskegon/2021/11/toxic-algae-blooms-continue-to-plague-lakes-in-muskegon-county.html).

Several species of interest were detected in Bear Lake samples. *Microcystis*, *Limnothrix*, and *Planktothrix* are all capable of producing microcystin (but may not necessarily be doing so all the time) and *Anabaena* can meet its nitrogen needs by fixing (using) atmospheric nitrogen. Of the total cyanobacteria observed in Bear Lake samples, *Limnothrix* and *Planktothrix* often composed the largest percentage of the observed phytoplankton community (Table 5, Figures 14-18). *Anabaena* composed 100% of all observed cyanobacteria in June 2022 (Table 5, Figure 19). *Microcystis* was relatively rare, which differs from the findings of Xie e al. (2011), who found this genus accounted for more than 75% of phytoplankton biovolume. This change in taxonomic dominance may merit more attention. The relative abundance of cyanobacteria species of interest is summarized in Figure 20. Diatoms (Bacillariophyta) were abundant in May, which is typical of Michigan lakes, but declined in relative abundance by June and remained at about 40% of total phytoplankton abundance throughout the sampling period (Figure 14).

Table 5. Mean abundance of cyanobacteria (blue-green algae) biovolume compared to all algae divisions and mean abundances of species of interest (*Microcystis, Limnothrix, Planktothrix,* and *Anabaena*) as respective species biovolume compared to all cyanobacteria.

Date	% Cyanobacteria	% *Microcystis*	% *Limnothrix*	% *Planktothrix*	% *Anabaena*
5/4/2022	9.0%	0.0%	42.2%	43.8%	0.0%
6/8/2022	0.1%	0.0%	0.0%	0.0%	100.0%
7/7/2022	17.9%	10.4%	0.1%	5.8%	1.2%
8/10/2022	48.8%	3.1%	26.7%	3.8%	0.4%
9/7/2022	39.2%	3.6%	8.8%	25.3%	0.0%
10/5/2022	54.2%	2.0%	21.2%	35.2%	0.0%

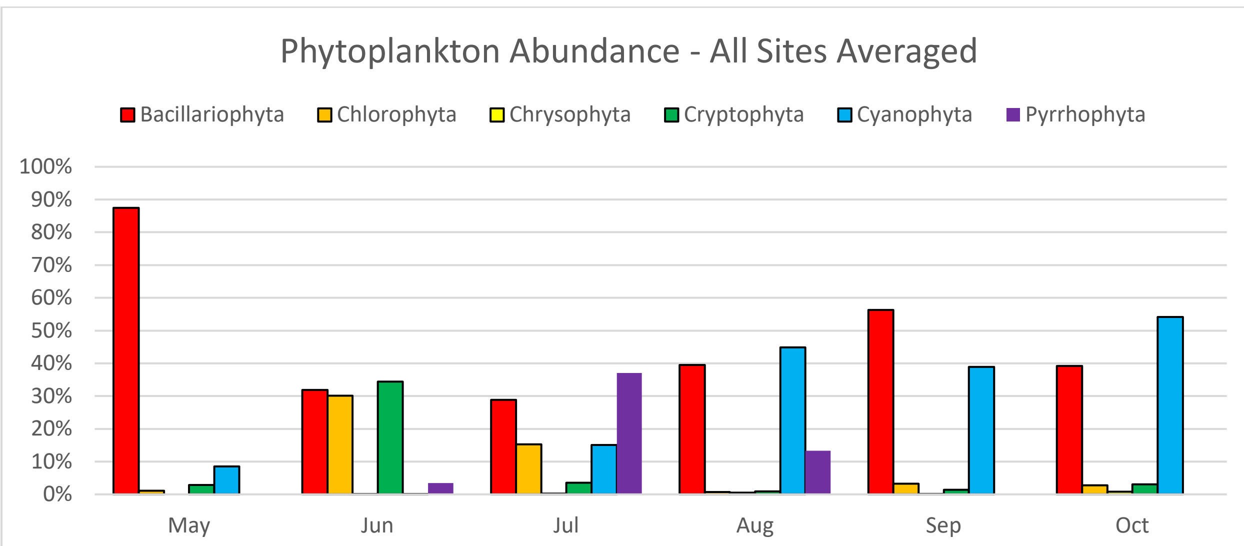

Figure 14. Relative abundance by biovolume of all observed phytoplankton taxonomic divisions.

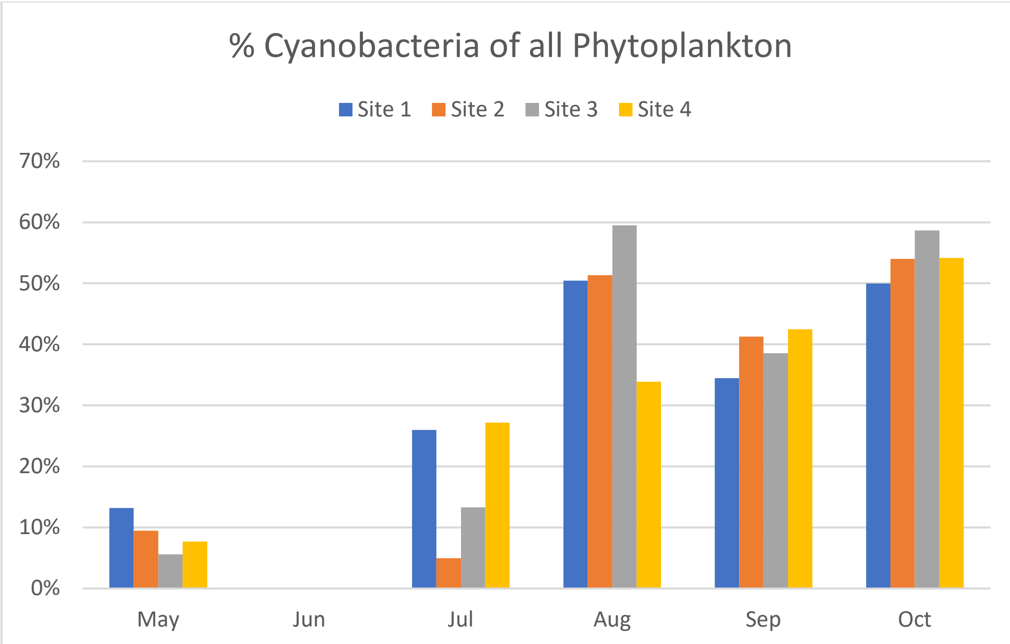

Figure 15. Relative abundance of cyanobacteria (blue-green algae) biovolume compared to all algae divisions in phytoplankton samples by site.

