PROJECT CLARITY
2024 Annual Report

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1. Overview

Project Clarity is a large-scale, multidisciplinary, collaborative watershed remediation project aimed at improving water quality in Lake Macatawa. A holistic approach that has included wetland restoration, in-stream remediation, Best Management Practices (BMPs), and community education has been implemented as part of a multimillion-dollar public-private partnership. The project has already reaped numerous economic, social, and ecological benefits – with the ultimate goal of improved water quality in Lake Macatawa.

Lake Macatawa is the terminus of a highly degraded watershed and has exhibited the symptoms of a eutrophic to hypereutrophic lake for more than 40 years (MWP 2012, Holden 2014). Extremely high nutrient and chlorophyll concentrations, excessive turbidity, low dissolved oxygen, and a high rate of sediment deposition have made it one of the most nutrient-rich lakes in Michigan (MWP 2012, Holden 2014). Nonpoint source pollution from the watershed, particularly agricultural areas, is recognized as the primary source of the excess nutrients and sediment that fuel the impaired conditions in Lake Macatawa (MWP 2012).

Because of this nutrient enrichment, Lake Macatawa and all of its tributaries are included on Michigan's 303(d) list of impaired water bodies, prompting the issuance of a phosphorus (P) Total Maximum Daily Load (TMDL) for Lake Macatawa in 2000. The TMDL set an interim target total phosphorus (TP) concentration of 50 µg/L in Lake Macatawa (Walterhouse 1999); a 72% reduction in phosphorus loads from the watershed would be required to meet the TP concentration target (Walterhouse 1999). In the past, monthly average TP concentrations often exceeded 125 µg/L, and at times exceeded 200 µg/L (Holden 2014). Annual mean TP concentrations between 2018 and 2021 started to decline, falling below 90 µg/L. However, over the past two years, annual mean TP concentrations have once again exceeded 100 µg/L. This suggests that while improvements are ongoing in the watershed, they have not yet translated into long-term lake water quality improvements. While a lag time is expected before these watershed improvements are reflected in lake water quality, these recent data suggest more work is needed.

The Annis Water Resources Institute (AWRI) of Grand Valley State University, in cooperation with the ODC (Outdoor Discovery Center) Network, the Macatawa Area Coordinating Council, and Niswander Environmental, initiated a long-term monitoring program in the Lake Macatawa watershed in 2013. This effort has provided critical information on the performance of restoration projects that are part of Project Clarity and continues to evaluate the ecological status of Lake Macatawa. This report documents AWRI's monitoring activities in 2024, in combination with data reported previously from 2013-2023. As noted previously, we terminated sampling upstream and downstream of the restored wetlands in April 2019 given the limited value of the information provided. Based on guidance from ODC, our efforts are now focused on Lake Macatawa itself, and the main body of this report provides the latest information on lake water quality. In addition, we have included appendices on the fish community in the lake and the Lake Macatawa water quality dashboard.

The 2024 water quality data are very similar to the past few years, indicating a plateau appears to have been reached in terms of water quality improvement. The phosphorus, chlorophyll, and water quality conditions, while somewhat better than pre-Project Clarity concentrations, are still indicative of impaired conditions. Of particular concern is the high concentration of bioavailable P, as this is the form of phosphorus that is readily used by algae, which certainly accounts for the high algal levels seen in Lake Macatawa. The fish assemblage data in Lake Macatawa are generally reflective of poor water quality, with little evidence of a change over the past decade.

In order to meet the TMDL for the lake, additional measures will be necessary. Steps are currently being taken to address several concerns. First, the upcoming installation of "a lake observatory" will result in collection of continuous water quality data, providing a more robust assessment of lake conditions. Second, a study to assess the feasibility of a public works project to treat Macatawa River inflow with chemical inactivants to bind phosphorus is being considered.

2. Methods

2.1 Overall site description

The Macatawa watershed (464 km^2/114,000 acres), located in Ottawa and Allegan Counties, includes Lake Macatawa, the Macatawa River, and many tributaries. It is dominated by agricultural (46%) and urban (33%) land uses, which have contributed to the loss of 86% of the watershed's natural wetlands (MWP 2012). The watershed includes the Cities of Holland and Zeeland and parts of 13 townships (MWP 2012). Lake Macatawa is a 7.2 km^2/1,780 acre drowned river mouth lake. It is relatively shallow, with an average depth of 3.6 m/12 ft and a maximum depth of 12 m/40 ft in the western basin. The Macatawa River, the main tributary to the lake, flows into the lake's shallow eastern basin. A navigation channel in the western end of the lake connects Lake Macatawa with Lake Michigan.

2.2 Lake Macatawa: Long-Term Monitoring

Water quality monitoring in the lake was conducted at 5 sites during spring, summer, and fall 2024 (Table 1, Fig. 1). These are the same sampling sites we have used in prior years, and also correspond with Michigan Department of Environment, Great Lakes & Energy (EGLE, formerly MDEQ) monitoring locations to facilitate comparisons with recent and historical data. At each sampling location, general water quality measurements (dissolved oxygen [DO], temperature, pH, specific conductivity, and turbidity) were taken using a YSI EXO V2 sonde at the surface, middle, and near-bottom of the water column. Water transparency was measured as Secchi disk depth. Water samples were collected from the surface and near-bottom of the water column using a Van Dorn bottle and analyzed for SRP, TP, NH_3, NO_3^-, TKN, and chl *a*. Samples also were taken for phytoplankton community composition and archived for possible future analysis.

Water for SRP and NO_3^- analyses was syringe-filtered through 0.45-µm membrane filters into scintillation vials; SRP was refrigerated at 4°C and NO_3^- frozen until analysis. NH_3 and TKN were acidified with sulfuric acid and kept at 4°C until analysis. SRP, TP, NH_3, NO_3^-, and TKN were analyzed on a SEAL AQ2 discrete automated analyzer (U.S. EPA 1993). Chl *a* samples were filtered through GF/F filters and frozen until analysis on a Shimadzu UV-1601 spectrophotometer (APHA 1992). Any values below detection were reported as ½ the detection limit for the purpose of analysis.

Paired t-tests (for normally distributed data) and Mann-Whitney rank sum tests (non-normal data) were used to detect significant differences in pre- and post-restoration distributions of SRP, TP, and chl *a*. An equal number (n=40) of seasonally corresponding data points from all pre-restoration (summer 2013 – fall 2015) and the most recent post-restoration (summer 2022 – fall 2024) sampling events were incorporated in the analysis, pooling data from all sites (1-5). Statistical significance was set with $\alpha = 0.05$, and testing was performed using SigmaPlot statistical software (SigmaPlot v15.0).

Additionally, we continued testing for microcystin, which began in 2017. Microcystin is the most common cyanotoxin produced by cyanobacteria (blue-green algae). We used the ELISA QuantiPlate kit for Microcystins High Sensitivity (Envirologix; Portland, ME), 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 adults; for recreational use, WHO is >20 µg/L and EPA is >8 µg/L (US EPA 2021). Since Lake Macatawa is used only for recreation, we applied the latter two criteria.

Table 1. Location and 2024 water column seasonal mean depth at Lake Macatawa long-term monitoring locations.

Site	Latitude	Longitude	Depth (m)
1	42.7913	-86.1194	8.3
2	42.7788	-86.1525	5.2
3	42.7872	-86.1474	3.6
4	42.7755	-86.1822	10.0
5	42.7875	-86.1820	4.3

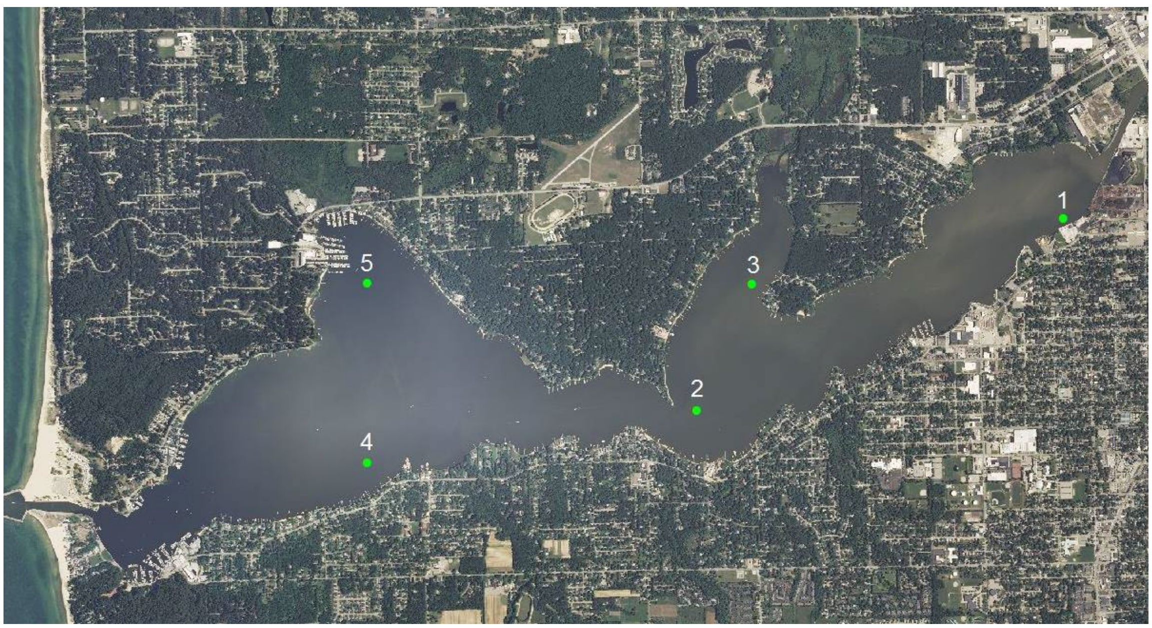


Figure 1. Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring.

2.3 Macatawa Watershed Phosphorus – Precipitation Analysis

P concentrations in water bodies are influenced by many variables, but one of the most significant is precipitation because rain and snow events create surface and subsurface runoff from farms and developed areas, which ultimately reach the downstream receiving waters (Baker et al. 2019). In addition, atmospheric deposition can contain significant amounts of P (cf. Brennan et al. 2016). Consequently, it is of interest to know if changes in lake P concentrations are related to precipitation, land use changes, or a combination of the two. This has been shown in the western basin of Lake Erie, where heavy spring rains transported recently applied P fertilizer into the Maumee River, and eventually Lake Erie, triggering massive harmful algal blooms (Michalak et al. 2013). Hence, years with anomalously good or bad lake condition may be driven largely by the timing of fertilizer application, tillage practices, and precipitation.

Sophisticated (i.e., computationally intensive) watershed models are often used for this kind of analysis, but developing those models was outside our scope of work. Rather, we took a coarse-level approach to look at how P concentrations in Lake Macatawa compared with precipitation amounts from the weather station at the West Michigan Regional Airport (formerly Tulip City Airport) in Holland using data from NOAA's National Centers for Environmental Information (NCEI, formerly the National Climatic Data Center). Linear regressions on P concentrations and precipitation amounts were conducted in Microsoft Excel. In Lake Macatawa, the relationship between lake TP and precipitation has not been clear-cut. Attempts in previous reporting years to analyze annual precipitation against annual mean TP resulted in trendless data with low statistical power (R^2<0.01, Hassett et al. 2024), likely because the annual data set contained so much seasonal variation. In order to control for that seasonal variation, we explored the relationship of Lake Macatawa TP and precipitation using shorter and more closely associated spans of time; daily precipitation from 2013-2024 was summarized into weeks and months of total precipitation prior to each specific sampling date as follows: 1 week, 2w, 3w, 4w (1 month), 2mo, 3mo, 4mo, 5mo, 6mo, 7mo, 8mo, 9mo, 10mo, 11mo, 12mo. Separately for each weekly or monthly summary, total precipitation was regressed against surface and bottom lake-wide average SRP and TP. In 2024, the combined annual data again resulted in trendless data, so annual data were separated into seasons with separate regressions composed of n=11 (spring) or n=12 (summer and fall) seasonal lake means. Outliers in seasonal datasets were identified and removed using multiple sequential Grubbs tests until no outliers were detected in the remaining data.

3. Results and Discussion

3.1 Sampling Year 2024

General water quality parameters followed expected trends for lakes across seasons (Table 2). Summer DO was stratified, with very low concentrations at the near-bottom of sites 1 and 4 (~0.3 mg/L). Bottom DO concentrations ranged from 6-8 mg/L in the Spring and were >8 mg/L in the fall at all sites (Fig. 2B). Surface DO concentrations increased westward, and were generally above 8 mg/L (Fig. 2A). Both surface and bottom DO concentrations in 2024 were similar to measurements made since 2013 (Fig. 3).

Multiyear LOWESS (locally weighted scatterplot smoothing) analysis of summer DO in near-bottom depth suggests that, although the lake was stratified, 2024 fairly typical of prior years; DO concentrations appear to be "leveling out" in the trendline over the past few years after a "peak" in 2018 (Fig. 4).

Mean specific conductivity was highest in spring, and then declined about 100 units in summer and fall (Table 2). TDS also was higher in spring than in summer and fall; turbidity was lowest in summer, which unexpectedly corresponded to the most shallow Secchi depth (Table 2). Normally, one would expect low turbidity to result in a deeper Secchi depth (greater clarity).

Surface and near-bottom SRP concentrations were highest in spring 2024 at all sites, with Site 1 having mean concentrations above 40 µg/L (Fig. 5A). This is likely associated with spring fertilizer applications on farms in the watershed. Means SRP concentrations declined at the remaining lake sampling sites, reflecting either rapid uptake or dilution, or a combination of the two. Mean SRP concentrations dropped below detection (<5 µg/L) in summer and fall, suggesting high biological demand, which is consistent with the high chlorophyll *a* concentrations in those two seasons (Table 3).

TP concentrations exceeded Lake Macatawa's 50 µg/L TMDL goal at all sites and depths with minimal seasonality and generally ranged 92-148 µg/L except for a Site 1 near-bottom spike of 272 µg/L in the spring (Table 3, Fig. 5C,D). These data reveal several important points: 1) the initial reductions in lake-wide TP appear to have stabilized and while there may be years when TP concentration drop further (e.g., during drought conditions), overall the watershed is still contributing significant amounts of phosphorus to Lake Macatawa; 2) the spring increase in SRP but not TP suggest that producers should continue to adopt best practices to limit soluble nutrient runoff; and 3) the role of internal nutrient loading (i.e., P from the sediments) is not well-resolved; if internal phosphorus loading was playing a major role, one would expect the highest TP concentrations to occur during the very low DO periods in summer at sites 1 and 4, but there is no evidence of that. Internal P loading can occur in a variety of ways (Steinman and Spears 2020), so it is possible that P diffusion from sediments during low DO conditions is a less important mechanism in Lake Macatawa than resuspension of sediments, in which case there may be a consistent, low-level release of P from continuously resuspended sediment.

Chl *a* trends were inversely related to SRP, with low concentrations in the spring resulting in a lakewide average meeting the lakewide TMDL goal of 22 µg/L (Table 3, Fig. 5E,F). However, chl *a* concentrations sharply increased at all sites and depths in summer and fall, reaching as high as 105 µg/L at site 2 (Table 3, Fig. 5E,F). Likewise, mean surface microcystin concentrations were below detection in the spring, increased to a lakewide mean of 0.94 µg/L in summer, and then nearly tripled to 3.44 µg/L in fall (Table 3). This trend of increasing microcystin concentrations over the sampling season is of potential concern but is still below the US EPA threshold of 8 µg/L; the trend is also very similar to what we measured in 2024 in White Lake, just 8 miles north of Bear Lake (Steinman et al. 2024).

NO_3^- concentrations varied seasonally and were highest in summer, but remained <1.7 mg/L at all sites lake-wide (Table 3, Fig. 6A,B). NH_3 remained ≤1 mg/L throughout the year, except for site 1 which spiked to 2 mg/L at both sampling depths in spring (Table 3, Fig. 6C,D). TKN averaged 2 mg/L in spring and fall and dropped to <1 mg/L in summer (Table 3, Fig. 6E,F). TKN measures both ammonia and organic nitrogen; given that the TKN concentrations were approximately 2× to 5× those of ammonia in Lake Macatawa, it is apparent that there is a sizeable amount of organic N in the system, especially in the fall. It is unclear if this derives from decomposing organic matter (e.g., leaf litter or unharvested matter) and if it is playing an ecological role in the lake. A prior study showed that benthic algal growth in Lake Macatawa was co-limited by both nitrogen and phosphorus (Steinman et al. 2016).

Table 2. Lake-wide means (1 SD) of select general water quality parameters recorded during 2024 monitoring year. Data are shaded for readability. Dates of sampling events: 5/23/2024; 7/18/2024; 10/24/2024. "n" is the number of lake sites composing the seasonal mean at each depth.

