PROJECT CLARITY
2023 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 has 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). Up until recently, 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 2023, in combination with data reported previously from 2013-2022. 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.

Although it will likely take many years before the benefits of restoration actions in the watershed are expressed in the lake, the trends seen in this report are mixed. There has been continued backsliding in total phosphorus and chlorophyll *a* concentrations compared to 2021 but improvement relative to pre-Project Clarity concentrations. Bioavailable P (soluble reactive phosphorus: SRP) continues to show increases; this is consistent with the findings in the western basin of Lake Erie, which also show declines in TP but increases in SRP (Jarvie et al. 2017). Nonetheless, this is concerning because this is the form of phosphorus that is readily used by algae. The amounts of TP and chlorophyll remain well above the target of a healthy lake. We conclude with recommendations for the future, including continued efforts to reduce phosphorus and sediment transport in the watershed, consideration of installing "a lake observatory", continued monitoring of key environmental parameters, consideration of in-lake restoration activities, and re-examination of a public works project to treat Macatawa River inflow with chemical inactivants to bind phosphorus.

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 2023 (Table 1, Fig. 1). The sampling sites 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 calculated as ½ the detection limit for the purposes of analysis.

Mann-Whitney rank sum tests 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 2021 – fall 2023) 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 R statistical software (v4.3.0; R Core Team 2023).

In addition, 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 >2 µg/L. Since Lake Macatawa is used only for recreation, we applied the latter two criteria.

Table 1. Location and 2023 water column seasonal mean depth at Lake Macatawa long-term monitoring locations.

Site	Latitude	Longitude	Depth (m)
1	42.7913	-86.1194	8.4
2	42.7788	-86.1525	5.3
3	42.7872	-86.1474	3.7
4	42.7755	-86.1822	10.1
5	42.7875	-86.1820	4.4

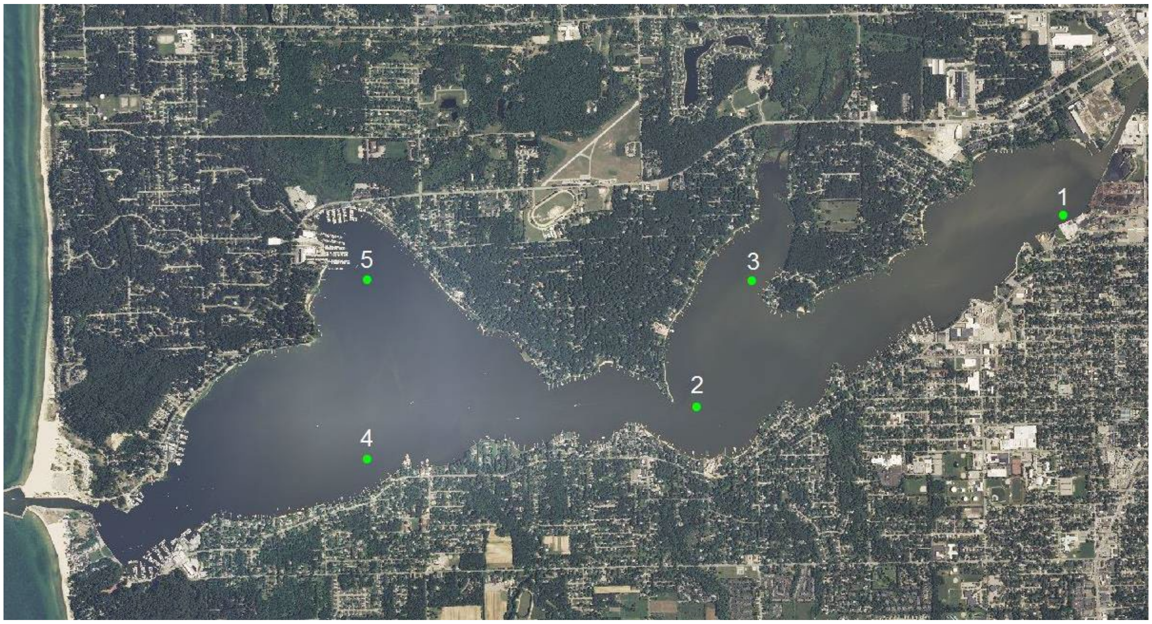

Figure 1. Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring.

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 TP concentrations in Lake Macatawa compared with precipitation amounts from the Tulip 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. 2023), 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 2013-2023 was summarized via Excel PivotTable 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. The best fits based on the 2020 results were applied to the 2023 data: the SRP fit is best with 2-month data while the TP fit is best with 1-day precipitation data.