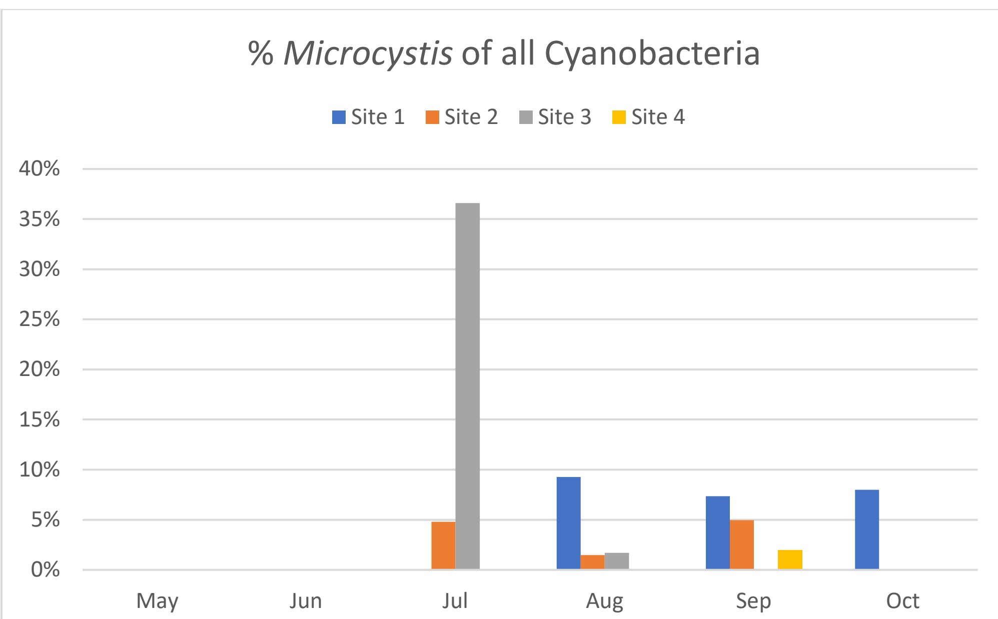

Figure 16. Relative abundance of *Microcystis* biovolume compared to all cyanobacteria in phytoplankton samples by site.

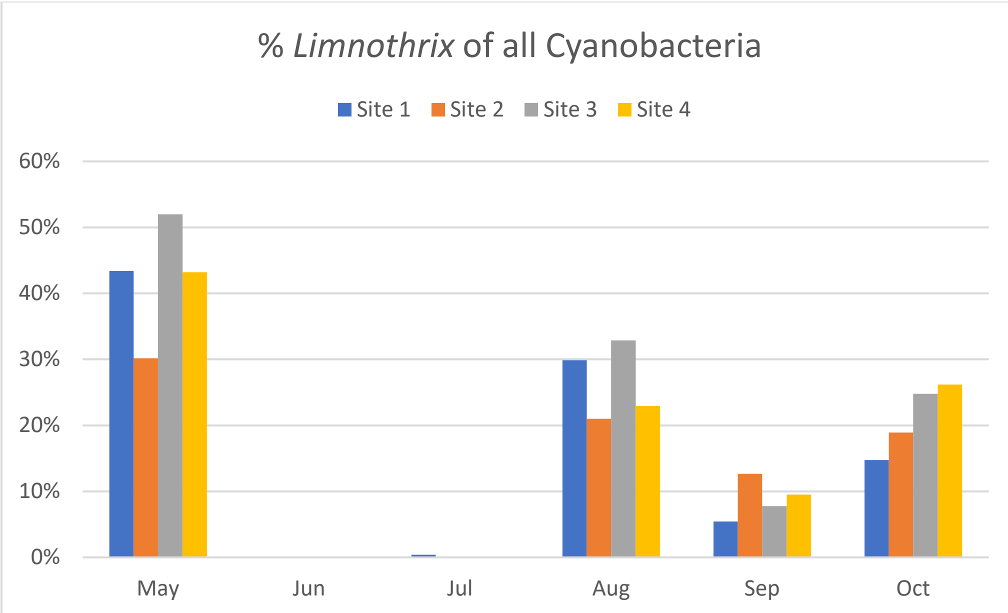

Figure 17. Relative abundance of *Limnothrix* biovolume compared to all cyanobacteria in phytoplankton samples by site.

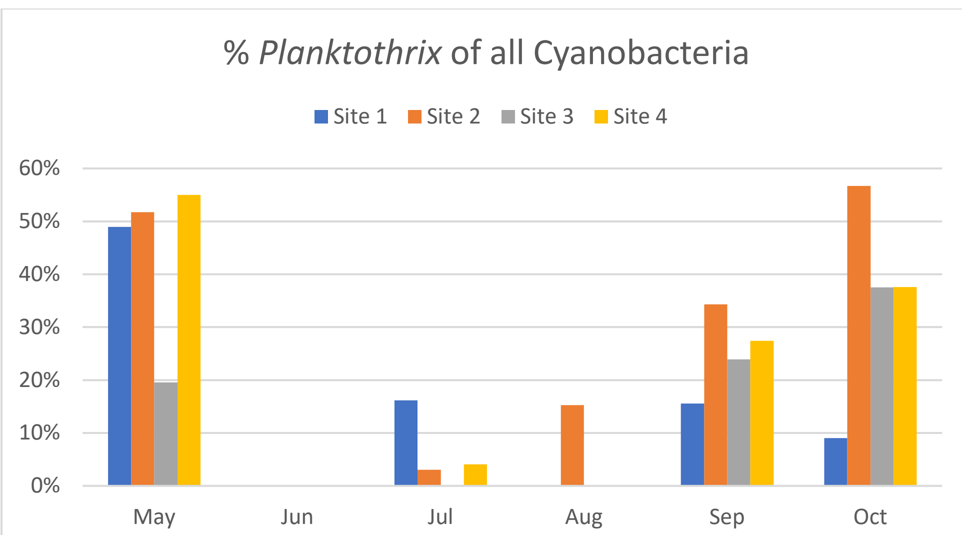

Figure 18. Relative abundance of *Planktothrix* biovolume compared to all cyanobacteria in phytoplankton samples by site.

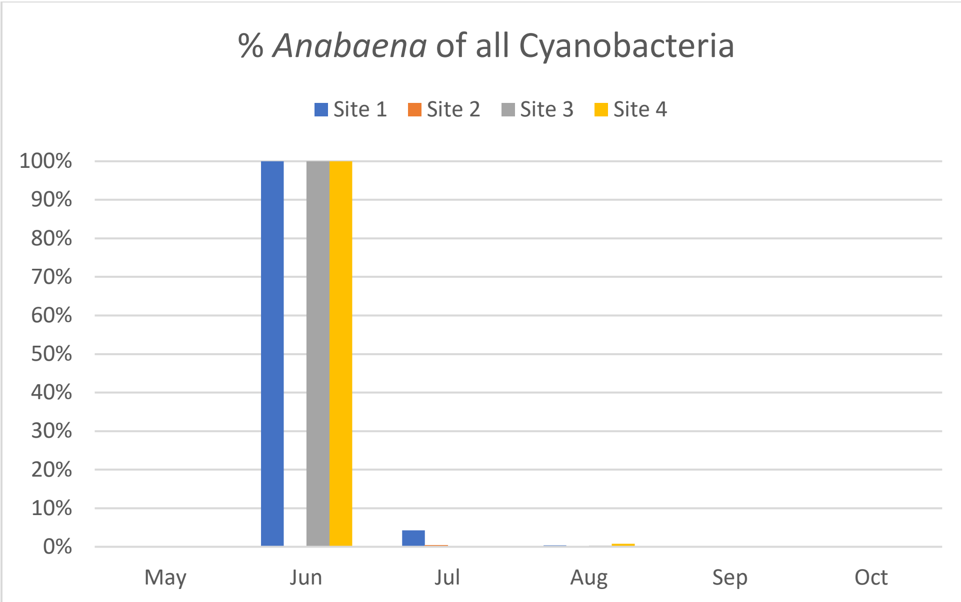

Figure 19. Relative abundance of *Anabaena* biovolume compared to all cyanobacteria in phytoplankton samples by site. Note that neither *Anabaena* nor any other cyanobacteria were observed in the Site 2 sample in June 2022, so the lake-wide mean on this sampling date is 100% *Anabaena*.