Season	Depth	n	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (FNU)	Secchi Depth (m)
Spring	Surface	5	20.92 (0.82)	8.40 (1.16)	607 (91)	0.395 (0.059)	10.0 (2.2)	0.8 (0.1)
	Middle	5	20.54 (0.86)	7.74 (0.98)	608 (95)	0.395 (0.062)	13.0 (6.0)	
	Bottom	5	20.01 (1.34)	6.80 (0.91)	599 (112)	0.390 (0.073)	20.1 (10.6)	
Summer	Surface	5	23.98 (1.01)	9.63 (0.49)	503 (71)	0.327 (0.046)	8.9 (1.7)	0.5 (0.1)
	Middle	5	23.62 (1.04)	7.85 (2.04)	499 (73)	0.324 (0.047)	9.2 (2.3)	
	Bottom	5	20.97 (3.59)	3.68 (3.37)	444 (63)	0.289 (0.041)	10.7 (2.8)	
Fall	Surface	5	14.67 (0.27)	9.61 (0.21)	513 (78)	0.334 (0.051)	17.3 (3.3)	0.6 (0.0)
	Middle	5	14.59 (0.20)	9.16 (0.25)	514 (80)	0.334 (0.052)	17.7 (3.5)	
	Bottom	5	14.51 (0.17)	8.73 (0.46)	515 (79)	0.335 (0.051)	19.7 (3.1)	

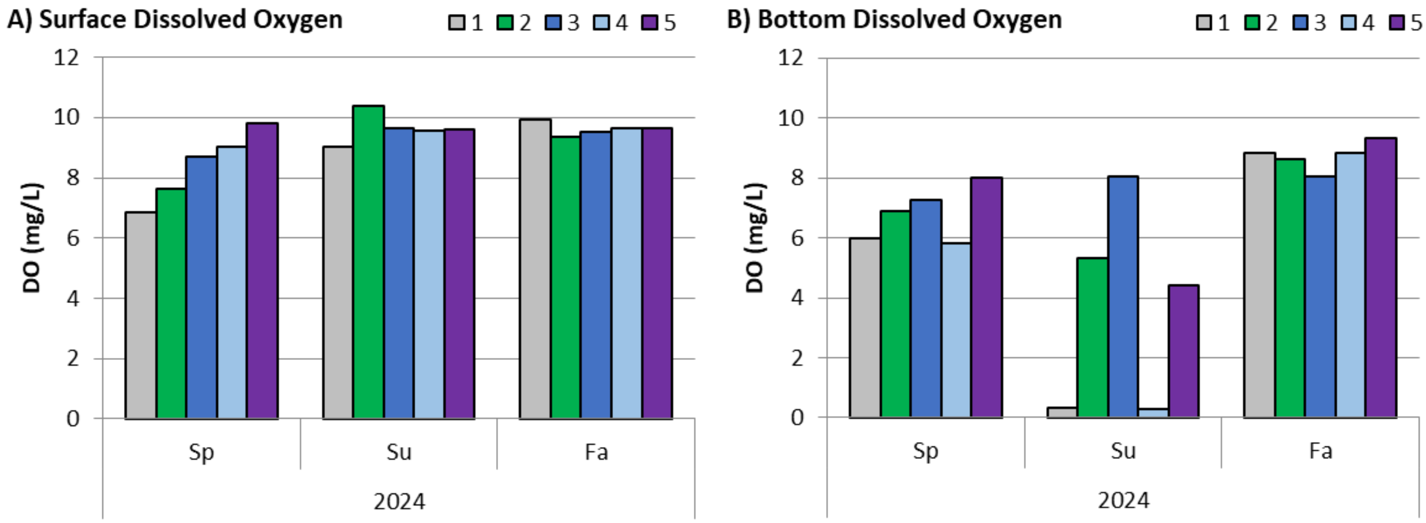
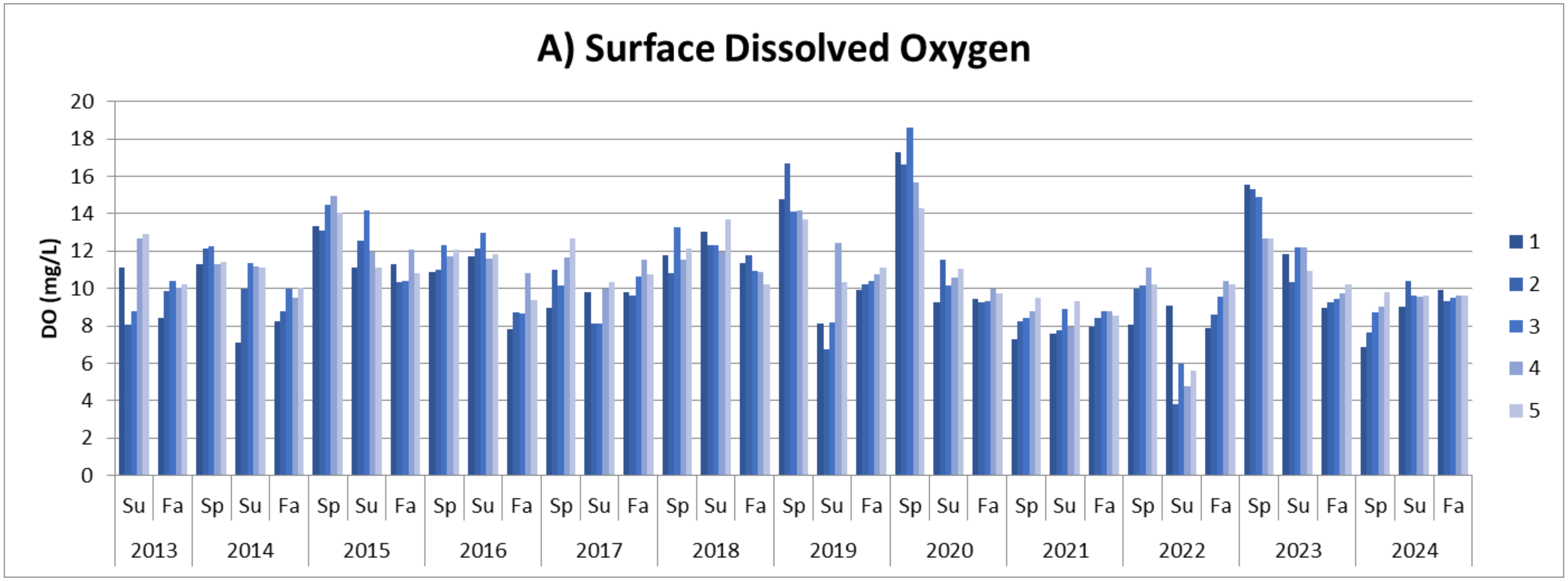


Figure 2. Dissolved Oxygen: A) surface; B) near-bottom concentrations measured at the 5 monitoring stations in Lake Macatawa during 2024.



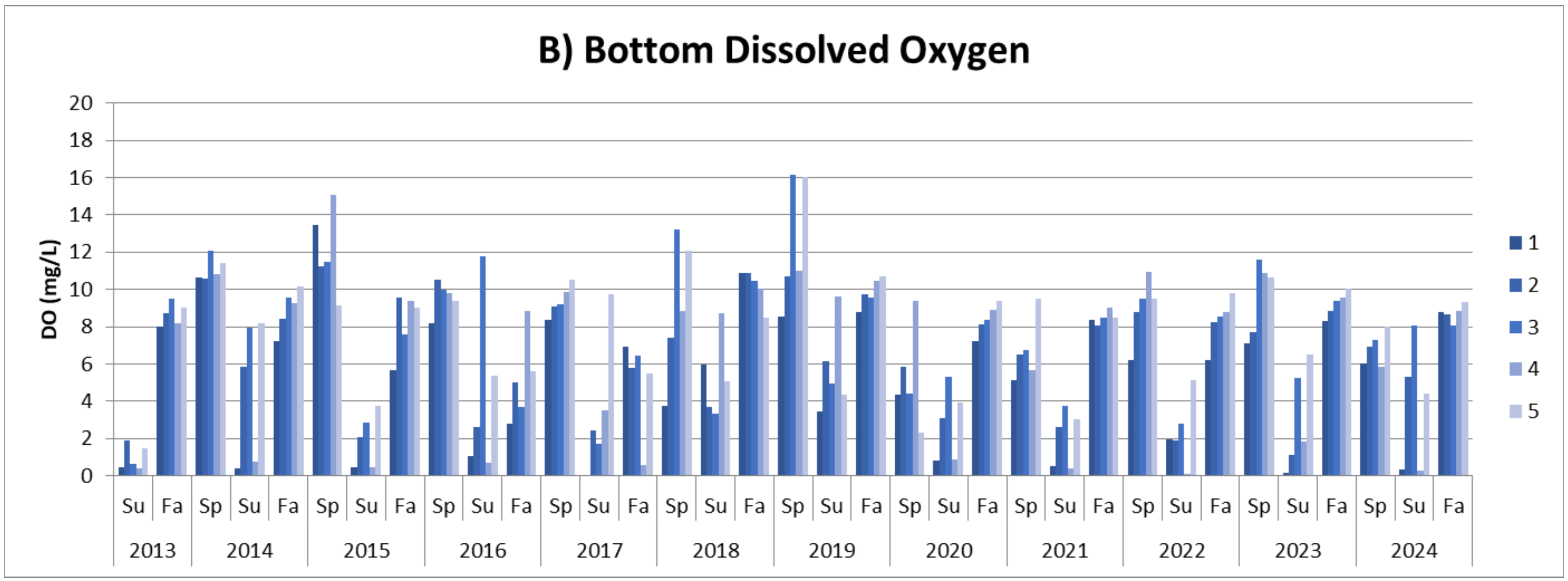


Figure 3. Dissolved Oxygen: A) surface; B) near-bottom concentrations measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2024.

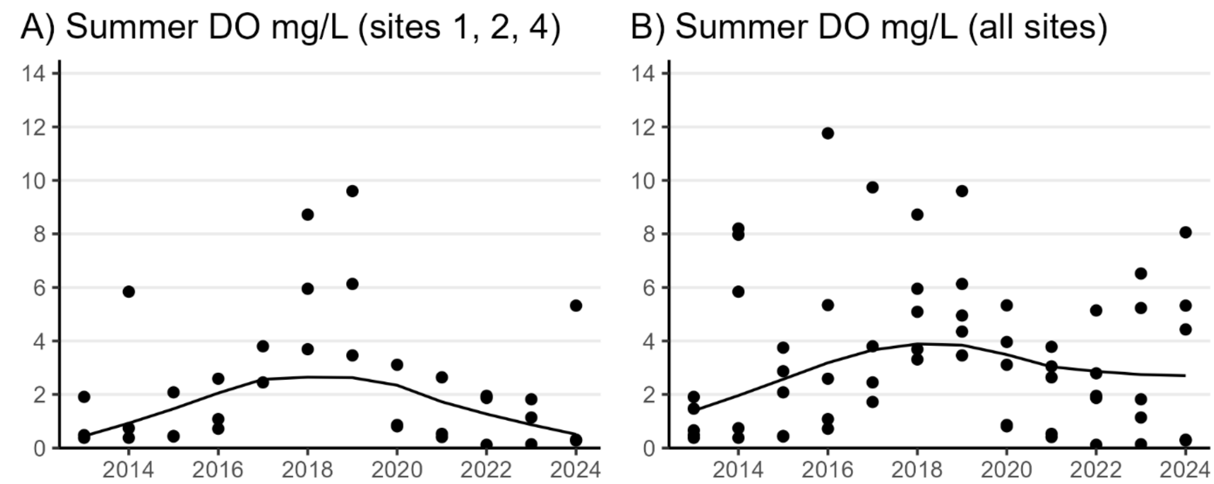


Figure 4. Locally weighted scatterplot smoothing (LOWESS) trend analyses of bottom summer DO site data from Lake Macatawa. A) Sites 1, 2, and 4 represent the main flow of Lake Macatawa via the Macatawa River watershed. B) All 5 sites, including the lake's northern Big Bay and Pine Creek Bay.

Table 3. Lake-wide means (1 SD) of phosphorus (soluble reactive phosphorus [SRP] and total phosphorus [TP]), nitrogen (nitrate [NO_3^-], ammonia [NH_3] and Total Kjeldahl Nitrogen [TKN]), and laboratory extracted chlorophyll *a* (chl *a*) measured during 2024 monitoring year. Data are shaded for readability. See Table 2 for dates of sampling events. Note different units for the analytes. "n" is the number of lake sites composing the seasonal mean at each depth. MCs = microcystins; BD = below detection.

Season	Depth	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)	ext. Chl (µg/L)	MCs (µg/L)
Spring	Top	5	17 (15)	87 (25)	0.85 (0.21)	0.81 (0.71)	2.05 (0.76)	22 (8)	BD (NA)
	Bottom	5	20 (11)	131 (81)	0.83 (0.27)	0.82 (0.75)	1.91 (1.06)	14 (7)	BD (NA)
Summer	Top	5	3 (0)	91 (29)	1.16 (0.49)	0.33 (0.17)	1.09 (0.16)	79 (18)	0.94 (0.29)
	Bottom	5	3 (1)	100 (17)	0.79 (0.42)	0.40 (0.17)	0.81 (0.15)	53 (23)	0.77 (0.31)
Fall	Top	5	3 (1)	116 (18)	0.46 (0.24)	0.39 (0.42)	2.08 (0.77)	76 (10)	3.44 (0.37)
	Bottom	5	3 (0)	121 (22)	0.49 (0.22)	0.43 (0.42)	2.08 (0.61)	80 (9)	3.29 (0.35)

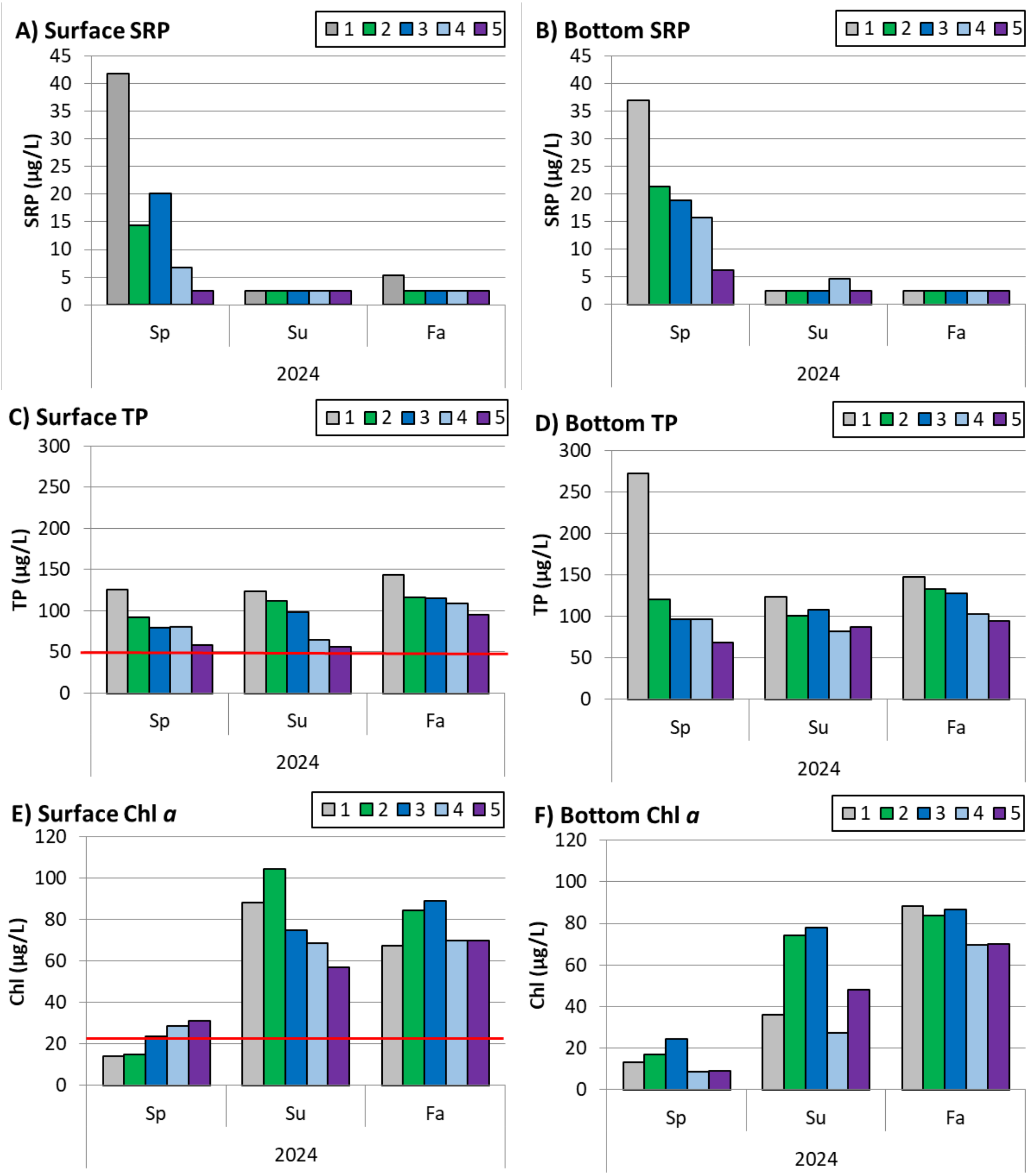


Figure 5. Soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); and chlorophyll *a* ([chl *a*]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2024. The red horizontal line on surface TP (C) indicates the interim total maximum daily load (TMDL) goal of 50 µg/L (Walterhouse 1999). The red horizontal line on surface chl *a* (E) indicates the hypereutrophic boundary of 22 µg/L used by EGLE for assessing chl *a* in Lake Macatawa (Holden 2014). Note scales change on y-axes.

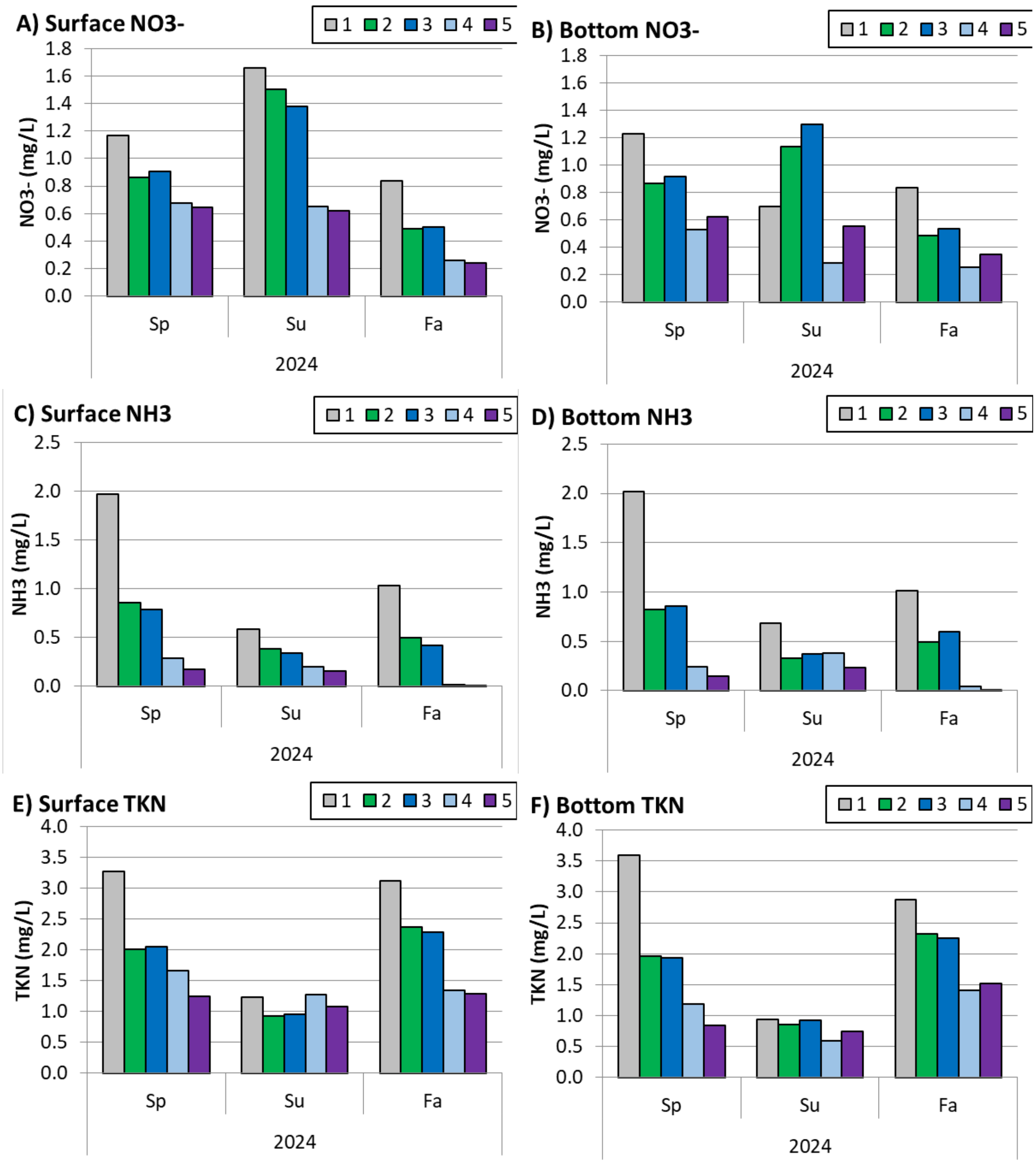


Figure 6. Nitrate ([NO_3^-]: A, B); ammonia ([NH_3]: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2024. Note scales change on y-axes.