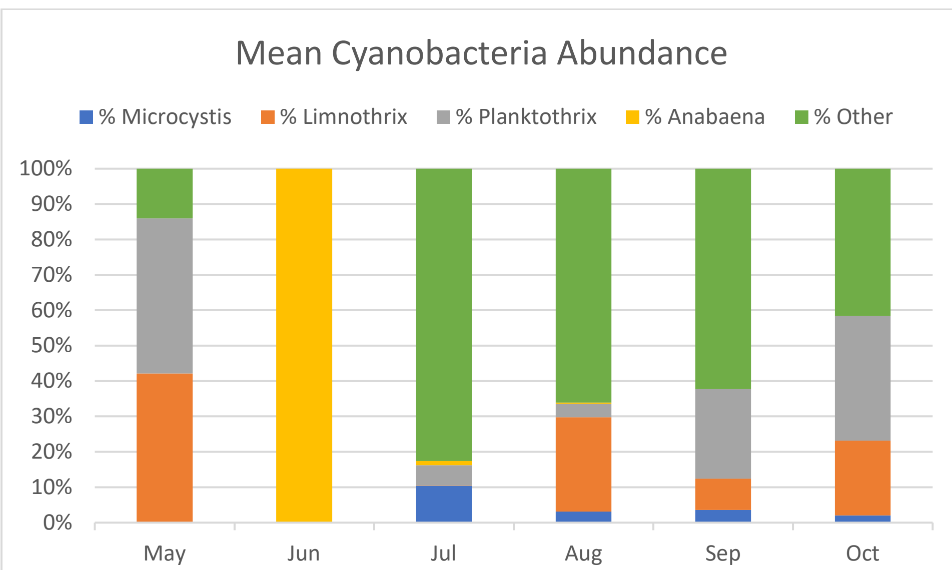

Figure 20. Summary of dominant cyanobacteria species biovolume relative abundance averaged across all sites by date.

Historical Water Quality

Current monitoring data showed small to moderate increases in DO, pH, and chlorophyll, and little change in specific conductivity, TP, TKN, and Secchi depth in Spring months (Table 6, Figures 21-23, 25-27). In summer months, DO and pH declined, TP changed little, and chlorophyll increased in 2022 compared to prior years (Table 7, Figures 21-23, 25-27). SRP was noticeably lower in 2022 but this may be related to methodological differences; AWRI's analytical chemistry laboratory has a minimum detection limit (MDL) of 0.005 mg/L for SRP and samples below detection are reported as 1/2 the MDL to better differentiate those results mathematically (Tables 6-7, Figure 24).

Comparisons of TKN with RLS-collected data is potentially problematic. RLS defines TKN as the sum of nitrate, nitrite, ammonia, and organic nitrogen, which is not standard practice – TKN should not include nitrate or nitrite. We do not know if this was a typo on RLS's part or if they did include oxidized forms of N, in which case their "TKN" values are inflated. Regardless, 2022 TKN concentrations measured by AWRI appear comparable to historic data (Tables 6-7, Figure 25).

Table 6. Long-term trends of Bear Lake deep basin mean (±SD) spring water quality parameters. Data are averaged across the water columns and then averaged across the two deep sites.

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)	0.04 (0)	0.010 (0)	1.1 (0.2)	9.1 (2)	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 (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 (2.8)	1.0 (0.1)

Table 7. Long-term trends of Bear Lake deep basin mean (±SD) summer water quality parameters. Data are averaged across the water columns and then averaged across the two deep sites.

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)	0.010 (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)

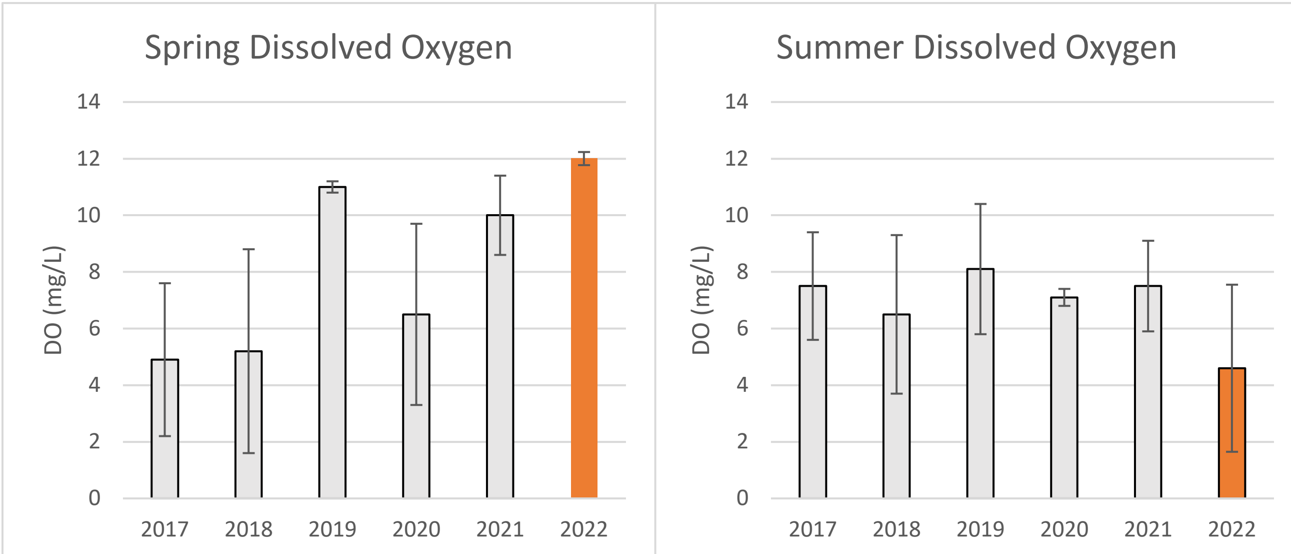

Figure 21. Site mean (±SD) DO averaged across the water column and averaged across both deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022 (AWRI).

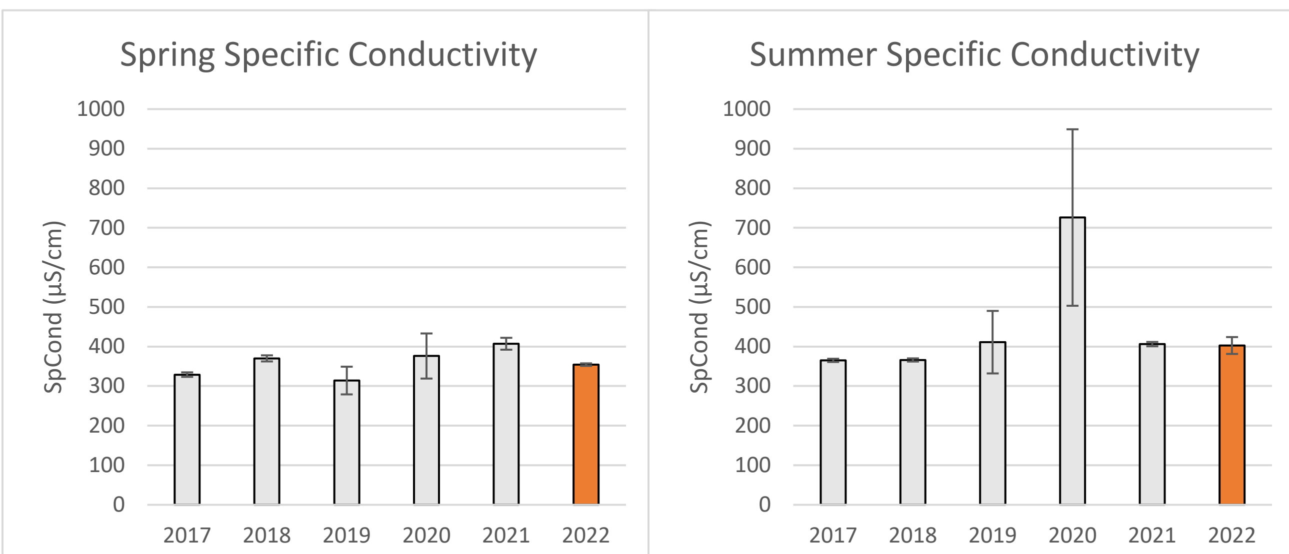

Figure 22. Site mean (±SD) specific conductivity averaged across the water column and averaged across both deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022 (AWRI in orange).

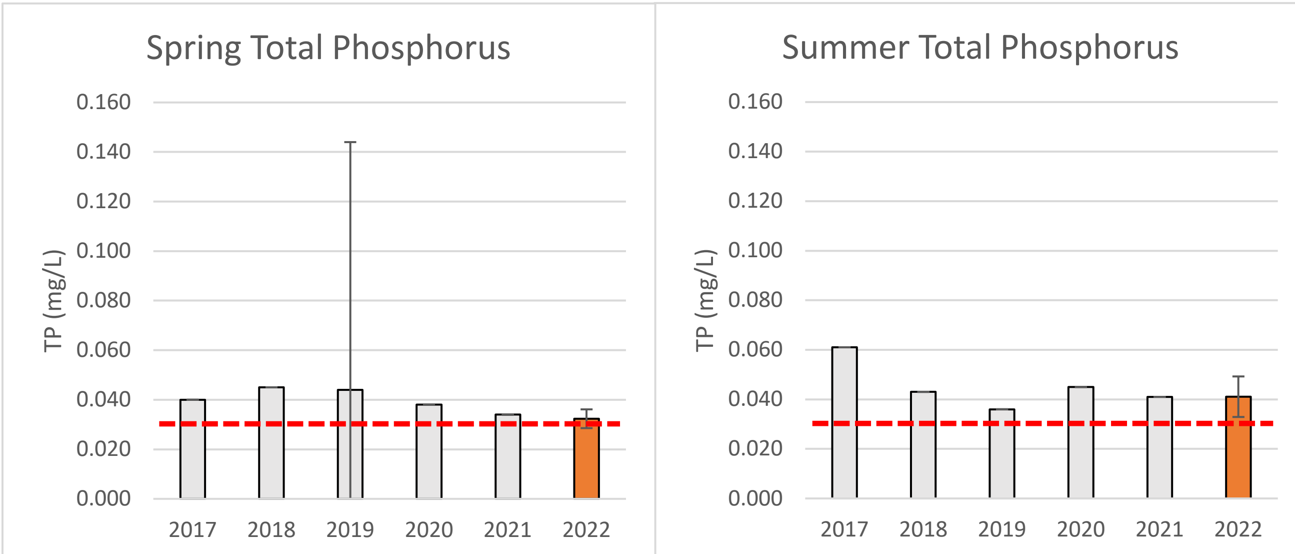

Figure 23. Site mean (±SD) total phosphorus averaged across the water column and averaged across both deep sites during May (left panel) and July (right panel) of each sampling year. Red dashed lines indicate Bear Lake's TMDL for TP: 0.030 mg/L. Data: 2017-2021 (RLS); 2022 (AWRI in orange).

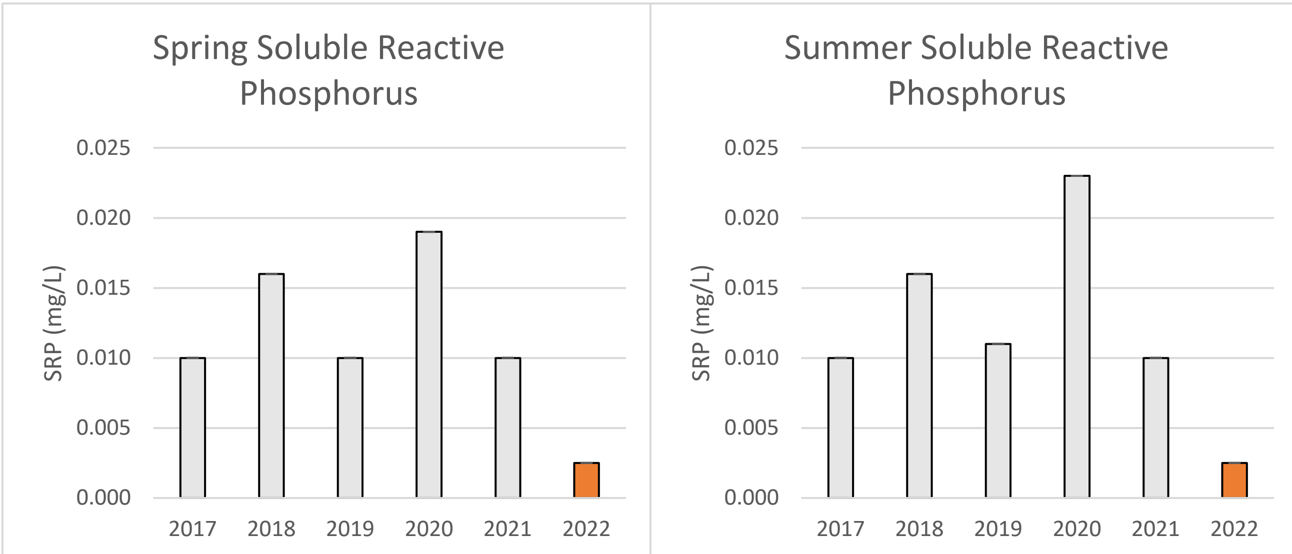

Figure 24. Site mean (±SD) soluble reactive phosphorus averaged across the water column and averaged across both deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022 (AWRI in orange).