3.2 Pre- vs. Post-Restoration Comparison

As noted in prior reports, it is likely that it will take a considerable period of time before lake water quality responds on a consistent basis to actions taken in the watershed. This is because lakes have a built-in resistance to change (cf. Abell et al. 2020) due to their relatively long hydraulic residence time (pollutants don't leave quickly), the quantity and location of implemented management actions in the watershed (cf. Fales et al. 2016, Steinman et al. 2018), and the potential importance of sediments as a source of nutrients to the lake (Steinman and Spears 2020). Given that watershed-based management changes are both relatively recent and of a modest scale in the Macatawa watershed, it was not expected that Lake Macatawa water quality would respond quickly. Nonetheless, the lack of progress, especially in phosphorus concentrations, suggests that the improvements have stabilized, and additional measures may be needed to meet the TMDL.

SRP concentrations in summer and fall 2024 are comparable to previous years. Spring concentrations were elevated compared to the past several years, although this spike was modest (<50 μg/L) compared to Lake Macatawa's historical highs (~150 at surface or ~225 μg/L at near-bottom; Table 4, Fig. 7). TP in 2024 was generally in line with past sampling results, though similarly to SRP, spring TP concentrations were higher than those of past springs, including a spike at site 1 near-bottom (272 μg/L; Table 4, Fig. 8). Chl *a* continued to be highest in summer and fall and consistently exceeded lake goals (Table 4, Fig. 9A,B). Water clarity backslid in 2024 compared to prior years, and has generally worsened since 2021(Table 4, Fig. 9C).

No pre-restoration data exists for any of the nitrogen forms measured in this study (nitrate, ammonia, TKN), but trends can still be qualitatively evaluated for change over time. Unlike most previous years, nitrate concentrations in 2024 increased from spring to summer (Table 4, Fig. 10). The 2024 ammonia and TKN concentrations were generally in line with trends from prior years, though spring levels were somewhat higher than those of previous spring sampling events (Table 4, Figs. 11-12).

We also compared the three years of pre-restoration water quality data dates (summer 2013 – fall 2015) with an equal and seasonally corresponding number of the most recent post-restoration sampling dates (summer 2022 – fall 2024) to assess changes over time (Fig. 13). SRP post-restoration remains significantly greater than the pre-restoration at both depths (Fig. 13A, B). Mean TP and chl *a* (which showed a significant improvement from pre-restoration condition as recently as 2022) continues a trend from 2023 to show no significant differences between pre- and post-restoration monitoring periods (Fig. 10C-F). Water clarity as measured by Secchi disk depth has worsened (become more shallow) and is statistically not different in 2024 for pre- vs post-restoration due in part to high chl concentrations (Fig. 13G).

Table 4. Lake-wide grand means (1 SD) of phosphorus concentrations (soluble reactive phosphorus [SRP] and total phosphorus [TP]), laboratory extracted chlorophyll *a* (chl *a*), and Secchi disk depths measured during multi-year project history. Grand mean cells have two rows per cell: data in the top row represent pre-restoration sampling (Summer 2013 – Fall 2015) and data in bottom row represent post-restoration sampling (Spring 2016 – Fall 2024). ND = no data.

Season	Depth	Period	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)	ext. Chl (µg/L)	Secchi Depth (m)
Spring	Surface	Pre	2	3 (0)	66 (4)	ND	ND	ND	25 (4)	0.6 (0.1)
		Post	9	13 (17)	96 (49)	1.24 (0.44)	0.34 (0.29)	1.84 (0.31)	49 (27)	0.7 (0.3)
	Bottom	Pre	2	3 (1)	98 (30)	ND	ND	ND	24 (3)	
		Post	9	13 (17)	99 (52)	1.16 (0.44)	0.48 (0.31)	1.72 (0.48)	34 (15)	
Summer	Surface	Pre	3	6 (3)	110 (66)	ND	ND	ND	67 (39)	0.4 (0.1)
		Post	9	13 (20)	94 (46)	0.55 (0.65)	0.32 (0.14)	1.51 (0.34)	68 (29)	0.7 (0.2)
	Bottom	Pre	3	17 (18)	107 (49)	ND	ND	ND	32 (13)	
		Post	9	21 (29)	105 (51)	0.45 (0.48)	0.51 (0.24)	1.47 (0.50)	36 (16)	
Fall	Surface	Pre	3	10 (12)	134 (23)	ND	ND	ND	63 (43)	0.4 (0.1)
		Post	9	7 (4)	81 (19)	0.99 (0.71)	0.42 (0.20)	1.54 (0.36)	53 (23)	0.6 (0.1)
	Bottom	Pre	3	11 (13)	158 (19)	ND	ND	ND	61 (35)	
		Post	9	14 (15)	92 (19)	1.04 (0.72)	0.37 (0.22)	1.45 (0.39)	47 (17)	

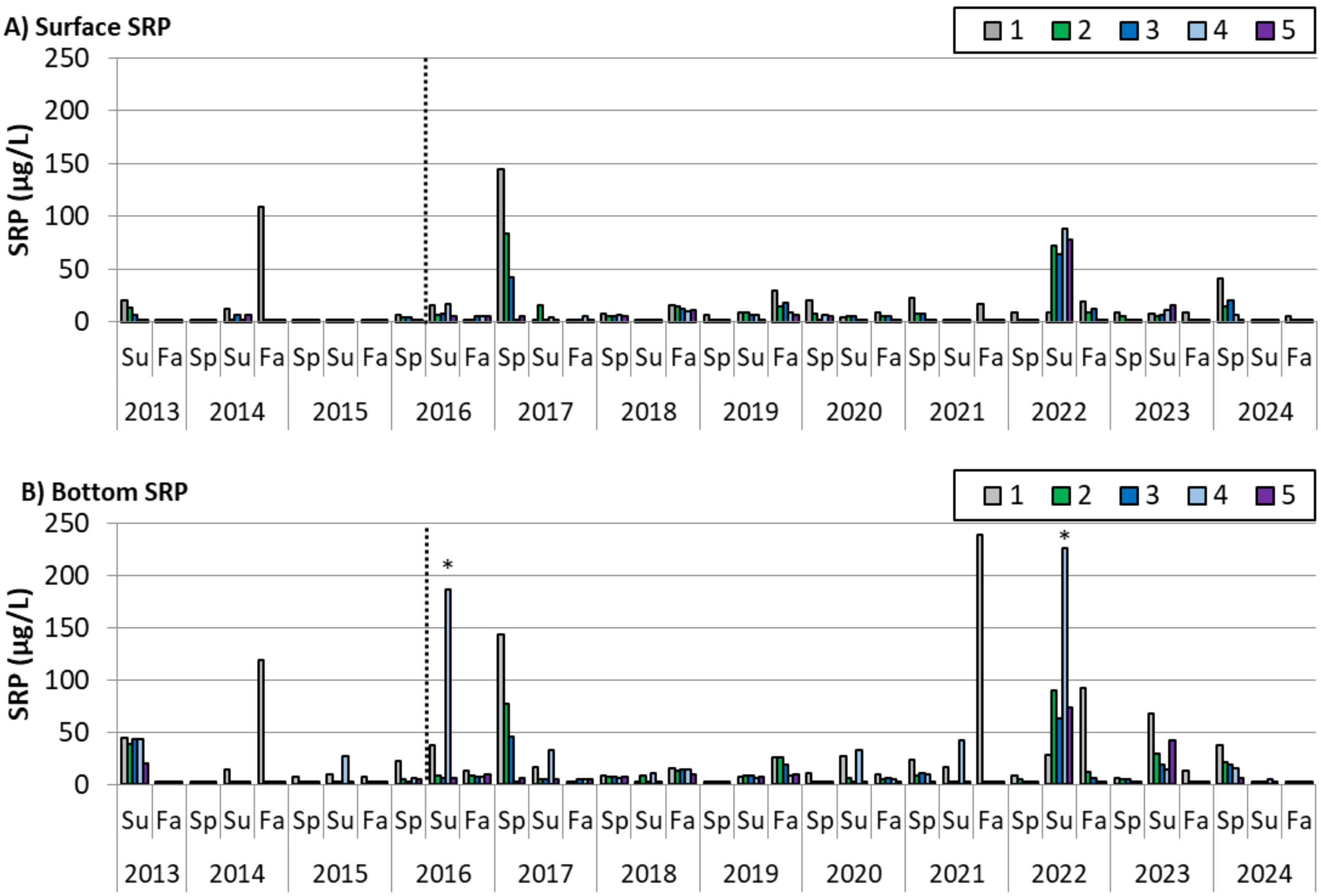


Figure 7. Soluble reactive phosphorus (SRP) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2024. Vertical dotted lines represent approximate restoration construction completion dates for Middle Macatawa and Haworth wetlands. Asterisks in bottom SRP figure indicate possible outliers due to sediment disturbance.

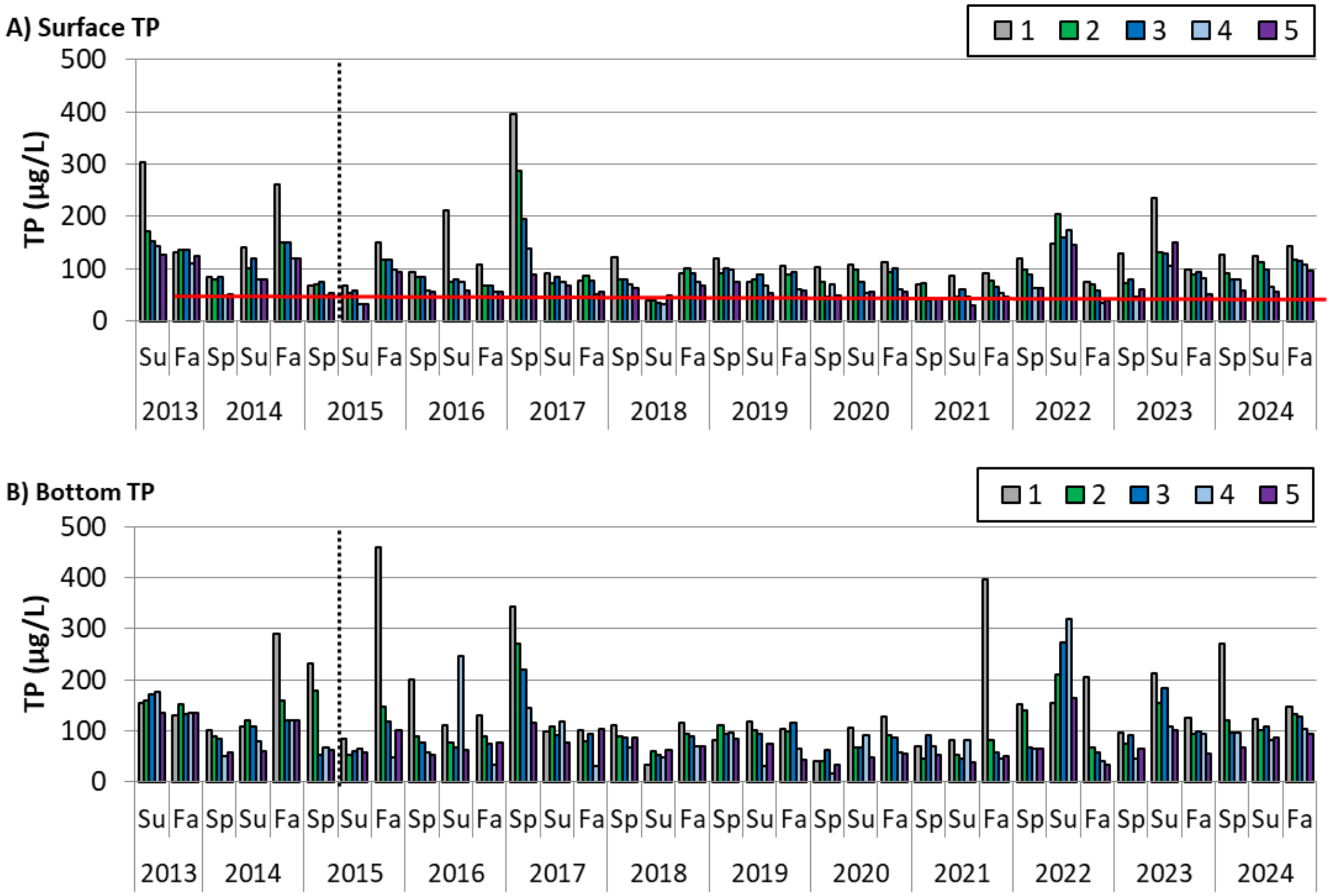


Figure 8. Total phosphorus (TP) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2024. The red horizontal lines on surface TP (A) indicate the interim total daily maximum load (TMDL) goal of 50 µg/L (Walterhouse 1999). Vertical dotted lines represent approximate restoration construction completion dates for Middle Macatawa and Haworth wetlands.

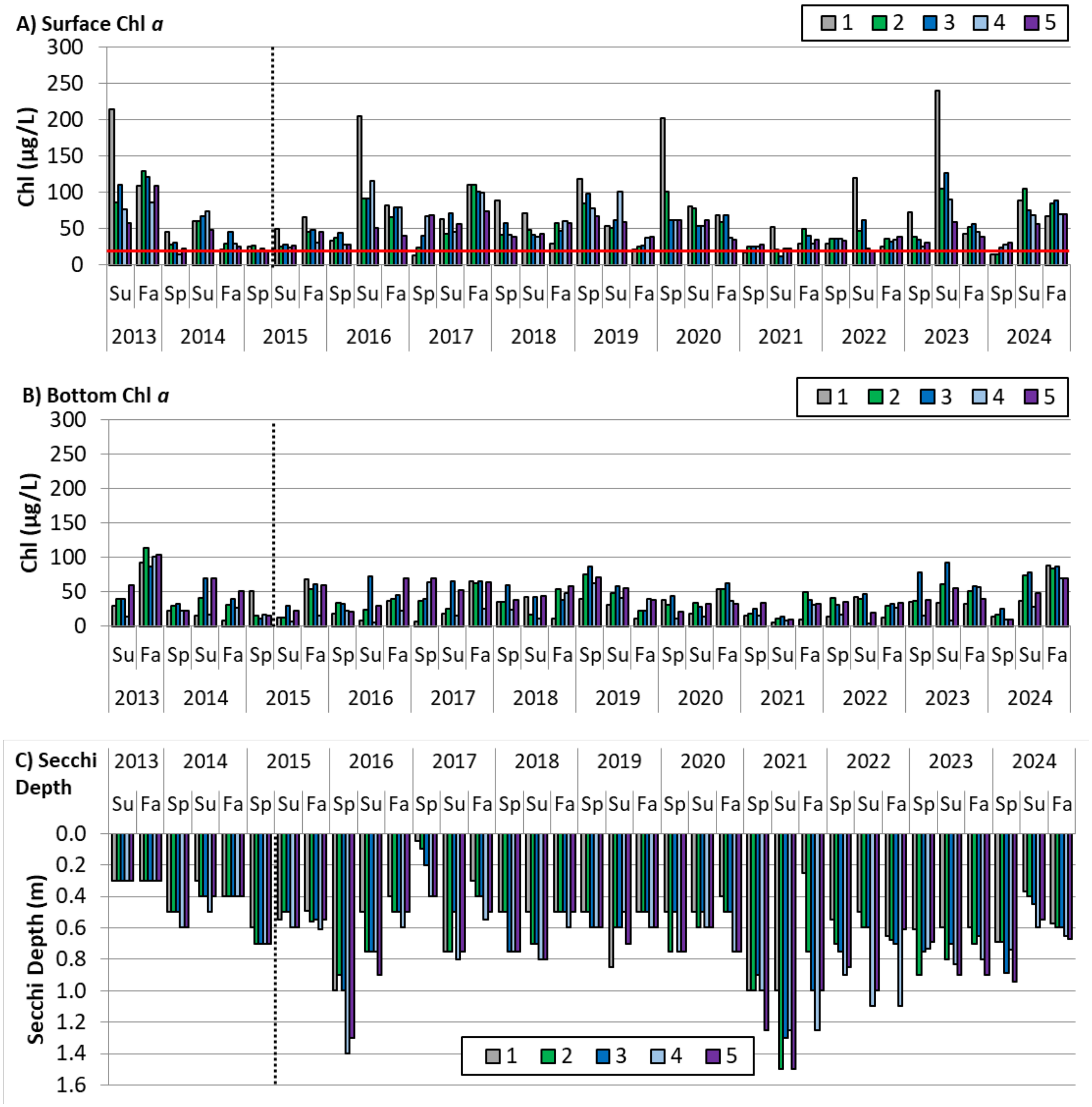


Figure 9. Chlorophyll *a* ([chl *a*]: A, B); and Secchi disk depth: (C) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2024. The red horizontal line on surface chl (A) indicates the hypereutrophic boundary of 22 µg/L used by EGLE to assess chl *a* in Lake Macatawa (Holden 2014). Note scales change on y-axes. Vertical dotted lines represent approximate restoration construction completion dates for Middle Macatawa and Haworth wetlands.

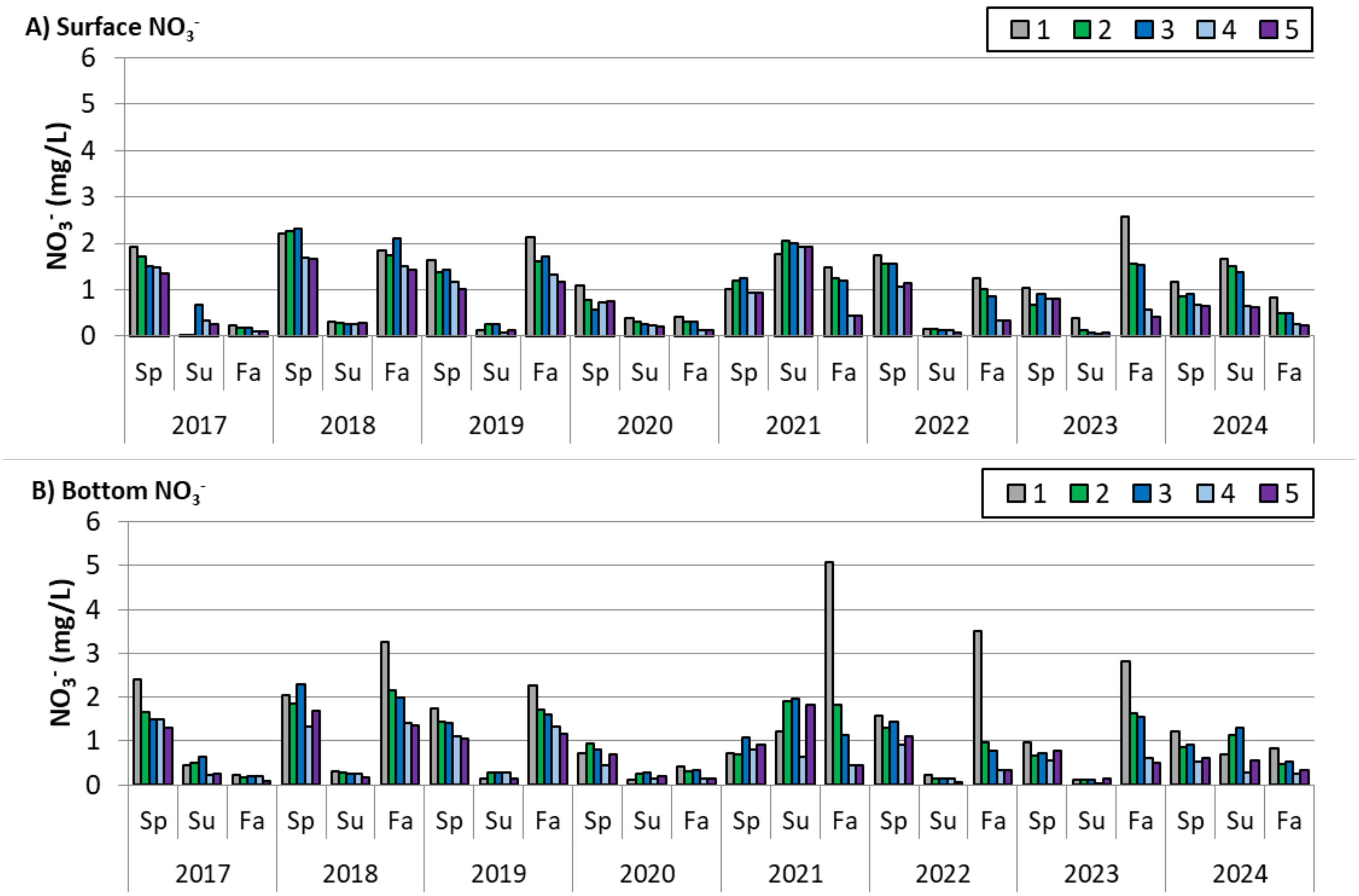


Figure 10. Nitrate (NO_3^-) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2017 through 2024. Note scales change on y-axes.

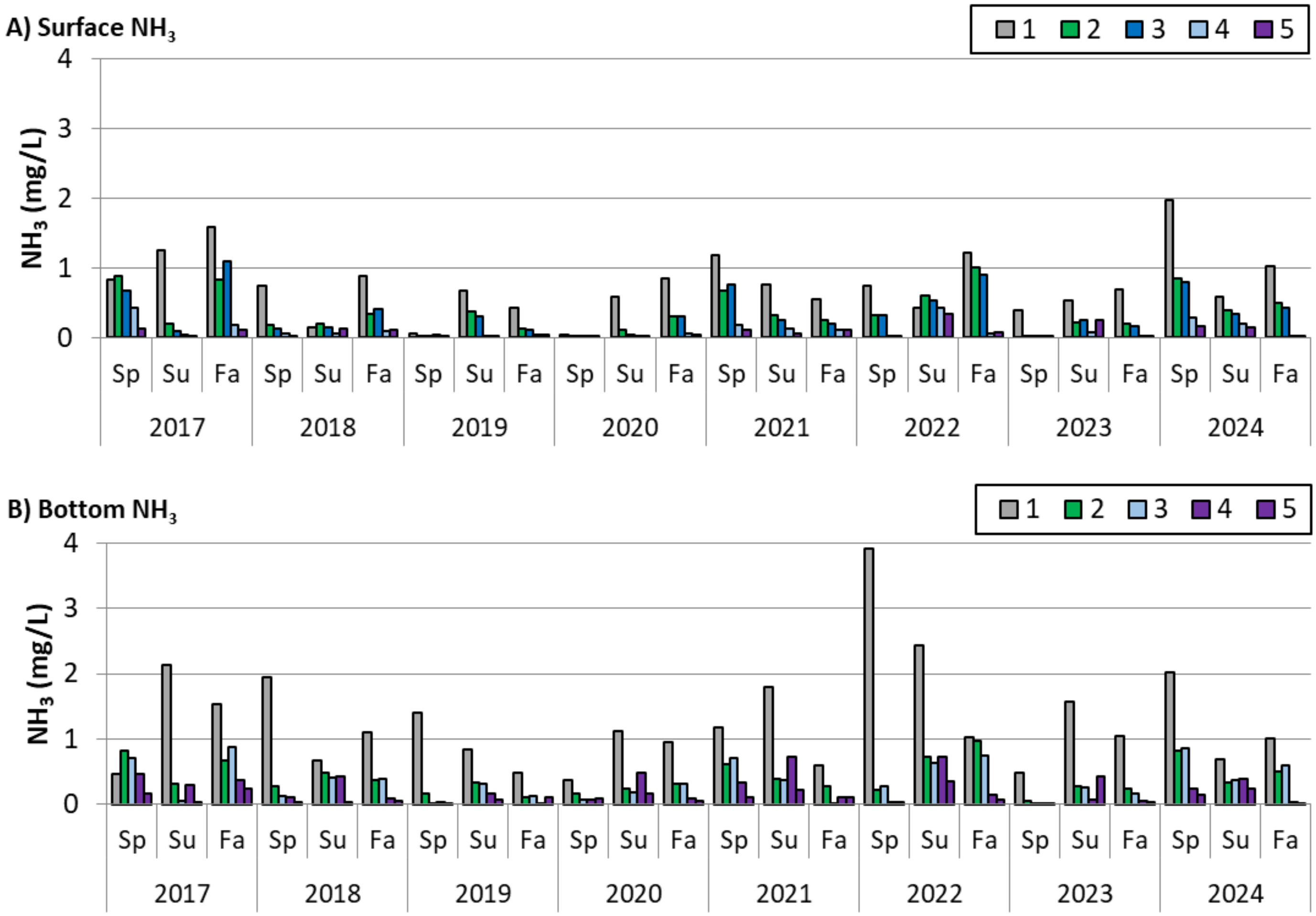


Figure 11. Ammonia (NH_3) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2017 through 2024. Note scales change on y-axes.

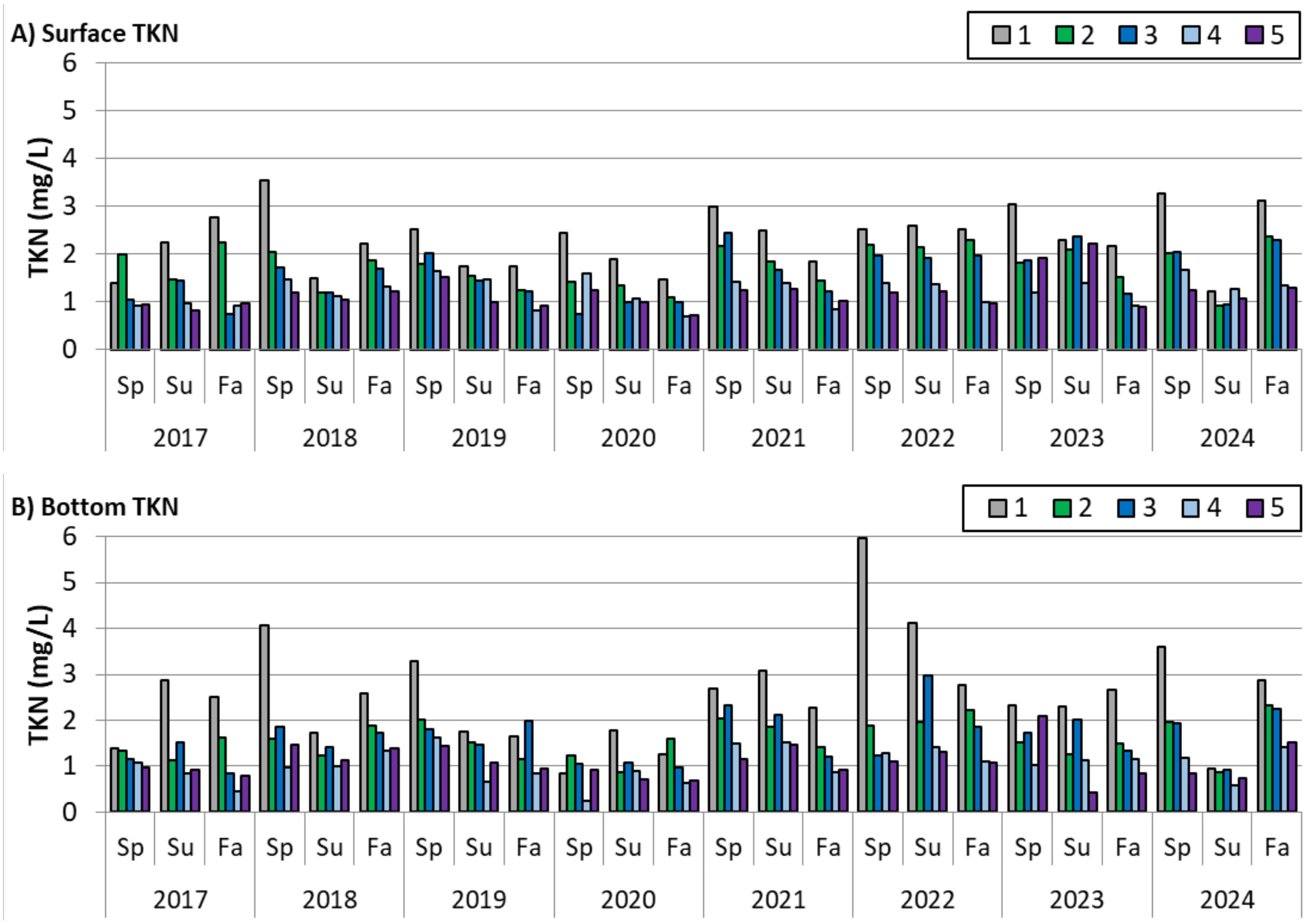


Figure 12. Total Kjeldahl Nitrogen (TKN) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2017 through 2024. Note scales change on y-axes.

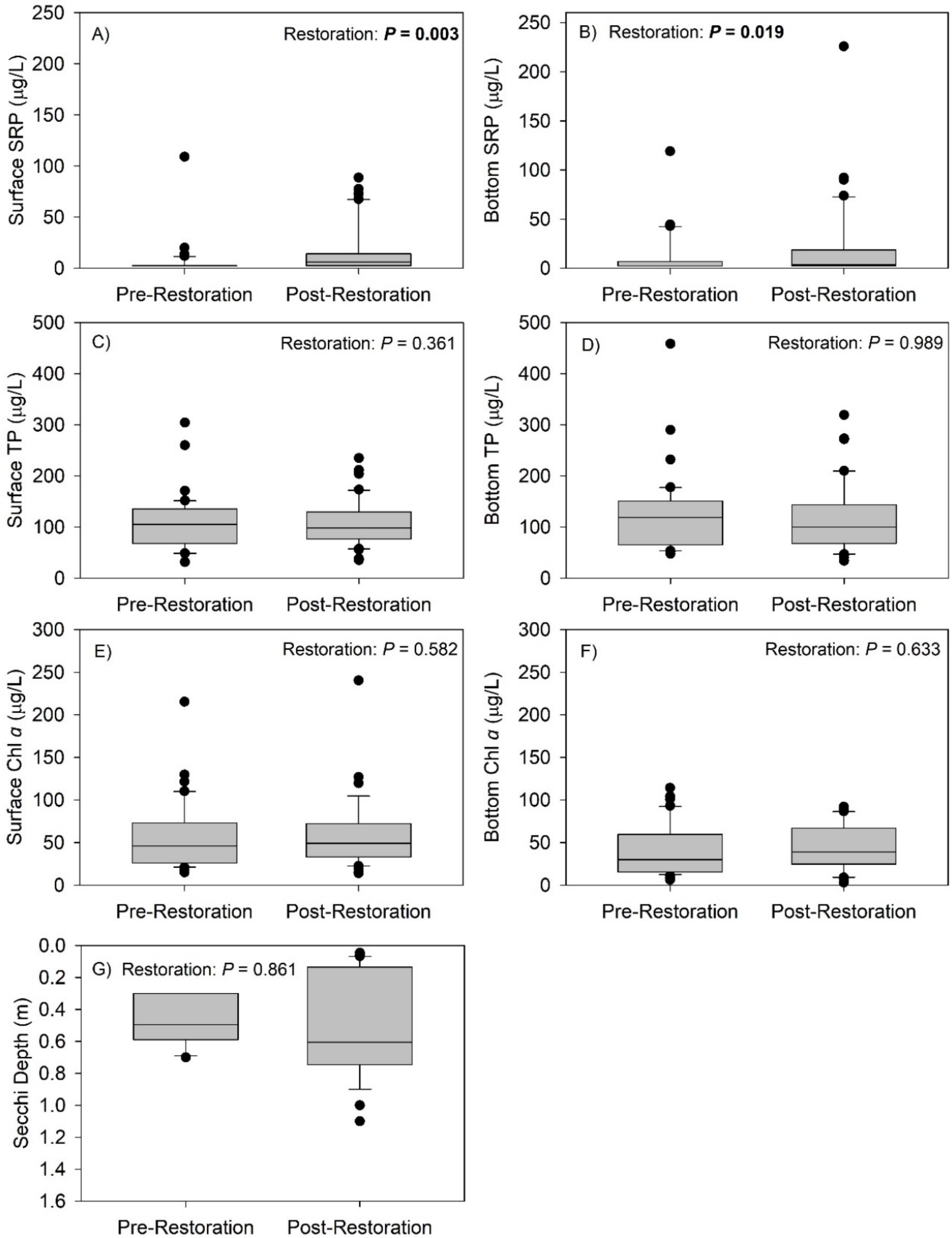


Figure 13. Box plots of soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); chlorophyll *a* ([chl *a*]: E, F; and Secchi disk depth: G) levels measured at the 5 monitoring stations in Lake Macatawa during all pre-restoration sampling dates (summer 2013 – fall 2015) and an equal and seasonally corresponding number of post-restoration sampling dates (summer 2022 – fall 2024). Boxes represent the middle 50% of data; the horizontal line crossing the box is the median data value; whiskers represent the upper 25% and lower 25% of data, excluding outliers; points outside of the box and whiskers are considered outliers. Note scales change on y-axes.

3.3 Lake Macatawa Precipitation-Phosphorus Relationship

Phosphorus (and nitrogen) concentrations in lakes are heavily influenced by precipitation because rain and snow events result in runoff from the watershed, transporting phosphorus that is either dissolved or attached to sediment particles. Therefore, it is of interest to know if annual changes in lake phosphorus are related to precipitation.

The best-fit precipitation periods determined in previous years' analyses (Hassett et al. 2024) for surface SRP and TP values were updated to incorporate and separate data by sampling season, which were then regressed upon precipitation totals in the period preceding each sampling event that resulted in the best statistical fit for the data, ranging from 2 weeks to 8 months. Results varied but identified strongly significant relationships between precipitation and spring TP (R^2=0.53, P=0.017), summer TP (R^2=0.48, P=0.012), and fall SRP (R^2=0.76, P<0.001; Figure 14).

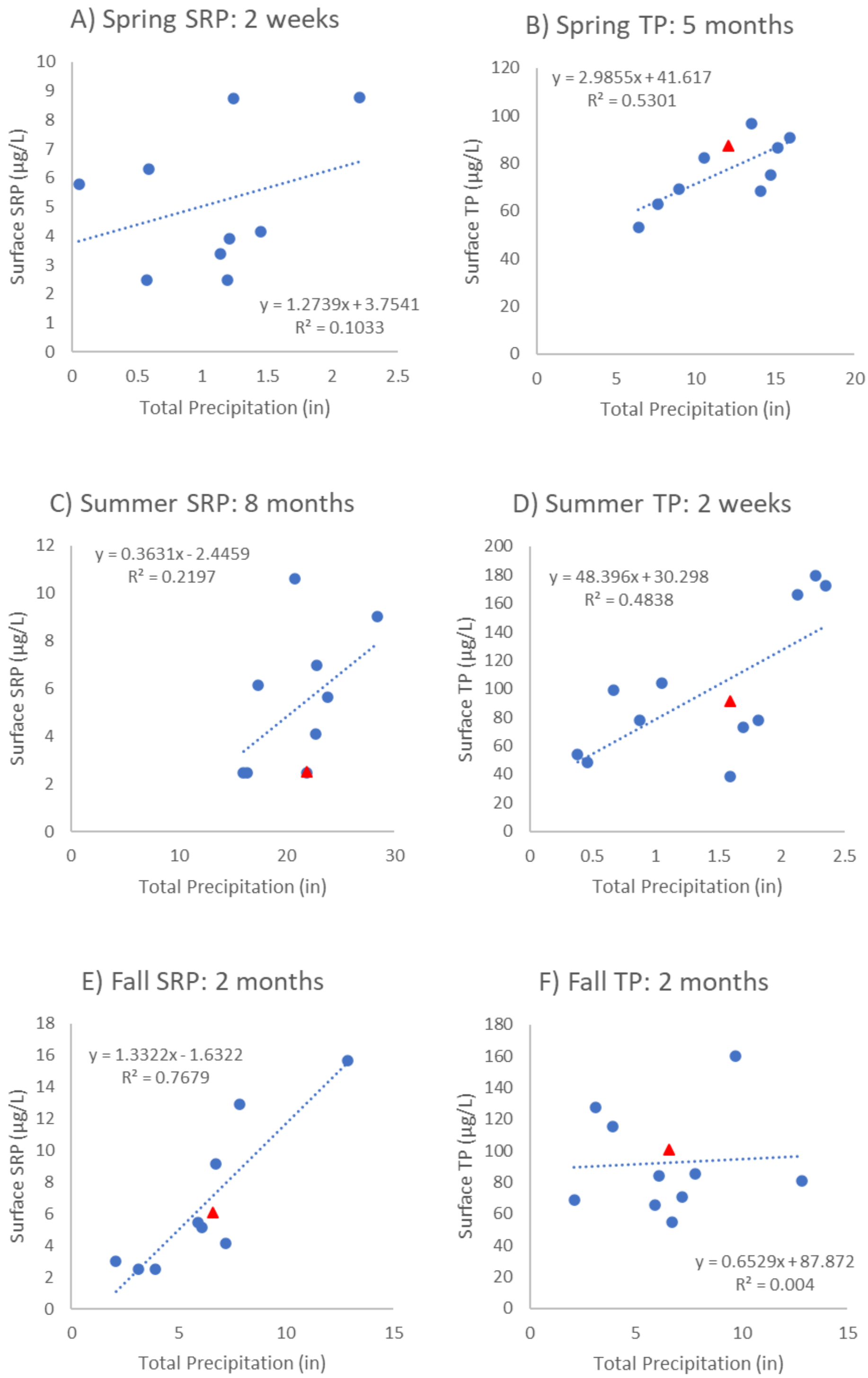


Figure 14. Linear regressions plotting total precipitation vs. mean soluble reactive phosphorus (SRP; panels A, C, E) and total phosphorus (TP, panels B, D, F) concentrations seasonally in Lake Macatawa. Surface SRP and TP data are lake-wide means of seasonal 2013-2024 AWRI sampling events. Precipitation data sources were provided by the National Climatic Data Center/National Centers for Environmental Information (2013-2024; NOAA). Note that y-axes and best-fit time frames vary between panels. Red triangles represent 2024 data (no 2024 data for Fig. 14A).

4. Summary

Over the past 11 years following the initiation of Project Clarity, there has been a tremendous amount of work undertaken in the watershed to restore the system including the implementation of various best management practices and education of stakeholders regarding the Macatawa watershed. These activities have collectively improved water quality in the local regions where the projects have been completed, increased community appreciation for the natural resources in their watershed, and resulted in economic benefits to the region. However, positive impacts to Lake Macatawa's water quality have been less evident, which is often the case, as there can be a significant lag time between restoration projects and water quality improvement (Sas 1990).