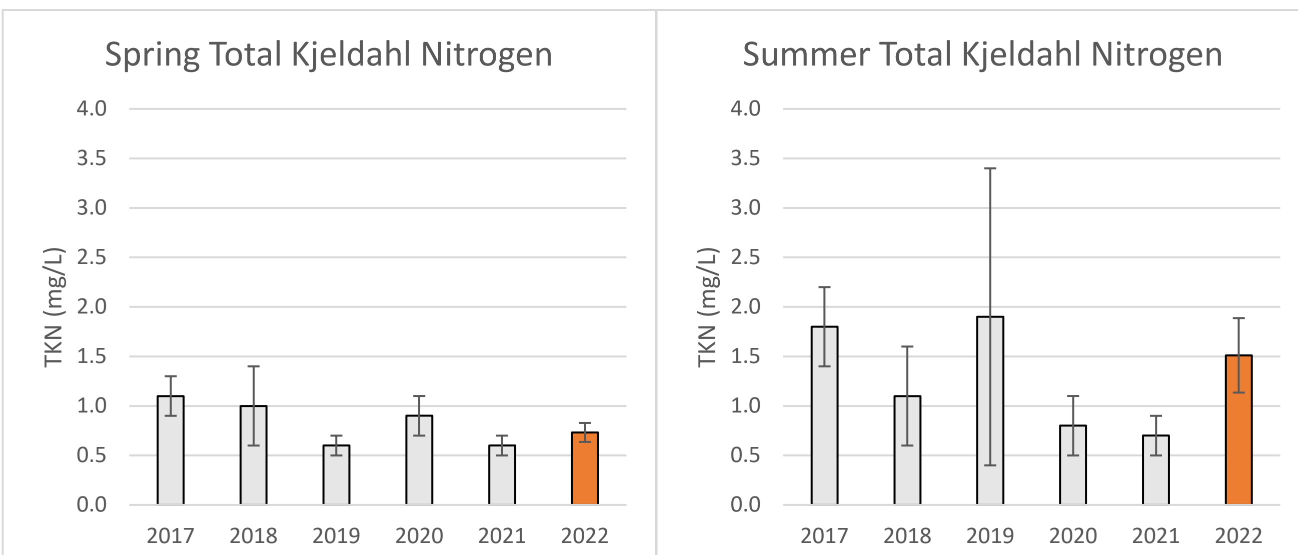

Figure 25. Site mean (±SD) total Kjeldahl nitrogen averaged across the water column and averaged across both deep sites during May (left panel) and July (right panel) of each sampling year. Data: 2017-2021 (RLS); 2022 (AWRI in orange).

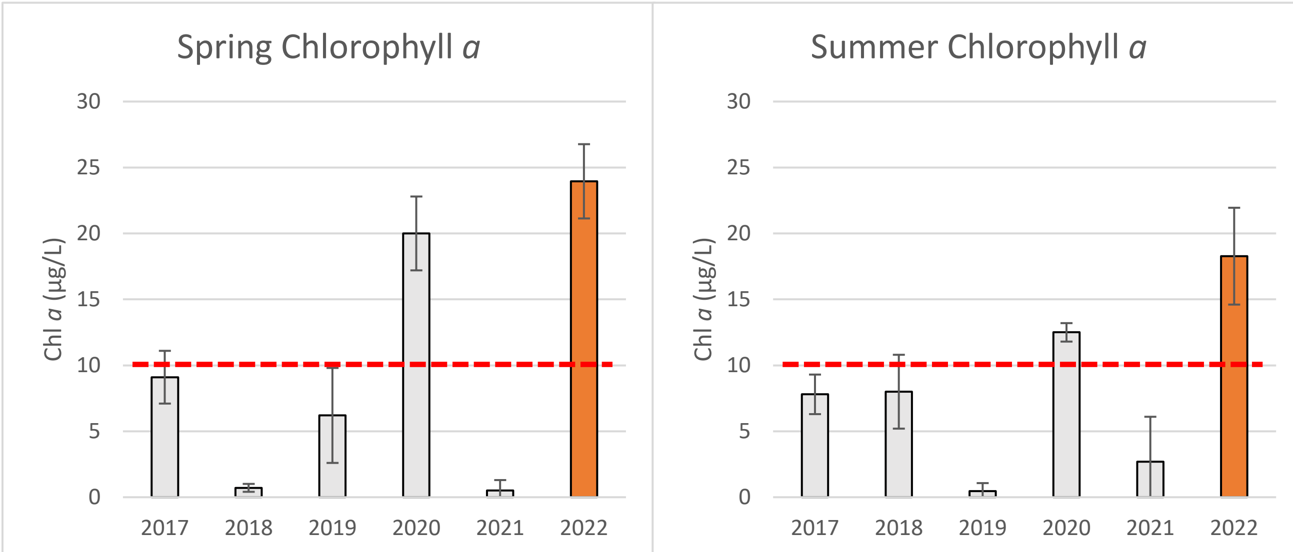

Figure 26. Site mean (±SD) chlorophyll *a* averaged across the water column and averaged across both deep sites during May (left panel) and July (right panel) of each sampling year. Red dashed lines indicate Muskegon Lake's restoration goal for chl *a*: 10 µg/L. Data : 2017-2021 (RLS); 2022 (AWRI in orange).

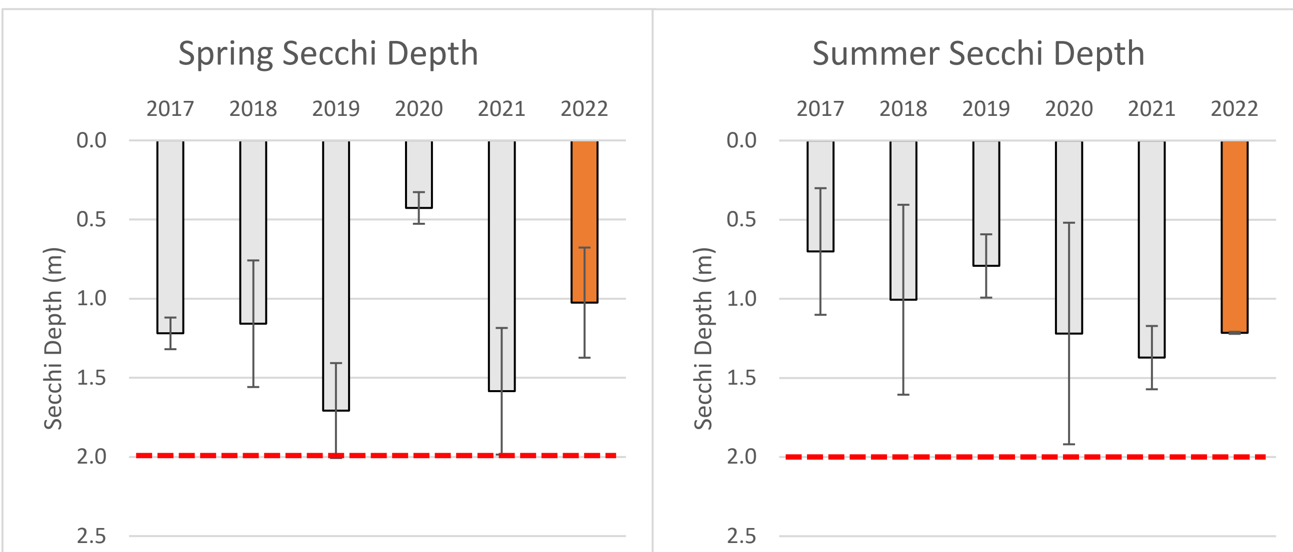

Figure 27. Site mean (±SD) Secchi depth averaged across the water column and averaged across both deep sites during May (left panel) and July (right panel) of each sampling year. Note that the y-axes are inverted so that data indicate the depth from the lake's surface. Red dashed lines indicate Muskegon Lake's restoration goal for Secchi depth: 2 m (~6.5 ft). Data: 2017-2021 (RLS); 2022 (AWRI in orange).