The 2024 water quality data show little or no improvement from the previous few years, suggesting that conditions may have plateaued in Lake Macatawa. Indeed, a statistical comparison of water quality for the 3-year time periods before (2011-2013) and after (2022-2024) implementation of Project Clarity indicates no significant improvement; the only significant difference was an *increase* in bioavailable phosphorus concentration in the lake. Total phosphorus concentrations remain at ~100 µg/L and chlorophyll *a* concentrations at ~50 µg/L, levels indicative of substantially impaired waters. On the positive side, mean water clarity improved slightly and despite the high algal biomass, cyanotoxin concentrations remain below the EPA threshold for recreational water usage.

As we have cautioned previously, any one year's data should be viewed with caution, especially with only 3 sampling dates per year. The installation of a lake observatory, which can take water quality readings on a continuous basis throughout the day, will greatly enhance our understanding of temporal changes in Lake Macatawa. Although the spatial coverage of the observatory is limited, any major lake-wide changes will be detected. This type of instrumentation complements the 6-station, long-term monitoring program in Muskegon Lake (https://www.gvsu.edu/wri/buoy/) and similarly, will provide a more robust picture of Lake Macatawa water quality in the future.

The appendices include the Lake Macatawa dashboard (Appendix A) and results from the long-term fish monitoring study on Lake Macatawa (Appendix B).

The Lake Macatawa Dashboard (Appendix A) provides a visual option for quickly surveying how critical water quality parameters (total phosphorus, chlorophyll *a*, and water clarity) are changing over time and responding to restoration efforts in the watershed. Mean conditions show limited to no improvement, and remain indicative of a highly impaired lake.

The long-term fish monitoring (Appendix B) work notes that after 10 years of fish monitoring, there are both positive and negative indicators of Lake Macatawa's ecological health. The fish assemblage data in Lake Macatawa are generally reflective of poor water quality, especially compared to the long-term fish data from Muskegon Lake. There has been little evidence of a change in the fish composition over the past decade based on strictly observational comparisons. A more rigorous analysis is beyond the scope of current funding, but may be revealing. More details on fish composition are provided in the Appendix.

We conclude with a list of observations/recommendations:

- The installation of a monitoring observatory in in 2025 will provide near real-time data on a continuous basis throughout the time it is deployed. These data will complement the long-term monitoring at 5 sites in the lake, providing a much more robust understanding of lake water quality. Of particular interest will be changes in dissolved oxygen, which influences fish distribution and phosphorus biogeochemistry, and chlorophyll *a*, which will help resolve short-term changes in algal biomass.

• We recommend greater utilization of the SWAT model (Iavorivska et al. 2021) developed for the Lake Macatawa watershed to identify agricultural management options. In addition, continued discussions with MDARD for funding to optimize iron slag filters and an experimental “watershed” are encouraged.

• The current monitoring program does not analyze two important biotic components in the lake: algal taxonomic composition, and aquatic vegetation cover, biomass, and taxonomic composition. The phytoplankton community structure can provide important information on water quality and algal species composition can serve as an early warning sign for the onset of cyanobacteria species capable of forming cyanotoxins. Aquatic vegetation provides critical habitat for fish and wildlife, stabilizes lake sediments, and takes up nutrients in the lake. In addition, it is important to know if invasive vegetation is developing in the lake so it can be quickly controlled. If funding is available, we recommend that consideration be given to plant surveys and phytoplankton identification in the future.

• There is still uncertainty about the role of sediments as a source of phosphorus; the 2024 data are inconclusive regarding the importance of internal nutrient loading in Lake Macatawa. The observatory data should provide useful information and at some point in the future, a rigorous analysis of internal nutrient loading from sediments in Lake Macatawa should occur, as well as the development of a comprehensive nutrient budget.

• Finally, we are pleased to see that the feasibility of a public works program, designed to treat phosphorus in Macatawa River inflow before it enters Lake Macatawa, is being explored. Our 2024 data indicate water quality improvements have stabilized and additional measures are needed to reach the TMDL level. A modeling study on the watershed indicated that to achieve the 50 µg/L TMDL-mandated TP concentration in the lake, adoption of almost all BMPs (i.e., continuous no-till with high residue; cover crops, filter strips, conversion of some crops to perennial grasslands) across 100% of the watershed’s row crop land would be needed (Iavorivska et al. 2021); this is not a viable option. A chemical treatment facility certainly has limitations—cost of construction, operation, and maintenance—as well as concerns over treating the symptom, not the disease. These factors should be weighed against its efficacy and what stakeholders value most highly as part of any feasibility study.

5. Acknowledgements

Funding was provided through Project Clarity funds; our thanks to Travis Williams, Dan Callam, David Nyitray, and Kelly Goward of ODC for their help and knowledge of the area, as well as the other partners of Project Clarity including Steve Bulthuis and Rob Vink formerly of MACC, Todd Losee and Steve Niswander of Niswander Environmental, and Dr. Aaron Best, Sarah Brokus, Randy Wade, Carolyn Cooper, Ben Turner, Natalie Huisman, and Lauren Cribbs of Hope College.

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7. Appendices

Appendix A. Lake Macatawa Dashboards

Appendix B. Long-Term Fish Monitoring of Lake Macatawa

Appendix A. Lake Macatawa Dashboards

Lake Macatawa Water Quality Dashboard

2024

Prepared: January 2025

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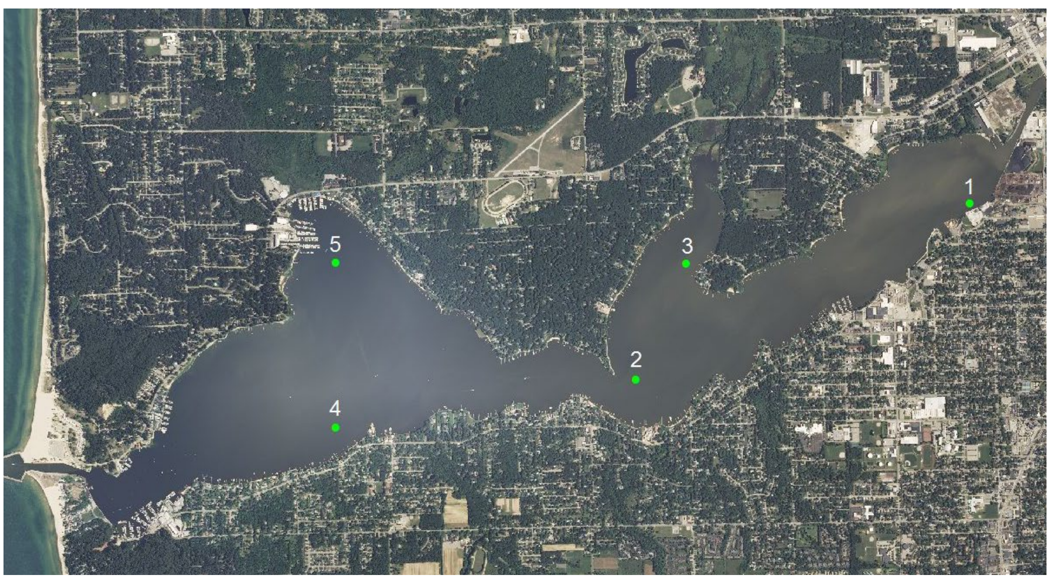
Introduction

As part of Project Clarity, Grand Valley State University's Annis Water Resources Institute (AWRI) established a monitoring program on Lake Macatawa in 2013. The goal of the monitoring program is to evaluate and document the progress toward achieving Project Clarity's goal of improved water quality in Lake Macatawa. The monitoring program involves sampling the lake 3 times per year for a suite of biological, physical, and chemical parameters. Hence, information is not collected continuously and may either capture or miss episodic, short-term conditions. The value of the dashboard is an assessment of long-term trends, not of short-term events.

Key water quality indicators were selected from the many parameters that are monitored to create a water quality dashboard for Lake Macatawa (see full annual report for all parameters). The goal of the dashboard is to provide a visual representation of the current status and historical trends in Lake Macatawa water quality, by rating each indicator along a scale from desirable (green) to undesirable (red) conditions. Each scale also includes a category that indicates the water quality goal for the lake is being met (yellow). The indicators that were chosen are commonly used to assess lake health: total phosphorus concentration, chlorophyll *a* concentration, and Secchi disk depth (water clarity). Each indicator is described in more detail below.

Historical data are included in the dashboard to facilitate comparison of current findings with past status of the selected water quality indicators. Sources for historical data include U.S. EPA (1972; STORET), Michigan Department of Environment, Great Lakes, and Energy (formerly MDEQ; 1982-2012; S. Holden, personal communication), and AWRI (since 2013). All current and historical data shown represent the annual average value of an indicator across Sites 1 (east basin), 2 (central basin), and 4 (west basin; see map below).

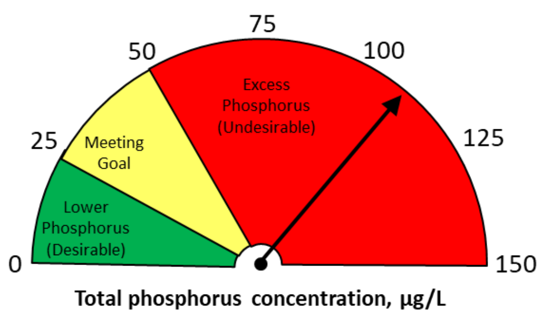


Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring. Dashboard indicators were calculated based on data from Sites 1, 2, and 4.

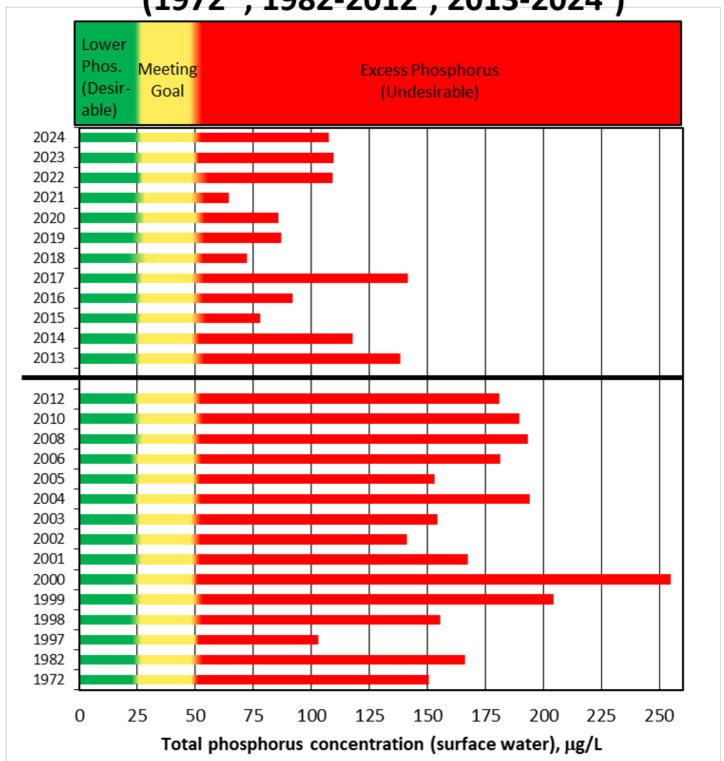
Total Phosphorus

2024 Mean Concentration: 107 µg/L
Target Concentration: 50 µg/L

Current status (2024)



Historical Status (1972*; 1982-2012†; 2013-2024‡)



*U.S. EPA; †EGLE; ‡AWRI

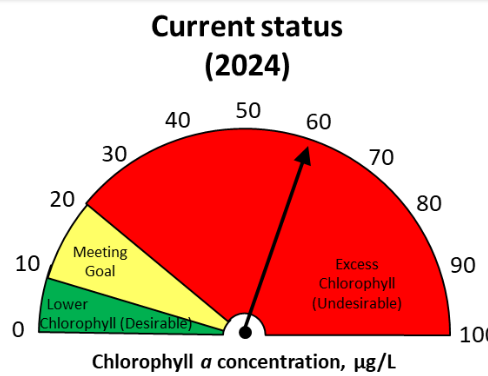
Phosphorus (P) is an essential element for living organisms. In many freshwater systems, P is the element that limits algal growth. However, when it becomes too abundant, it can help stimulate undesirable algal blooms. Phosphorus comes in many forms; we selected Total Phosphorus (TP) as the dashboard indicator because it includes all the forms of P in the lake (i.e., particulate and dissolved).

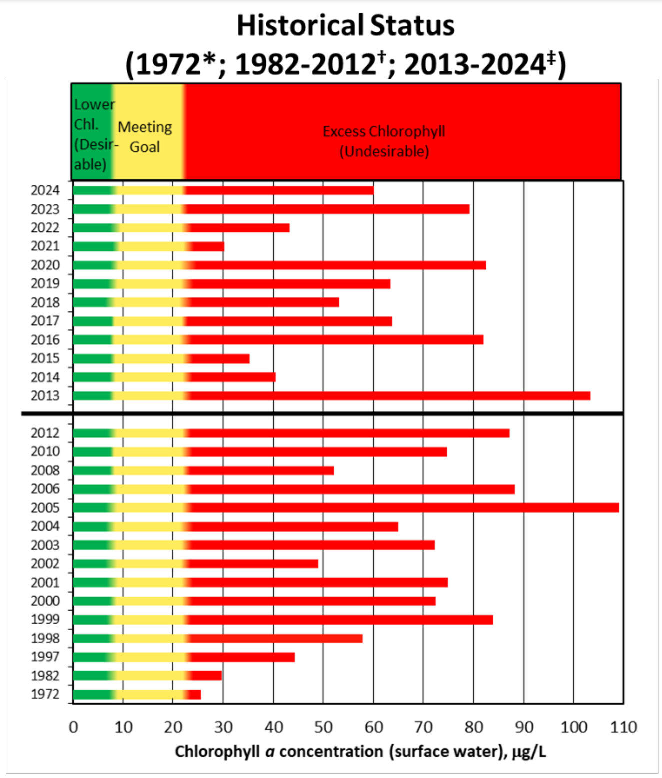
Lake Macatawa has a history of extremely high TP concentrations (i.e., > 100 µg/L), placing it in the "hypereutrophic" trophic state. As a result of this nutrient enrichment, the State of Michigan established an interim target TP concentration of 50 µg/L in Lake Macatawa. Thus, the TP dashboard shows the water quality goal as being met when TP concentrations are < 50 µg/L. While attaining this goal would be a significant improvement in water quality from current conditions, Lake Macatawa would still be in an impaired "eutrophic" state, which we define as TP concentration > 24 µg/L. Therefore, the TP dashboard shows the ultimate desired TP concentration as < 24 µg/L.

The 2024 status for the total phosphorus indicator remains **Undesirable**, indicating that the average TP concentration in 2024 exceeded the water quality goal. Although the annual mean has seemingly stabilized since 2022, seasonal means have actually shifted, with decreases in summer TP and increases in fall TP over the same timeframe (see Fig. 8 in main body of this report).

Chlorophyll *a*

2024 Mean Concentration: 60 µg/L
Target Concentration: 22 µg/L





*U.S. EPA; †EGLE; ‡AWRI

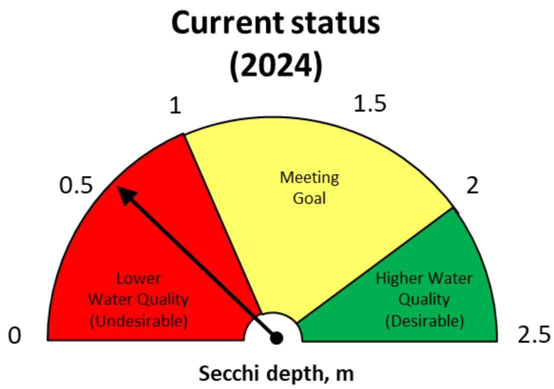
Chlorophyll *a* is the green pigment found in photosynthetic plants and algae. Measuring chlorophyll *a* is a relatively simple way to estimate the amount of algal biomass present in lake water, although it has some limitations. First, chlorophyll *a* does not provide information on whether or not the algae present produce toxins. Second, chlorophyll concentrations can change depending upon environmental conditions, such as light or nutrient level. Finally, chlorophyll *a* concentrations may be low due to very active predation by grazers (zooplankton), so the measurement may give an underestimate of how much algal biomass would otherwise be present.

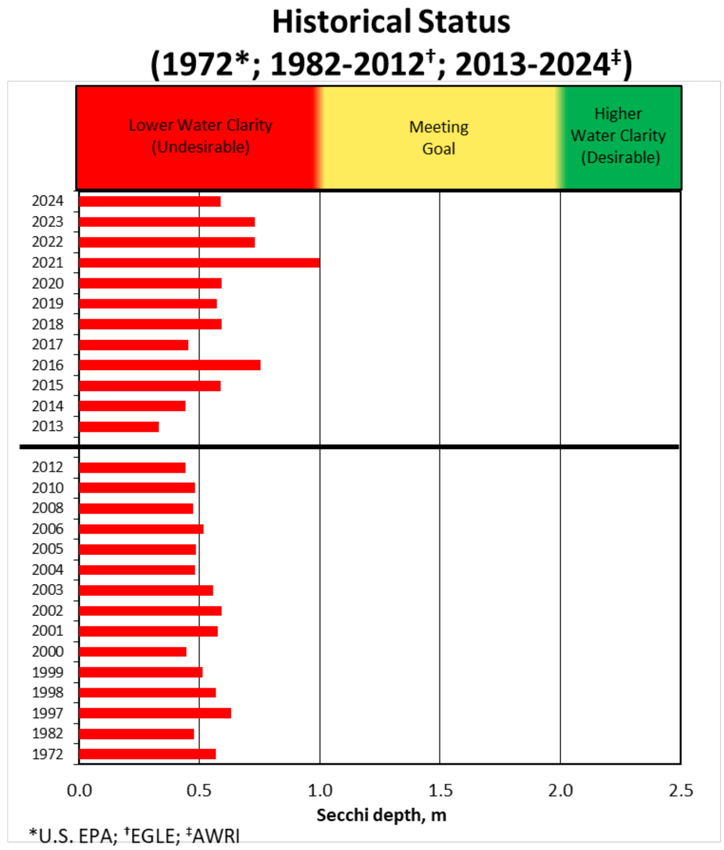
Lake Macatawa has a history of excess algal biomass and high chlorophyll *a* concentrations, typically exceeding the "hypereutrophic" threshold commonly used by EGLE (22 µg/L) in its assessments of the lake. The chlorophyll *a* dashboard shows that the concentration will meet the water quality goal once it is < 22 µg/L. Although meeting the chlorophyll *a* goal would be a significant improvement in water quality, Lake Macatawa would still be categorized as "eutrophic" (i.e., > 7 µg/L chlorophyll *a*). Thus, the chlorophyll *a* dashboard shows that the ultimate desired chlorophyll *a* concentration is < 7 µg/L.

The current status for the chlorophyll *a* indicator is **Undesirable** and is nearly 3× the restoration goal for Lake Macatawa. It is encouraging to see the 20 µg/L reduction from 2023's dashboard; however, similar annual increases and decreases of this magnitude are not uncommon in Project Clarity's sampling history, which likely reflects both the variability in algal growth in the lake as well as our limited monitoring program.