Dashboards

As discussed above, TP concentrations in 2022 are in excess and qualify for the Undesirable category, especially in summer and fall. Note that fall water quality was not reported by RLS in every prior reporting year; data from AWRI's past work in Bear Lake in 2011-2012 has been included in each of the dashboards to provide additional historical context. Historically, the AWRI data show that spring and fall TP concentrations did meet TMDL goals in 2011, although TP concentrations from spring and summer in the past 4 years are consistent with 2022 in being above the target concentration of 30 µg/L (Figure 29). 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. However, our data from 2022 clearly show a negative relationship between precipitation and TP concentration, so the 2022 summer and fall increase in TP compared to the prior few years is not due to increased rainfall (Figure 28).

Chlorophyll *a* concentrations in 2022 were far in excess of the desired 10 µg/L threshold, and higher than any prior year that was monitored (Figure 30). Indeed, historic chl *a* data shows lower concentrations have been Meeting Goals or even the Desirable range in recent years. Notably, chlorophyll concentrations are extremely variable, and can change dramatically within hours of sampling depending on environmental conditions. Hence, while the 2022 numbers are certainly disconcerting, they are based on only one sampling date per month, and if we sampled during a short-term bloom in August and September (cf. Figure 14), the numbers can be distorted. More frequent sampling would result in a more realistic portrayal of chlorophyll levels in Bear Lake.

Secchi disk depth as currently classified continues a trend of being Undesirable. Notably, there has been some improvement over time, as Secchi disk depths have increased especially in spring and summer (Figure 31). The improvement in clarity is not consistent with the increase in chlorophyll, suggesting that other materials, such as dissolved organic matter (DOM) also may have been responsible for low water clarity in the past, and restoration activities in the upper watershed and at the Willbrandt farm have reduced the DOM levels in Bear Lake.

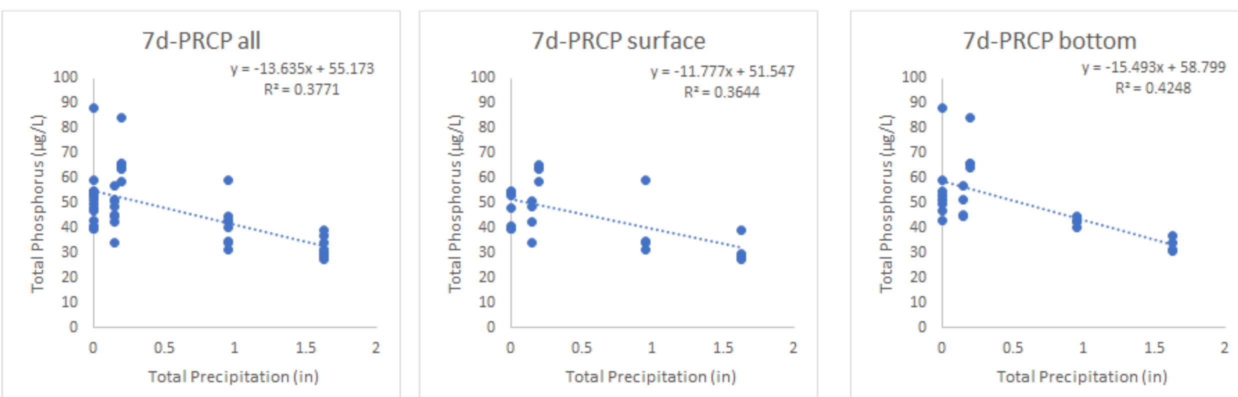

Figure 28. Regression of TP at the 4 sampling sites vs. precipitation for 2022. Left panel: surface and bottom waters combined; middle panel: surface water; right panel: bottom water. Precipitation data are summed for the 7 days prior to sampling TP to account for the lag in rainfall in the watershed reaching Bear Lake.

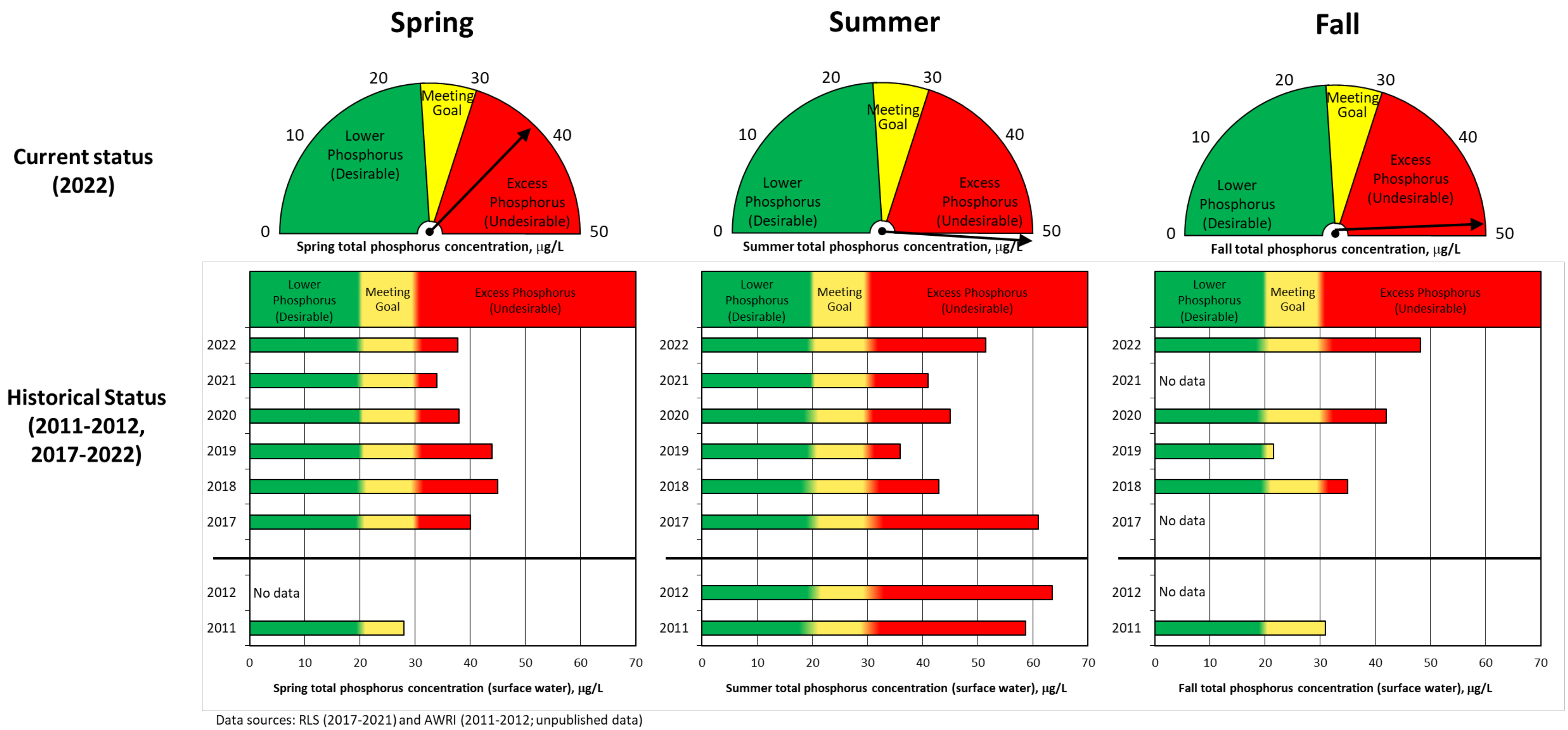

Figure 29. Bear Lake total phosphorus seasonal dashboard. Classifications are based on >30 µg/L "undesirable" threshold of Bear Lake TMDL, and the <30 µg/L "meeting goal" threshold and <24 µg/L "desirable" threshold of the Muskegon Lake long-term monitoring dashboard.

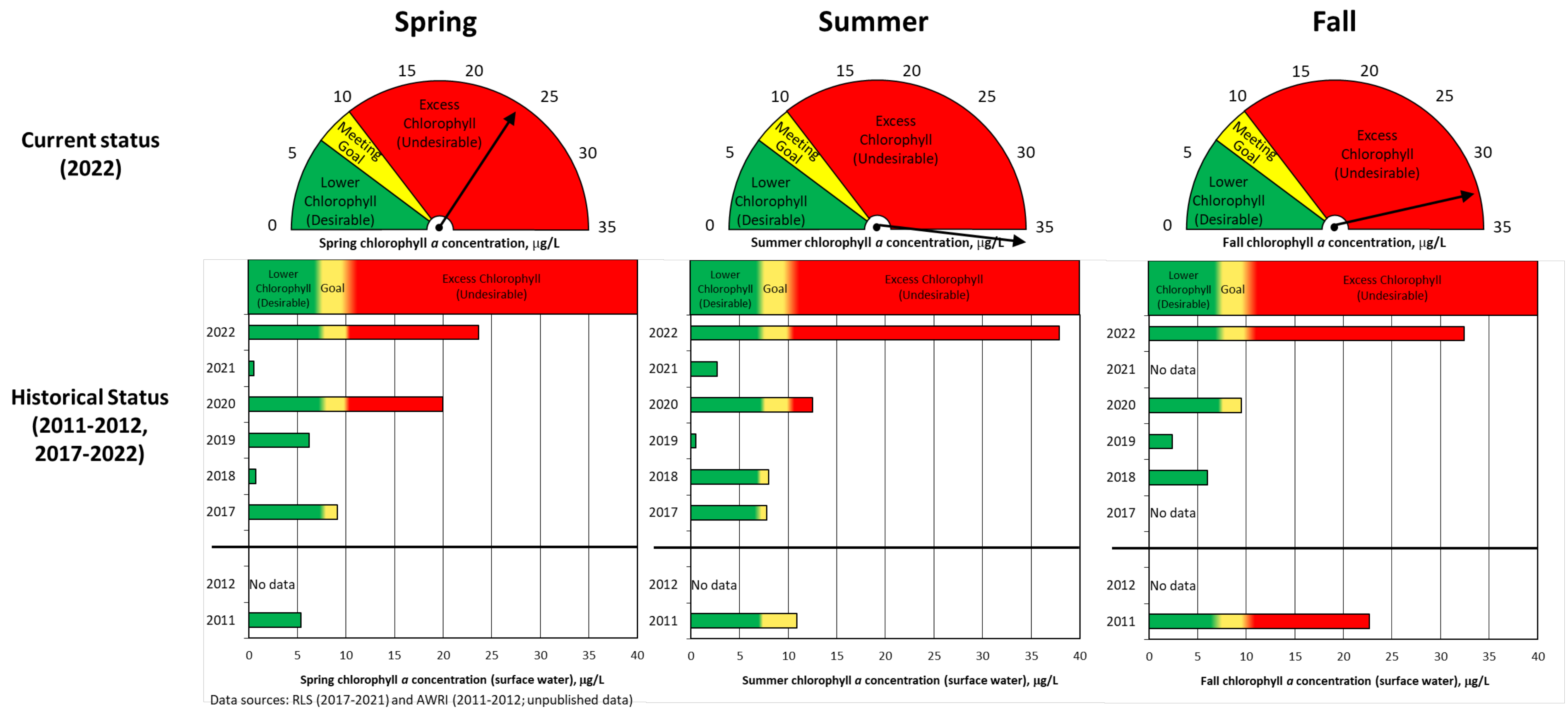

Figure 30. Bear Lake chlorophyll *a* seasonal dashboard. Classifications are based on >10 µg/L "undesirable" threshold, <10 µg/L "meeting goal" threshold, and <7.3 µg/L "desirable" threshold of the Muskegon Lake long-term monitoring dashboard.