Secchi Disk Depth (Water Clarity)

2024 Mean Depth: 0.59 m (~1.9 ft)
Target Depth: 1 m (~3.3 ft)



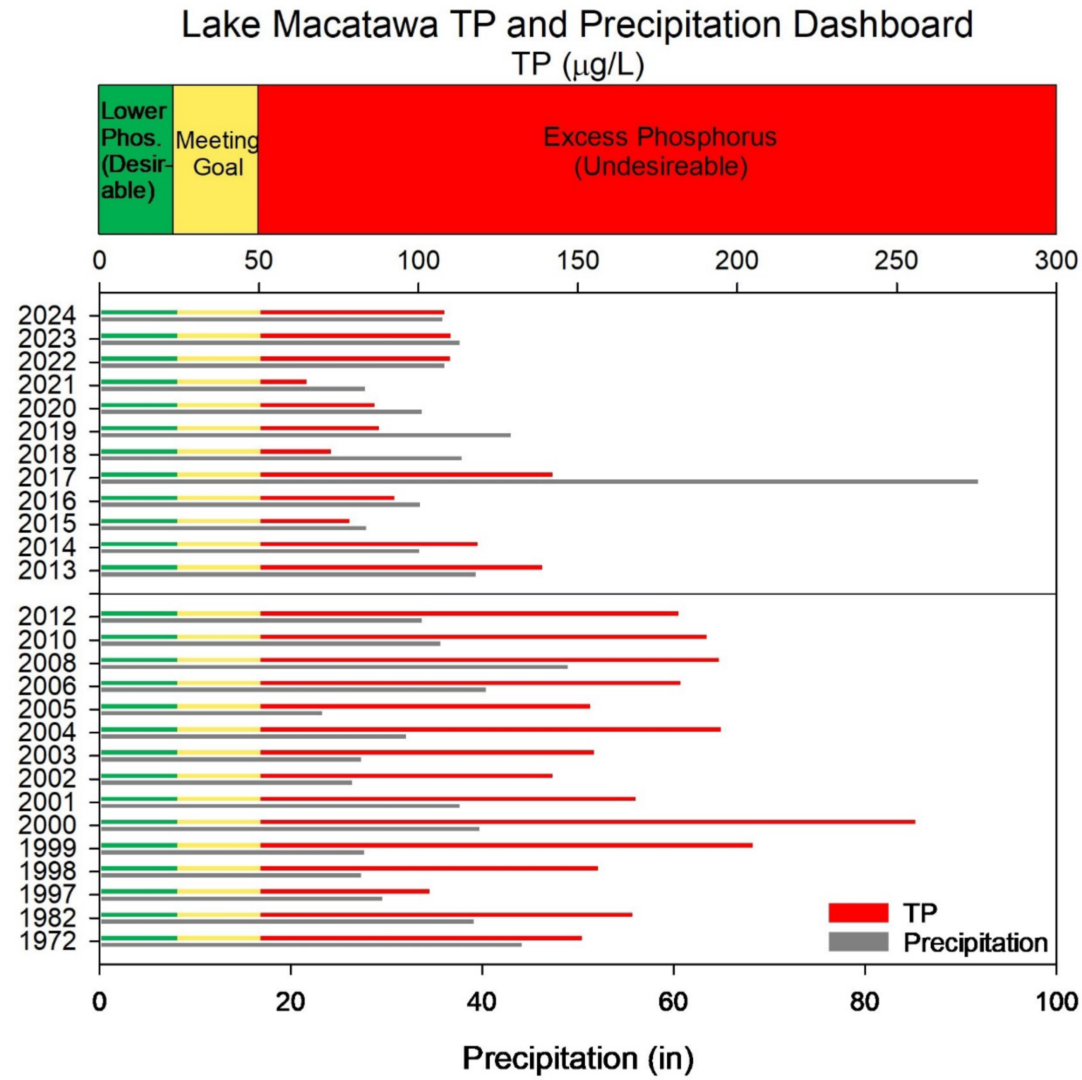


Secchi disk depth is an estimate of water clarity. It is measured using a standard black and white disk, named after the Italian priest Angelo Secchi, who first used an all-white disk for marine waters in 1865. Lake ecologists modified it to black and white in the late 1800s. The Secchi disk is a simple and easy way to measure water clarity, although if waters are cloudy, the disk depth tells you nothing about why the lake is turbid (e.g., is it due to suspended algae or suspended sediment?).

Along with excess phosphorus and chlorophyll *a* concentrations, Secchi depths have historically reflected impaired conditions in Lake Macatawa. Oligotrophic lakes, such as Lake Tahoe, have Secchi disk depths down to 21 m (~70 ft) or deeper. Conversely, hypereutrophic lakes, such as Lake Macatawa, typically have Secchi depths shallower than 1 m (~3 ft). The water clarity goal for Lake Macatawa is modest, with a Secchi depth > 1 m. Because Secchi depths between 1 and 2 m are indicative of a eutrophic state, a desirable Secchi depth is > 2 m.

The current status for the Secchi depth indicator is **Undesirable**, and in fact, the average Secchi depth has been on a declining trend (become more shallow) since 2021and currently does not meet the criteria of the water quality goal.

Total Phosphorus and Precipitation



Phosphorus concentrations in Lake Macatawa are influenced by many variables, but one of the most significant is precipitation because rain and snow events create runoff from farms and urban areas, when phosphorus can be transported to Lake Macatawa either in the dissolved form or as attached to sediment particles; precipitation also results in atmospheric deposition, which can contribute phosphorus directly to the lake and landscape. Consequently, it is of interest to know if annual changes in lake phosphorus concentrations are related to precipitation.

To answer this question, we examined total phosphorus (TP) concentrations in the lake, based on data from EGLE and AWRI (sampled 3× per year at 3 sites), and compared them to precipitation data from the Tulip City Airport in Holland. As seen above, between 1972 and 2024, the relationship between precipitation and TP concentration in the lake is not directly related; for example, some years have very high TP concentrations but relatively low precipitation (e.g., 2000 and 2004), whereas other years have modest levels of TP but relatively high precipitation (e.g., 2017). Indeed, past Project Clarity dashboards have shown that the statistical relationship between the two is not significant.

The relationship between TP and precipitation is much improved when isolated seasonally and by considering only the rainfall in the preceding weeks or months instead of the entire year; these relationships are statistically significant in the spring (R^2=0.53, P=0.017) and summer (R^2=0.48, P=0.012). In addition, the relationship between TP and precipitation has been much tighter the past 3 years; it is unclear if this is related to management actions in the watershed or just happenchance.

We view these data as appropriate only for screening purposes, as the TP concentrations are means of seasonal lake sampling events, which likely miss pulses of high P concentrations after storm events throughout the rest of the not-monitored season.

Long-Term Fish Monitoring of Lake Macatawa: Results from 2024

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5 February 2025

An Annual Report
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Introduction

This study was initiated to provide critical information on littoral fish populations in Lake Macatawa and ultimately to evaluate the performance of watershed restoration activities that are part of Project Clarity. In autumn 2014, we initiated long-term monitoring of the littoral fish assemblage of Lake Macatawa to establish baseline ecological conditions and evaluate ecological change over time. Our fish sampling plan for Lake Macatawa is similar to our ongoing, long-term (since 2003) monitoring effort in Muskegon Lake (Ruetz et al. 2007; Bhagat and Ruetz 2011). By using the same monitoring protocols in each water body, Muskegon Lake can serve as a "control" to evaluate temporal changes in Lake Macatawa in an effort to better assess how the lake is responding to watershed restoration activities.

Our primary objective in the eleventh year (2024) of sampling was to continue characterizing the littoral fish assemblage. We made comparisons with work in Muskegon Lake (see Bhagat and Ruetz 2011) as well as with six Lake Michigan drowned river mouths for which we have data (see Janetski and Ruetz 2015). We also assessed patterns over time and how littoral fish assemblages are responded to restoration activities in the watershed.

Methods

Study sites.—Lake Macatawa is a drowned river mouth lake in Holland, Michigan that is located on the eastern shore of Lake Michigan in Ottawa County (Mader et al. 2023). Lake Macatawa has an area of 7.20 km^2, mean depth of 3.66 m, and maximum depth of 12.19 m (MDNR 2011). The shoreline has high residential and commercial development, and the watershed consists mainly of agricultural land (MDNR 2011; Mader et al. 2023). Sampling was conducted at four littoral sites in Lake Macatawa that represented a gradient from the mouth of the Macatawa River to the connecting channel with Lake Michigan (Figure 1; Table 1). In 2016, much of the riparian vegetation was removed at site #2 for a construction project (Figure 1), which substantially changed littoral habitat. In 2020, high water levels in the Great Lakes made fish sampling challenging; as a result, fyke nets were not fished at site #3 (but all other sampling was completed). Water levels in Lake Michigan receded in 2021, and we have been able to sample fish at all sites henceforth.

Fish sampling.—At each study site, we sampled fish via fyke netting and boat electrofishing. Using both sampling gears should better characterize the littoral fish assemblage than either gear by itself because small-bodied fishes are better represented in fyke netting and large-bodied fishes are better represented in nighttime boat electrofishing (Ruetz et al. 2007). Fyke nets were set on 6 September 2024 during daylight hours (i.e., between 1000 and 1500) and fished for about 23.3 h (range = 22.8-23.9 h). Except for 2021 when poor weather conditions delayed sampling into October, fyke nets had been previously set in September. Three fyke nets (4-mm mesh) were fished at each site; two fyke nets were set facing each other and parallel to the shoreline, whereas a third fyke net was set perpendicular to the shoreline following the protocol used by Bhagat and Ruetz (2011). A detailed description of the design of the fyke nets is reported in Breen and Ruetz (2006). We conducted nighttime boat electrofishing at each site on 4 September 2024. All previous nighttime electrofishing surveys were conducted during 5-22 September (2014-2023). A 10-min (pedal time) electrofishing transect was conducted parallel to the shoreline at each site with two people at the front of the boat to net fish, although for some transects (particularly sites #2 and #3) we had to navigate around boat docks. The electrofishing boat was equipped with a Smith-Root 5.0 generator-powered pulsator control box (pulsed DC, 220 volts, ~7 amp). For both sampling methods, all fish captured were identified to species, measured (total length), and released in the field; however, some specimens were humanely euthanized to confirm identifications in the laboratory. We follow Bailey et al. (2004) for scientific names of fishes.

We measured water quality variables (i.e., temperature, dissolved oxygen, specific conductivity, turbidity, pH, and chlorophyll *a*) in the middle of the water column using a YSI sonde. We made one measurement at each fyke net (n = 12 per year) and one measurement at the beginning of each electrofishing transect (n = 4 per year). We measured the water depth at the mouth of each fyke net and visually estimated the percent macrophyte cover for the length of the lead between the wings of each fyke net (see Bhagat and Ruetz 2011). We also visually estimated the percent macrophyte cover for the length of each nighttime electrofishing transect. For both fyke netting and boat electrofishing surveys, percentage macrophyte cover was estimated only when water clarity was sufficient to observe the lake bottom.

Results and Discussion

We characterized water quality variables at each site during fish sampling in 2024 (Tables 2 and 3), although inferences about changes in water quality over time should be based on the companion monitoring efforts by the Steinman Lab (see main body of report). The mean water depth at fyke nets was 85 cm (Table 2), which was similar to the long-term mean water depth of 91 cm (range = 83-104 cm; n = 11 years) at fyke nets. Mean water temperature during fyke netting (23.2 °C; Table 2) was similar to conditions during nighttime boat electrofishing (24.2 °C; Table 3). The long-term mean water temperature during fyke netting was 22.2 °C (range = 18.3-25.5 °C; n = 11 years) and nighttime boat electrofishing was 22.1 °C (range = 19.2-24.2 °C; n = 11 years). The mean estimated percent macrophyte cover at sites during fyke netting was: 0% at site #1, 25% at site#2, 59% at site #3, 32% at site #4. For nighttime electrofishing, the estimated percent macrophyte cover was: 85% at site #3, and 65% at site #4; we were unable to visually estimate macrophyte cover at sites #1 and #2 during the electrofishing survey because of a lack of water clarity. The mean percent macrophyte cover in 2024 was the highest we have recorded, although our estimates also appeared similar with previous years (Figure 2). We hypothesize that macrophyte growth in Lake Macatawa will be lower in years when insufficient light penetrates the water column to allow submersed plants to grow; both turbidity from inflowing sediment and abundant phytoplankton growth in the lake water column can reduce light penetration.

As stated in past reports, aquatic macrophytes are important habitat for fish (e.g., Radomski and Goeman 2001), and their return is an important goal for the restoration of the fish assemblage in Lake Macatawa. The presence of macrophyte beds in the vicinity of our fish sampling sites is likely related to turbidity (i.e., lower turbidity is associated with more macrophytes), with overall mean turbidity (26.3 NTU, n = 12 nets) in 2024 greater than the long-term mean (18.0 NTU, n = 132 nets; Figure 3) at the time of autumn fish sampling. A detailed macrophyte survey, conducted every 3-5 years, would provide useful information for Lake Macatawa's ecological status (see Ogdahl and Steinman 2014; Kleindl and Steinman 2021).

We captured 2,081 fish comprising 26 species in Lake Macatawa during 2024 sampling surveys (Table 4). The total catch in 2024 was above the long-term mean of 1,559 fish (SD = 593, n = 11 years), but the number of fish species captured was similar to the long-term mean of 27 species (SD = 2.6, n = 11 years; Figure 4). The most common fishes in the combined catch (i.e., fyke netting and boat electrofishing) were White Perch (30%), Round Goby (16%), Gizzard Shad (13%), Spottail Shiner (9%), Yellow Perch (9%), Brook Silverside (9%), and Bluegill

(5%), which composed 91% of the total catch (Figure 5A). Four of the 26 species captured during 2024 were non-native to the Great Lakes basin (Bailey et al. 2004)—Alewife, Common Carp, White Perch, and Round Goby—which composed 47% of the total catch, although most of the non-native fishes were Round Goby and White Perch (Table 4). For comparison, we captured 2,770 fishes comprising 29 species in Muskegon Lake during autumn 2024 (with similar sampling effort in terms of sites and gear to the sampling reported here for Lake Macatawa). Similar to Lake Macatawa, 4 of the 29 species in Muskegon Lake were non-native to the Great Lakes basin—Alewife, Common Carp, White Perch, and Round Goby. However, the non-native species in Muskegon Lake composed less of the total catch than Lake Macatawa (7% vs. 47%, respectively), and 90% of non-native fish species captured in Muskegon Lake in autumn 2024 were Round Goby. Rock Bass—associated with excellent biotic integrity (Cooper et al. 2018)—composed about 3% of the catch in Muskegon Lake during autumn 2024, whereas this species was not captured in Lake Macatawa during 2024.

In fyke netting alone, Round Goby (24%), White Perch (24%), Brook Silverside (14%), Spottail Shiner (12%), and Bluegill (7%) were the most common fishes in the catch, composing 81% of all fish captured (Figure 5B). The most common species in the catch at each site were White Perch at site #1, White Perch, Bluegill, and Round Goby at site #2, Brook Silverside and Spottail Shiner at site #3, and Round Goby and White Perch at site #4 (Table 5). The number of fish captured also varied among sites, with the most fish captured at site #4 and the least at site #2 (Table 5; Figure 6A). Compared with previous fyke netting surveys, the most common species in the catch varied among years (Figure 7), as did the patterns in total catch among sites (Figure 6A). Based on relative abundance (i.e., percentage of a fish species in the total catch for a given year) in 2024, Round Goby and White Perch were more common and Spotfin Shiner less common in the catch than in most previous years (Figure 7).

In boat electrofishing alone, the most common fishes captured were White Perch (41%), Gizzard Shad (30%), and Yellow Perch (14%), which composed 85% of the total catch (Figure 5C). The most common species in the catch were White Perch at sites #1 and #2, Gizzard Shad at site #3, and Yellow Perch and White Perch at site #4 (Table 6). Total catch also varied among sites in 2024, with the highest catch at site #3 and lowest catch at site #1 (Table 6; Figure 6B). Compared with previous boat electrofishing surveys, the most common species in the catch varied among years (Figure 8). In 2024, White Perch was more common and Pumpkinseed and Largemouth Bass were less common in the catch than in most previous years (Figure 8).

After 11 years of fish monitoring, there are both positive and negative indicators of Lake Macatawa's ecological condition. Yellow Perch, Bluegill, and Pumpkinseed were common species captured in our surveys, and they are indicators of good water quality (Janetski and Ruetz 2015; Cooper et al. 2018). However, other common fish species in our surveys, such as Gizzard Shad and Spotfin Shiner, are often associated with poor water quality (Janetski and Ruetz 2015). The near absence of Rock Bass in the catch also likely indicates poor water quality and/or habitat (Janetski and Ruetz 2015; Cooper et al. 2018). In the 11 years of sampling, the Rock Bass was captured in only one year (2021) in Lake Macatawa, whereas this species was captured every year in Muskegon Lake (with similar sampling effort for the same time period). Taken in aggregate, the littoral fish assemblage in Lake Macatawa is more reflective of poor ecological condition. If environmental conditions (e.g., water quality) in Lake Macatawa were to substantially improve (e.g., to conditions more similar in Muskegon Lake), then we predict that the littoral fish assemblage would respond accordingly (Janetski and Ruetz 2015; Cooper et al.

2018). A rigorous statistical analysis of the spatiotemporal patterns in the fish assemblage and environmental conditions of Lake Macatawa and Muskegon Lake is necessary to better evaluate the patterns discussed here but is beyond the scope of this report. A current part-time graduate student in the Ruetz Lab (Maria Scarborough) is working toward this goal of conducting a more rigorous statistical analysis.

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Table 1. Locations (latitude and longitude) for each 2024 fish sampling site; coordinates are the mean of the three fyke nets and the start and end of each boat electrofishing transect. Electrofishing endpoint coordinates for Site 3 were not recorded. Approximate site locations are depicted in Figure 1.

			Electrofishing			
	Fyke Netting		Start		End	
Site	Lat (°)	Long (°)	Lat (°)	Long (°)	Lat (°)	Long (°)
1	42.79590	86.12135	42.79569	86.12051	42.79565	86.12334
2	42.79022	86.14393	42.79048	86.14421	42.78795	86.14462
3	42.78610	86.17447	42.78434	86.17279	.	.
4	42.77914	86.19766	42.77915	86.19775	42.78038	86.19566

Table 2. Mean ± 1 standard error (n = 3) of water quality variables at fish sampling sites in Lake Macatawa. Water quality measurements were made during fyke netting on 7 September 2024 with a YSI sonde.

Site	Depth (cm)	Water Temperature (°C)	Dissolved Oxygen (mg/L)	Dissolved Oxygen (%)	Specific Conductivity (µS/cm)	Turbidity (NTU)	pH	Chlorophyll *a* (µg/L)
1	99 ± 6	24.24 ± 0.02	13.54 ± 0.41	161.9 ± 4.8	601 ± 1	37.6 ± 1.8	8.82 ± 0.04	84.5 ± 5.2
2	89 ± 9	23.29 ± 0.05	12.03 ± 0.66	140.9 ± 7.8	517 ± 1	25.5 ± 4.9	8.77 ± 0.06	70.2 ± 6.2
3	79 ± 10	22.85 ± 0.09	9.57 ± 0.26	111.4 ± 3.2	453 ± 1	20.3 ± 6.8	8.81 ± 0.04	13.6 ± 0.7
4	72 ± 9	22.38 ± 0.03	11.41 ± 0.21	131.4 ± 2.6	427 ± 1	21.9 ± 0.9	9.06 ± 0.02	13.0 ± 0.3

Table 3. Water quality variables at fish sampling sites in Lake Macatawa. Water quality measurements were made during nighttime boat electrofishing on 4 September 2024 with a YSI sonde.