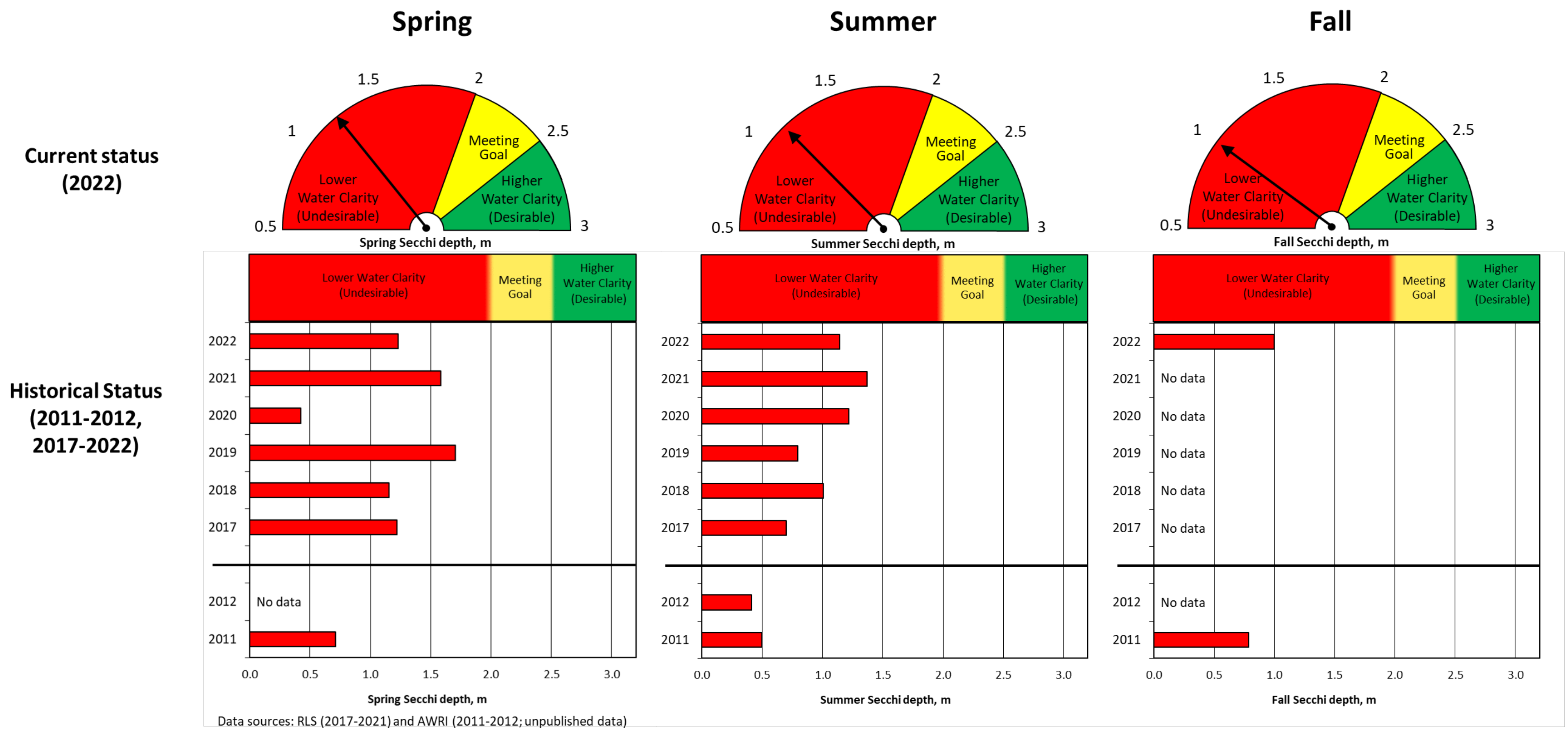

Figure 31. Bear Lake Secchi depth seasonal dashboard. Classifications are based on >2 m "undesirable" threshold, <2 m "meeting goal" threshold, and <2.5 m "desirable" threshold of the Muskegon Lake long-term monitoring dashboard.

Summary:

Bear Lake TP concentrations remain above the 30 µg/L threshold established in the TMDL. While the 2022 spring and summer TP concentrations do not exceed historical highs, they average 10 to 20 µg/L higher than meeting the goal. This is a concern not only for the ecological health of Bear Lake, but it also potentially creates a barrier for delisting the Muskegon Lake AOC, as the eutrophication and nuisance algae BUI (beneficial use impairment) targets are not being met.

Internal phosphorus and nitrogen loading is limited overall in Bear Lake, with Site 1 (the deepest site) contributing the highest internal loads. Nonetheless, the bottom water concentrations at Site 1 are still relatively modest compared to other lakes in the region, although above the TMDL threshold so should not be ignored (see recommendations).

The chlorophyll *a* concentrations are higher than what have been measured in the past; it is unclear if this is a response to the high nutrient concentrations, the variability of chlorophyll levels (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 high chlorophyll levels, the cyanotoxin concentrations measured in Bear Lake are far 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 has shifted over the past 10 years from dominance by *Microcystis* in summer/fall to dominance by *Planktothrix* and *Limnothrix*. All three genera are capable of producing cyanotoxins but at least in 2022, they were not doing so at levels of concern.

In summary, Bear Lake is still dealing with too much phosphorus and algae, and additional efforts are needed to address these concerns.

Recommendations:

1) **Expanded nutrient monitoring**: It is unclear if the high TP and chlorophyll concentrations were anomalies or part of a trend of higher values. While it is believed that the flow-through marsh created at the Willbrandt site will, in time, help reduce TP loads coming from upstream in the watershed, it is important to determine if there are other sources contributing nutrients to Bear Lake. The only way to parse out this question is through continued monitoring. Indeed, we recommend for nutrients to continue the 4 in-lake sites, as well as sample nutrients from the major inflows to Bear Lake (Bear Creek and Fenners Ditch, and possibly Bear Lake Direct 1 and Bear Lake Direct 2) and the outflow of Bear Lake to Muskegon Lake in order to improve our understanding of temporal and spatial trends.

2) **Other P sources**: Examine possible sources of P from direct runoff into lake (septage, yard runoff, restored ponds);

3) **More frequent chlorophyll monitoring**: The high chlorophyll concentrations also may be a function of infrequent sampling, when low chlorophyll conditions in summer and fall 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.

   3a) 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.

3b) 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/.

4) The application of Phoslock to strip P from the water column and create a benthic cap to limit internal loading makes good sense for Fenners Ditch (and possibly other inflows depending on P concentrations) as well as the deeper portions of Bear Lake. Based on our prior analysis (Steinman and Ogdahl 2015), we recommend application at depths greater than 10 ft; if the Lake Board wants to be highly protective, application can be expanded to areas deeper than 9 ft (see Fig. 32) although prior data indicate internal loading from sediment at depths shallower than 10 ft is very limited.

5) Finally, we recommend conducting a watershed survey to determine lake user priorities (target 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).

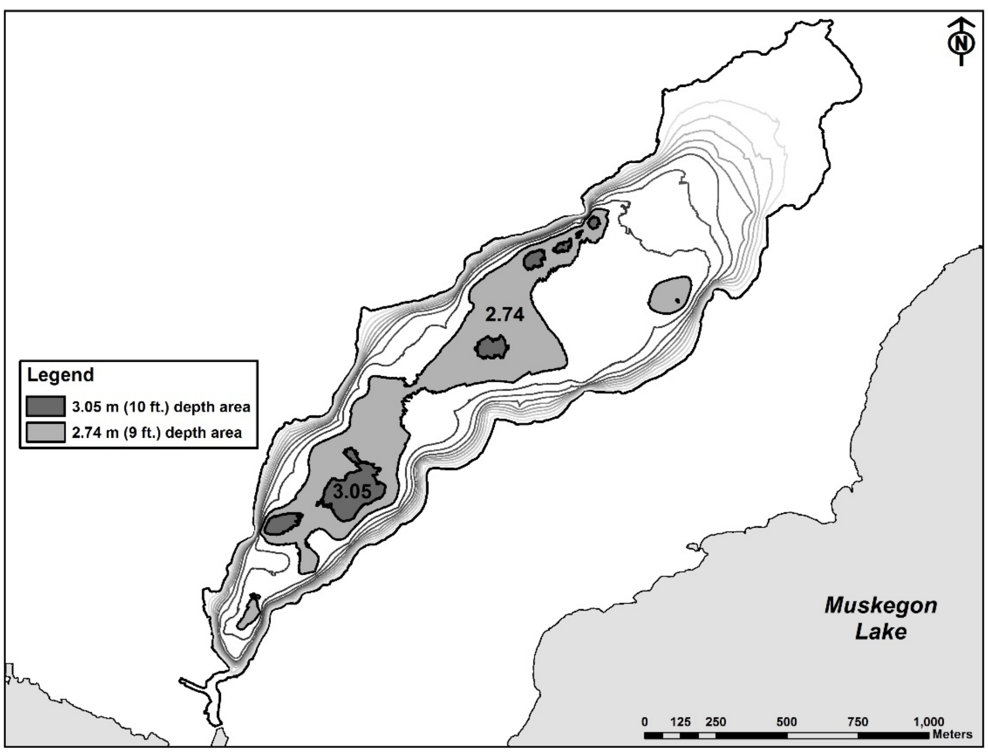

Figure 32. Sampling locations and bathymetry of Bear Lake. Light and dark gray shading show depths >2.7 m and >3 m, respectively. From Steinman and Ogdahl (2015).

Acknowledgments

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