Site	Water Temperature (°C)	Dissolved Oxygen (mg/L)	Dissolved Oxygen (%)	Specific Conductivity (µS/cm)	Turbidity (NTU)	pH	Chlorophyll *a* (µg/L)
1	25.43	21.37	261.5	597	20.6	9.12	96.2
2	25.34	18.91	231.8	512	24.2	9.16	94.5
3	23.86	14.67	174.3	459	18.6	9.13	39.9
4	22.16	11.19	128.3	430	15.8	9.01	15.2

Table 4. Number and total length (TL; mean, minimum, and maximum) of fish captured by fyke netting (n = 12 nets) on 7 September at four sites and boat electrofishing (n = 4 transects) on 4 September 2024 at four sites in Lake Macatawa. Total is the total catch combined for both gear. Scientific names are based on Bailey et al. (2004).

			Fyke netting				Electrofishing			
				TL (cm)				TL (cm)		
Common name	Scientific name	Total	Catch	Mean	Min	Max	Catch	Mean	Min	Max
Alewife	*Alosa pseudoharengus*	15	15	7.2	3.1	9.4	--	--	--	--
Yellow Bullhead	*Ameiurus natalis*	1	1	26.7	--	--	--	--	--	--
Bowfin	*Amia calva*	1	--	--	--	--	1	41.4	--	--
Freshwater Drum	*Aplodinotus grunniens*	6	--	--	--	--	6	29.0	19.8	40.6
Quillback	*Carpiodes cyprinus*	1	--	--	--	--	1	56.4	--	--
White Sucker	*Catostomus commersoni*	22	13	35.0	9.0	49.5	9	30.3	19.2	48.1
Bloater	*Coregonus hoyi*	2	2	6.2	5.6	6.8	--	--	--	--
Common Carp	*Cyprinus carpio*	7	1	35.0	35.0	35.0	6	53.5	16.5	81.2
Spotfin Shiner	*Cyprinella spiloptera*	11	11	8.0	4.7	12.6	--	--	--	--
Gizzard Shad	*Dorosoma cepedianum*	276	49	12.9	2.9	31.3	227	12.3	8.1	30.6
Banded Killifish	*Fundulus diaphanus*	2	1	10.8	--	--	1	6.2	--	--
Channel Catfish	*Ictalurus punctatus*	2	1	6.0	--	--	1	46.8	--	--
Brook Silverside	*Labidesthes sicculus*	179	178	7.5	4.8	10.9	1	11.7	--	--
Pumpkinseed	*Lepomis gibbosus*	21	18	7.0	4.9	14.8	3	14.8	14.5	15.3
Bluegill	*Lepomis macrochirus*	100	91	5.3	2.1	21.5	9	15.8	12.1	19.4
Largemouth Bass	*Micropterus salmoides*	30	8	13.2	8.0	24.2	22	17.0	8.0	27.2
White Perch	*Morone americana*	625	313	10.3	5.4	26.2	312	12.0	7.6	30.6
Silver Redhorse	*Moxostoma anisurum*	3	--	--	--	--	3	60.2	59.4	60.8
Round Goby	*Neogobius melanostomus*	326	320	6.7	2.4	14.0	6	9.4	7.1	14.2
Emerald Shiner	*Notropis atherinoides*	18	15	9.3	4.6	10.7	3	9.1	8.4	9.6
Golden Shiner	*Notemigonus crysoleucas*	38	32	13.1	6.4	21.2	6	15.5	14.5	17.6
Spottail Shiner	*Notropis hudsonius*	197	158	9.2	5.7	12.7	39	9.8	7.2	12.2
Yellow Perch	*Perca flavescens*	191	80	11.1	5.9	23.9	111	11.8	8.4	23.4
Bluntnose Minnow	*Pimephales notatus*	2	2	5.5	4.5	6.5	--	--	--	--
Black Crappie	*Pomoxis nigromaculatus*	3	3	11.8	9.3	16.5	--	--	--	--
Walleye	*Sander vitreus*	2	--	--	--	--	2	50.9	49.4	52.3
	Total	2081	1312				769			

Table 5. Number and total length (TL; mean, minimum, and maximum) of fish captured by fyke netting (*n* = 3 nets per site) at four sites in Lake Macatawa on 7 September 2024. Site locations are depicted in Figure 1. Scientific names are based on Bailey et al. (2004).

		Site #1				Site #2				Site #3				Site #4			
			TL (cm)				TL (cm)				TL (cm)				TL (cm)		
Common name	Scientific name	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max
Alewife	*Alosa pseudoharengus*	2	5.2	4.6	5.7	--	--	--	--	--	--	--	--	13	7.5	3.1	9.4
Yellow Bullhead	*Ameiurus natalis*	--	--	--	--	1	26.7	--	--	--	--	--	--	--	--	--	--
White Sucker	*Catostomus commersoni*	6	31.1	20.0	48.5	1	46.9	--	--	5	36.1	9.0	49.5	1	40.6	--	--
Bloater	*Coregonus hoyi*	--	--	--	--	--	--	--	--	--	--	--	--	2	6.2	5.6	6.8
Common Carp	*Cyprinus carpio*	1	35.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Spotfin Shiner	*Cyprinella spiloptera*	1	9.8	--	--	8	7.9	4.7	12.6	1	6.8	--	--	1	9.0	--	--
Gizzard Shad	*Dorosoma cepedianum*	22	13.0	2.9	31.3	10	12.3	3.2	15.8	6	12.0	10.8	13.4	11	13.9	12.2	16.5
Banded Killifish	*Fundulus diaphanus*	--	--	--	--	--	--	--	--	1	10.8	--	--	--	--	--	--
Channel Catfish	*Ictalurus punctatus*	--	--	--	--	1	6.0	--	--	--	--	--	--	--	--	--	--
Brook Silverside	*Labidesthes sicculus*	2	6.6	6.0	7.1	2	6.6	5.9	7.2	142	7.4	4.8	8.8	32	7.6	6.0	10.9
Pumpkinseed	*Lepomis gibbosus*	1	14.8	--	--	2	13.0	12.5	13.5	--	--	--	--	15	5.7	4.9	7.0
Bluegill	*Lepomis macrochirus*	24	4.7	2.6	10.1	21	5.0	2.1	21.5	13	5.4	2.5	7.1	33	5.9	4.5	10.9
Largemouth Bass	*Micropterus salmoides*	2	17.3	10.6	24.0	1	24.2	--	--	3	9.5	8.2	11.9	2	9.1	8.0	10.1
White Perch	*Morone americana*	109	11.0	7.7	23.6	38	10.7	7.8	26.2	12	10.4	9.0	11.3	154	9.8	5.4	22.4
Round Goby	*Neogobius melanostomus*	4	4.7	3.2	6.0	21	3.5	2.4	8.2	20	8.0	3.5	14.0	275	6.8	3.2	13.1
Emerald Shiner	*Notropis atherinoides*	1	4.6	--	--	--	--	--	--	6	9.0	6.6	10.0	8	10.0	9.0	10.7
Golden Shiner	*Notemigonus crysoleucas*	16	14.2	6.7	17.7	7	13.0	6.4	21.2	7	11.0	8.4	20.5	2	12.6	7.7	17.5
Spottail Shiner	*Notropis hudsonius*	37	9.7	5.9	12.3	8	9.2	7.9	12.7	64	8.9	6.2	11.3	49	9.2	5.7	12.2
Yellow Perch	*Perca flavescens*	1	18.8	--	--	3	15.7	10.3	20.0	27	11.7	9.5	23.9	49	10.3	5.9	21.8
Bluntnose Minnow	*Pimephales notatus*	1	4.5	--	--	1	6.5	--	--	--	--	--	--	--	--	--	--
Black Crappie	*Pomoxis nigromaculatus*	1	9.5	--	--	1	16.5	--	--	--	--	--	--	1	9.3	--	--
	Total	231				126				307				648			

Table 6. Number and total length (TL; mean, minimum, and maximum) of fish captured by nighttime boat electrofishing (n = 1 transect per site) at four sites in Lake Macatawa on 4 September 2024. Site locations are depicted in Figure 1. Scientific names are based on Bailey et al. (2004).

		Site #1				Site #2				Site #3				Site #4			
			TL (cm)				TL (cm)				TL (cm)				TL (cm)		
Common name	Scientific name	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max
Bowfin	*Amia calva*	--	--	--	--	--	--	--	--	--	--	--	--	1	41.4	--	--
Freshwater Drum	*Aplodinotus grunniens*	--	--	--	--	1	19.8	--	--	2	37.6	34.5	40.6	3	26.4	24.4	29.1
Quillback	*Carpiodes cyprinus*	--	--	--	--	--	--	--	--	1	56.4	--	--	--	--	--	--
White Sucker	*Catostomus commersoni*	2	22.4	21.4	23.3	--	--	--	--	3	30.4	21.1	38.0	4	34.2	19.2	48.1
Common Carp	*Cyprinus carpio*	--	--	--	--	--	--	--	--	3	52.4	22.1	81.2	3	54.5	16.5	76.5
Gizzard Shad	*Dorosoma cepedianum*	5	13.4	10.2	17.0	16	14.7	10.7	30.6	200	12.0	8.1	16.1	6	13.3	10.2	15.0
Banded Killifish	*Fundulus diaphanus*	--	--	--	--	--	--	--	--	--	--	--	--	1	6.2	--	--
Channel Catfish	*Ictalurus punctatus*	--	--	--	--	1	46.8	--	--	--	--	--	--	--	--	--	--
Brook Silverside	*Labidesthes sicculus*	--	--	--	--	--	--	--	--	1	11.7	--	--	--	--	--	--
Pumpkinseed	*Lepomis gibbosus*	1	14.6	--	--	1	14.5	--	--	--	--	--	--	1	15.3	--	--
Bluegill	*Lepomis macrochirus*	4	15.8	12.1	19.4	3	13.4	12.5	14.3	--	--	--	--	2	19.1	19.0	19.2
Largemouth Bass	*Micropterus salmoides*	3	21.3	13.3	27.2	3	18.4	10.9	22.6	7	18.9	11.5	26.0	9	13.5	8.0	23.9
White Perch	*Morone americana*	100	12.2	8.8	21.9	145	11.1	7.6	22.5	26	15.6	9.7	30.6	41	12.4	9.0	22.1
Silver Redhorse	*Moxostoma anisurum*	--	--	--	--	--	--	--	--	--	--	--	--	3	60.2	59.4	60.8
Round Goby	*Neogobius melanostomus*	--	--	--	--	--	--	--	--	2	11.5	8.7	14.2	4	8.3	7.1	11.6
Emerald Shiner	*Notropis atherinoides*	--	--	--	--	2	9.0	8.4	9.6	--	--	--	--	1	9.3	--	--
Golden Shiner	*Notemigonus crysoleucas*	5	15.4	14.5	17.6	1	15.9	--	--	--	--	--	--	--	--	--	--
Spottail Shiner	*Notropis hudsonius*	1	11.3	--	--	3	8.4	7.2	9.6	3	10.8	8.9	12.2	32	9.8	8.1	11.7
Yellow Perch	*Perca flavescens*	2	18.6	17.7	19.4	16	12.5	9.4	22.2	10	12.9	8.9	23.4	83	11.4	8.4	21.7
Walleye	*Sander vitreus*	2	50.9	49.4	52.3	--	--	--	--	--	--	--	--	--	--	--	--
	Total	125				192				258				194			

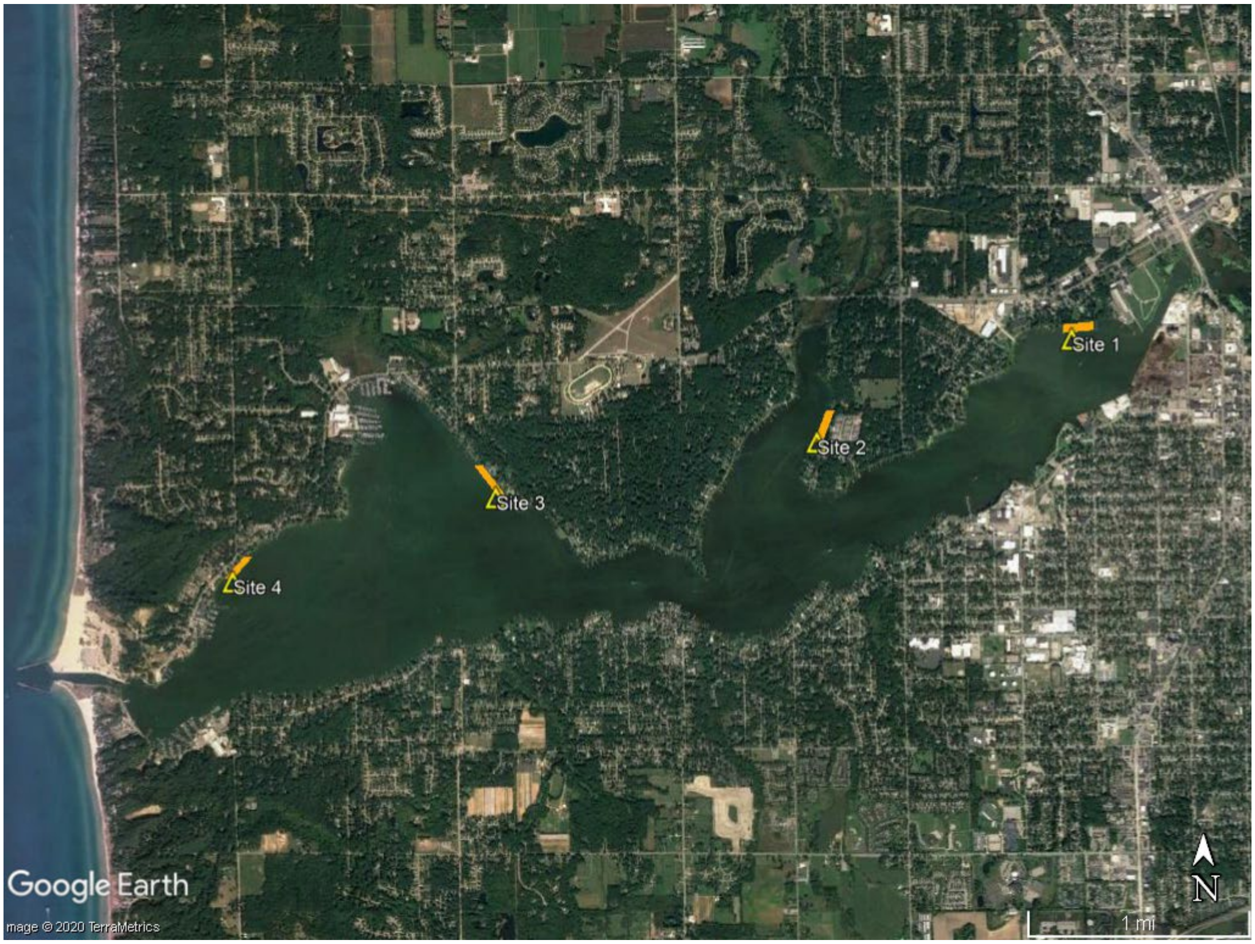

Figure 1. Map of Lake Macatawa (Ottawa County, Michigan) showing fish sampling sites (triangles). The orange transects depict approximately where boat electrofishing was conducted at each site. Site #1 is closest to the Macatawa River and site #4 is closest to Lake Michigan. Note that riparian vegetation was cleared at site #2 in 2016.

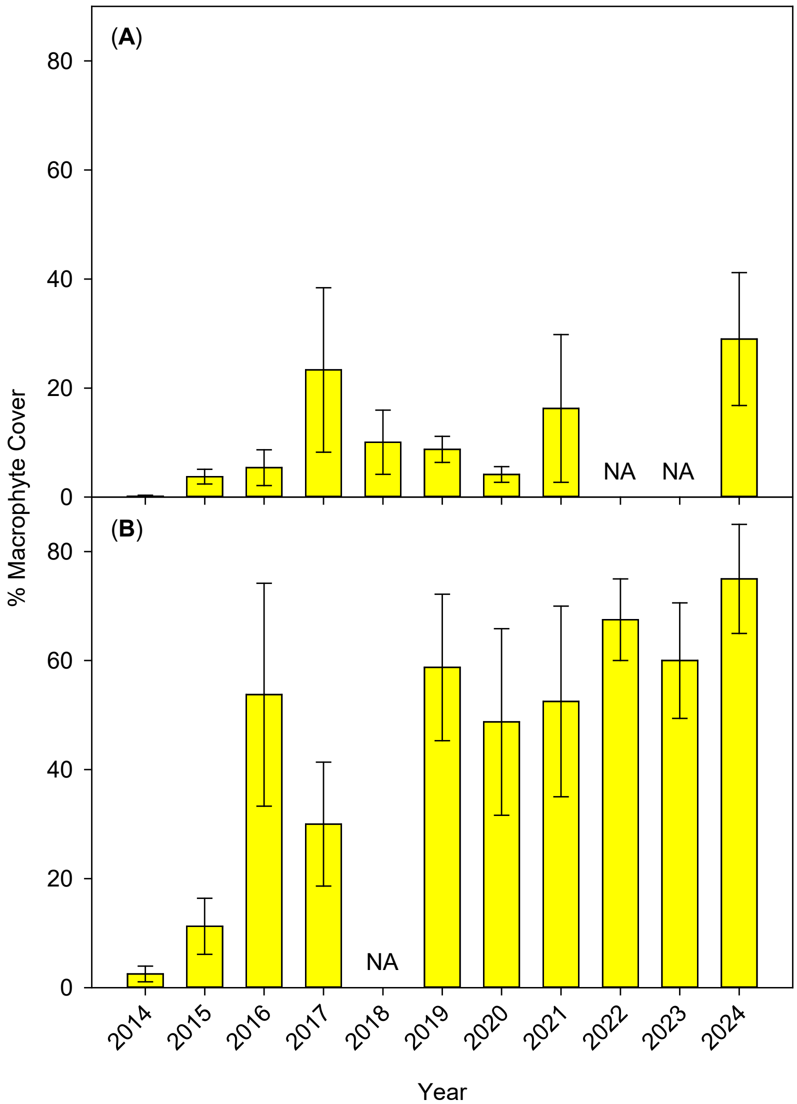

Figure 2. Mean (±1 standard error) percent macrophyte cover visually estimated at (**A**) fyke net locations and (**B**) boat electrofishing transects in Lake Macatawa (*n* = 4 sites per year; however, the *n* = 2 sites for the 2021, 2022, and 2024 boat electrofishing surveys because of poor visibility). The area where macrophyte cover was assessed during fyke netting is much less than for a boat electrofishing transect. NA means data were not available (i.e., water clarity prevented visual estimation).

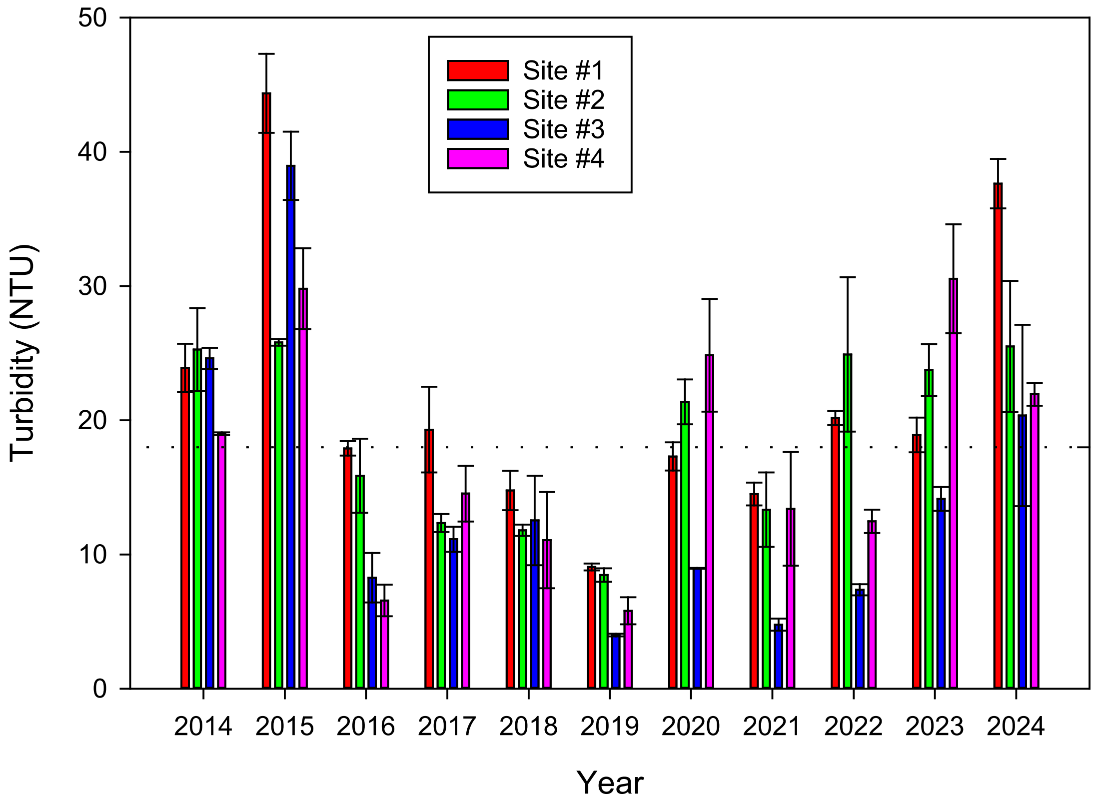

Figure 3. Mean (±1 standard error) turbidity measured during fyke netting in Lake Macatawa (*n* = 3 nets per site). Dashed line is the long-term mean (*n* = 11 years).

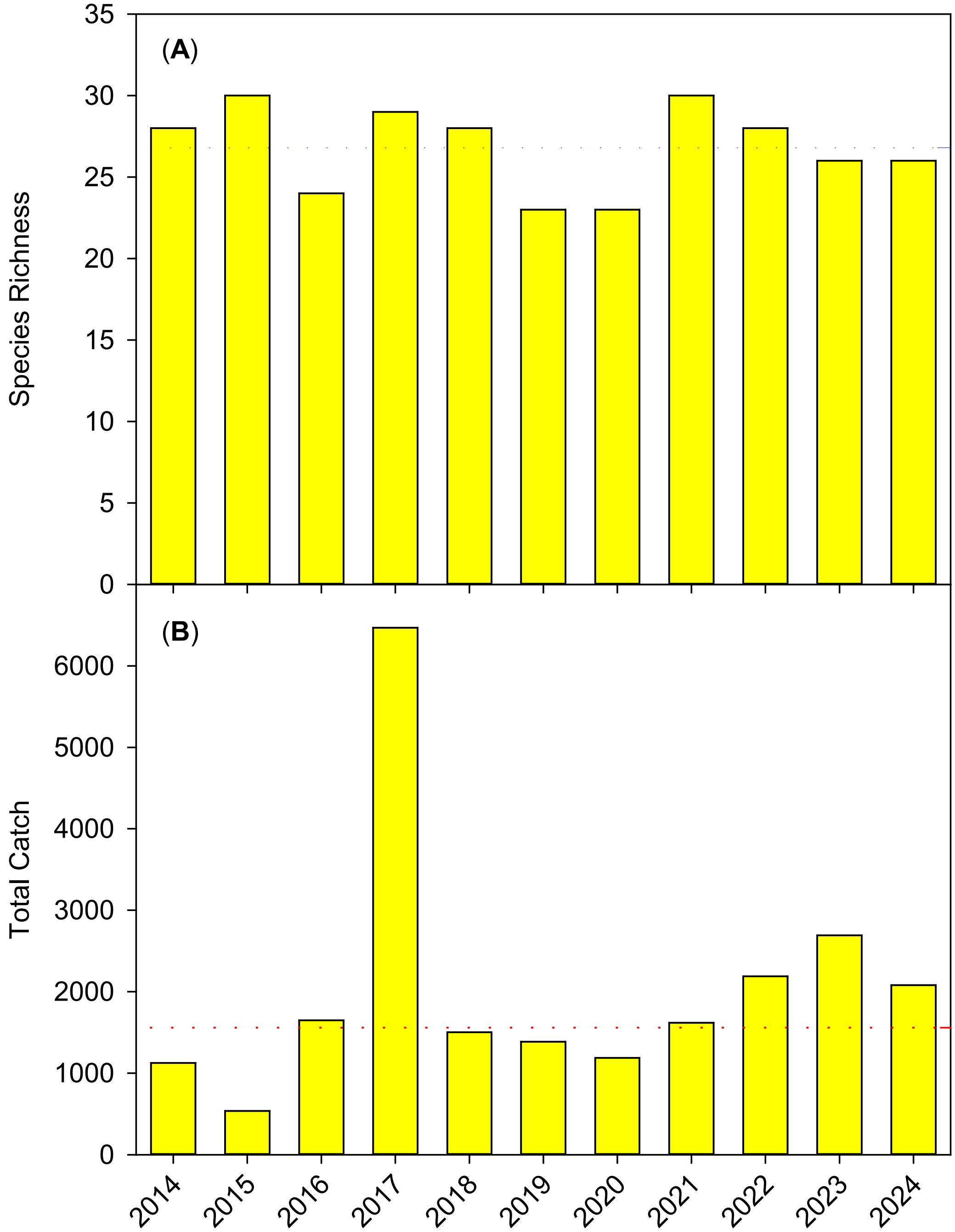

Figure 4. (**A**) Number of fish species captured (dashed blue line is long-term mean; *n* = 11 years) and (**B**) total number of fish captured using both fyke netting and boat electrofishing each year in Lake Macatawa (dashed red line is long-term mean; *n* = 11 years). The long-term mean total catch excludes 5,288 Brook Silversides captured in 2017 from a single fyke net at site #4 (i.e., a total catch of 1,180 fish in 2017 was used to calculate the long-term mean); fyke netting in 2020 was completed at three sites rather than the typical four sites.

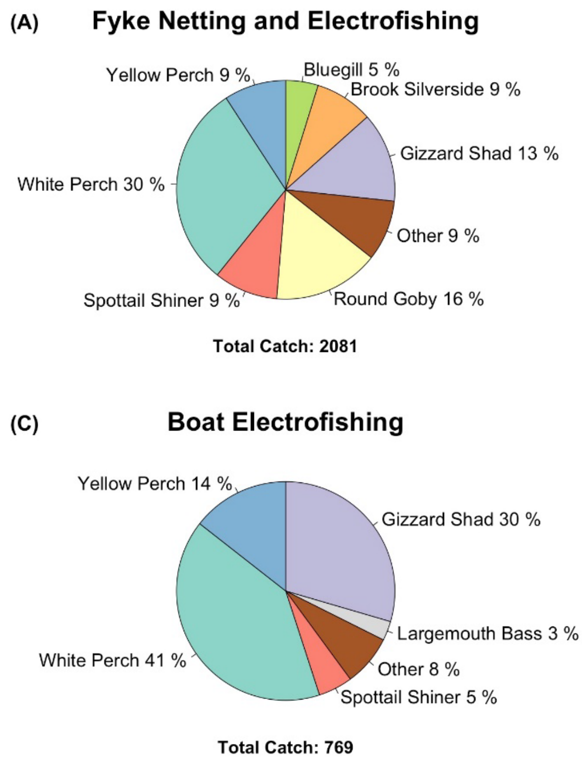

Figure 5. Fish species captured in littoral habitats of Lake Macatawa by (**A**) fyke netting and boat electrofishing (i.e., combined catch), (**B**) fyke netting (*n* = 12 nets), and (**C**) boat electrofishing (*n* = 4 transects) during September 2024. The species composition of the "Other" category is reported in Table 4.

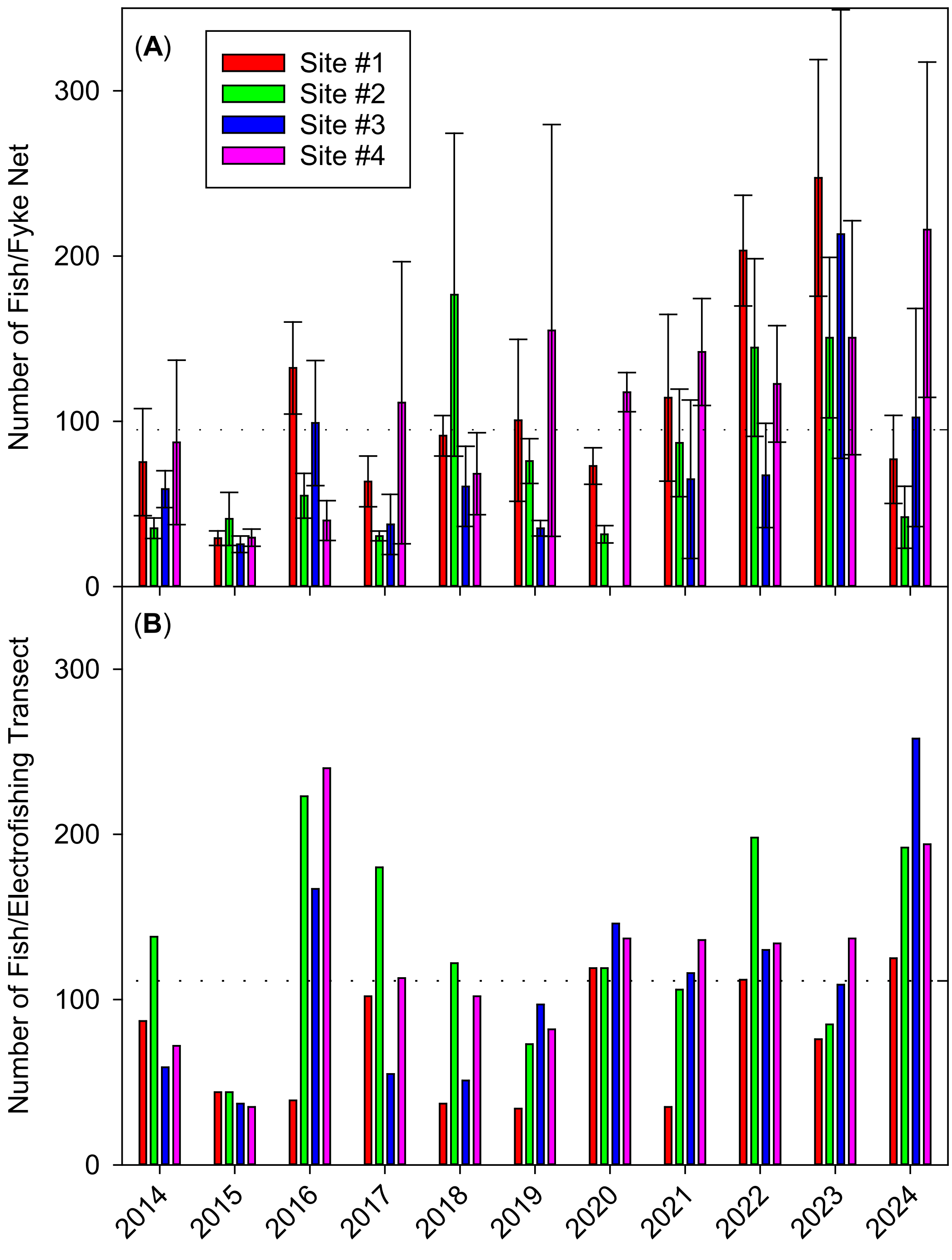

Figure 6. (**A**) Mean number (±1 standard error) of fish captured in fyke nets (*n* = 3 nets per site) and (**B**) number of fish captured during a boat electrofishing transect (*n* = 1 transect per site) in Lake Macatawa. The 5,288 Brook Silversides captured in a single fyke net at site #4 in 2017 were excluded when calculating means (and SE) for fyke netting. Fyke nets were not set at site #3 in 2020 because of high water levels in the lake. The dashed line represents the long-term mean for fyke netting (*n* = 43) and boat electrofishing (*n* = 44).

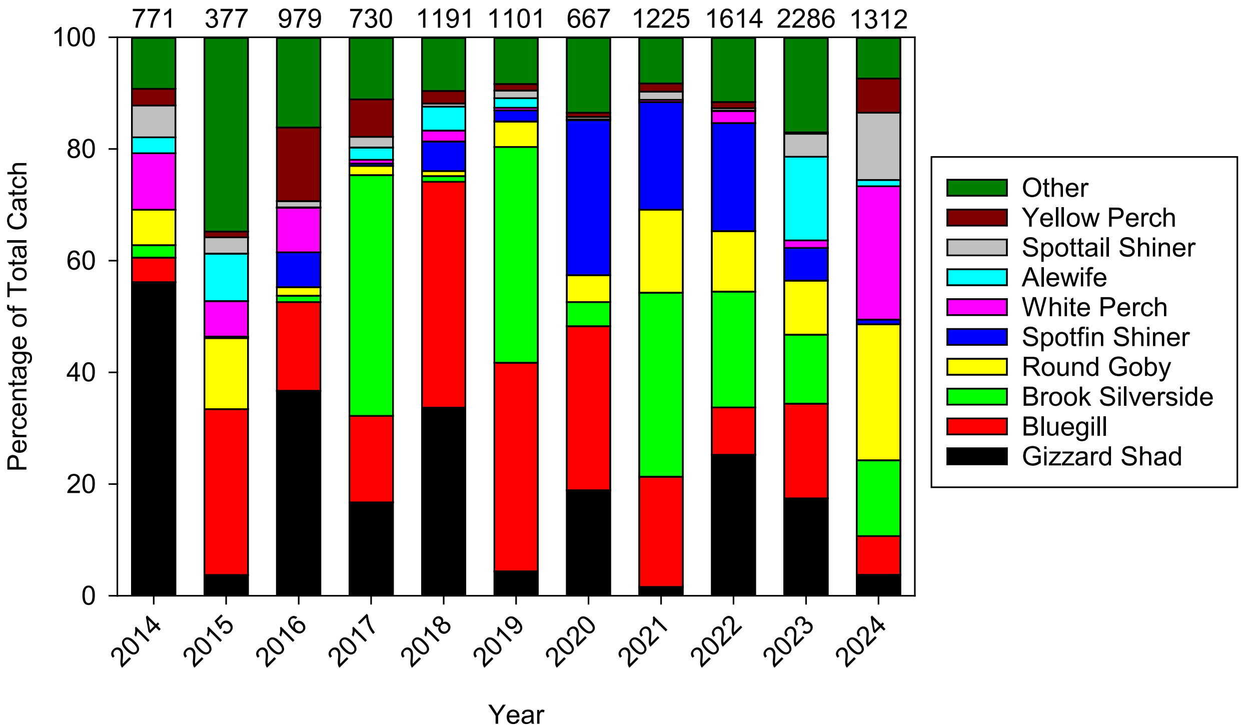

Figure 7. Fish species composition (pooled across sites) in fyke netting surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar. The 5,288 Brook Silversides captured in a single fyke net at site #4 in 2017 were excluded from the percentage of total catch and the number of fish reported at the top of the bar; fyke nets were not set at site #3 in 2020.

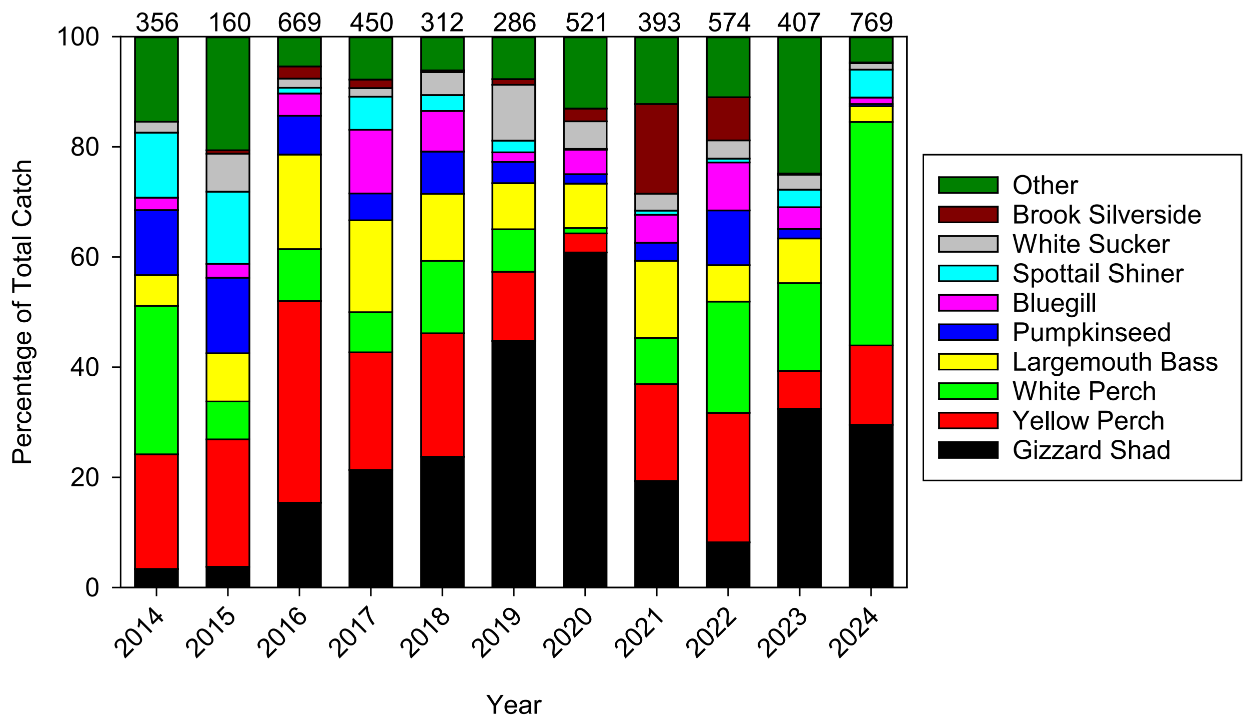

Figure 8. Fish species composition (pooled across sites) in nighttime boat electrofishing surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar. The fewest fish were captured in 2015, and the most were captured in 2024.