3. Results and Discussion

3.1 Sampling Year 2023

General water quality parameters followed expected trends for lakes across seasons (Table 2). DO was supersaturated in the spring with surface concentrations exceeding 12 mg/L at all sites and bottom concentrations ranging 7-11 mg/L (Figure 2). Summer DO was strongly stratified, and bottom depths at sites 1, 2, and 4 in the thalweg of Lake Macatawa ranged 0-2 mg/L, continuing a long-term trend of very low summer DO concentrations (Figures 2B, 3B).

Multiyear LOWESS (locally weighted scatterplot smoothing) analysis of summer DO in bottom depth samples shows that 2023 continued a multiyear decrease from 2018-2019's recent higher DO concentrations. This trend is apparent when considering both the main flow of Lake Macatawa (Sites 1, 2 and 4; Fig. 4A) or when considering all five lake sites (Fig. 4B).

Mean specific conductivity ranged 423-571 µS/cm across all sites and depths, and were lowest (423-504 µS/cm) in summer (Table 2). Turbidity varied both by season, being lowest in spring, and also by depth, being greatest at the near-bottom depths; however, it's possible that these high values may be the result of water quality sondes touching lake bottom and stirring sediment (Table 2). Mean water clarity as measured by Secchi disk depth was <1 meter in all seasons (Table 2).

Table 2. Lake-wide means (1 SD) of select general water quality parameters recorded during 2023 monitoring year. Data are shaded for readability. Dates of sampling events: 5/23/2023; 7/25/2023; 10/24/2023. "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)	Turbidity (FNU)	Secchi Depth (m)
Spring	Surface	5	18.45 (1.11)	14.21 (1.43)	551 (61)	6.7 (1.0)	0.7 (0.1)
	Middle	5	16.10 (1.00)	10.54 (2.18)	555 (78)	7.9 (0.9)	
	Bottom	5	14.79 (2.08)	9.58 (2.04)	502 (95)	14.4 (4.5)	
Summer	Surface	5	25.84 (0.53)	11.51 (0.83)	499 (67)	9.6 (2.3)	0.8 (0.1)
	Middle	5	25.06 (1.01)	7.56 (2.04)	504 (95)	8.7 (3.2)	
	Bottom	5	22.21 (3.05)	2.97 (2.76)	423 (64)	21.9 (25.3)	
Fall	Surface	5	11.76 (0.13)	9.51 (0.48)	554 (94)	9.0 (1.9)	0.7 (0.1)
	Middle	5	11.73 (0.12)	9.37 (0.57)	555 (95)	9.6 (2.3)	
	Bottom	5	11.74 (0.13)	9.23 (0.66)	571 (109)	11.0 (2.6)	

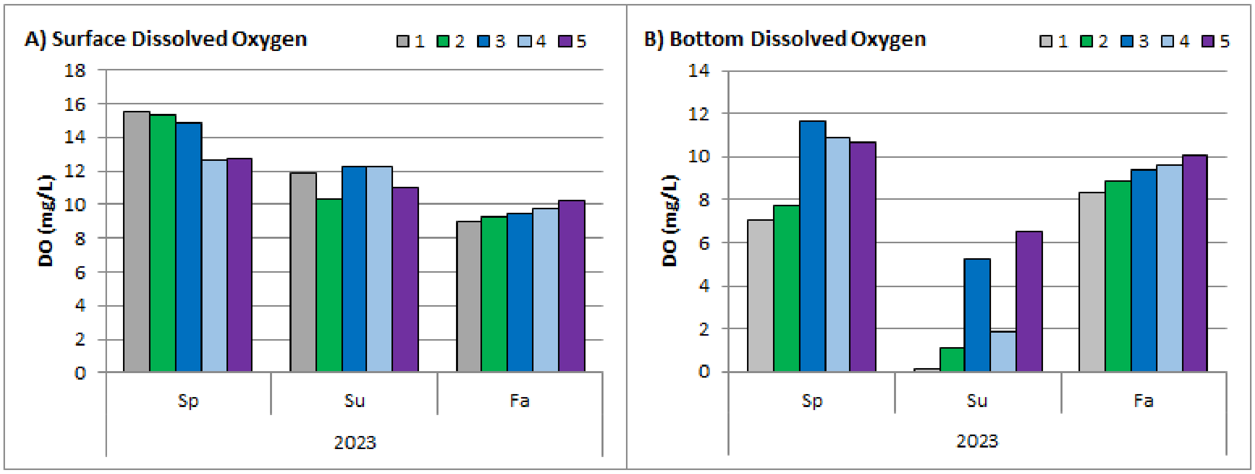

Figure 2. Dissolved Oxygen: A) surface; B) near-bottom concentrations measured at the 5 monitoring stations in Lake Macatawa during 2023.

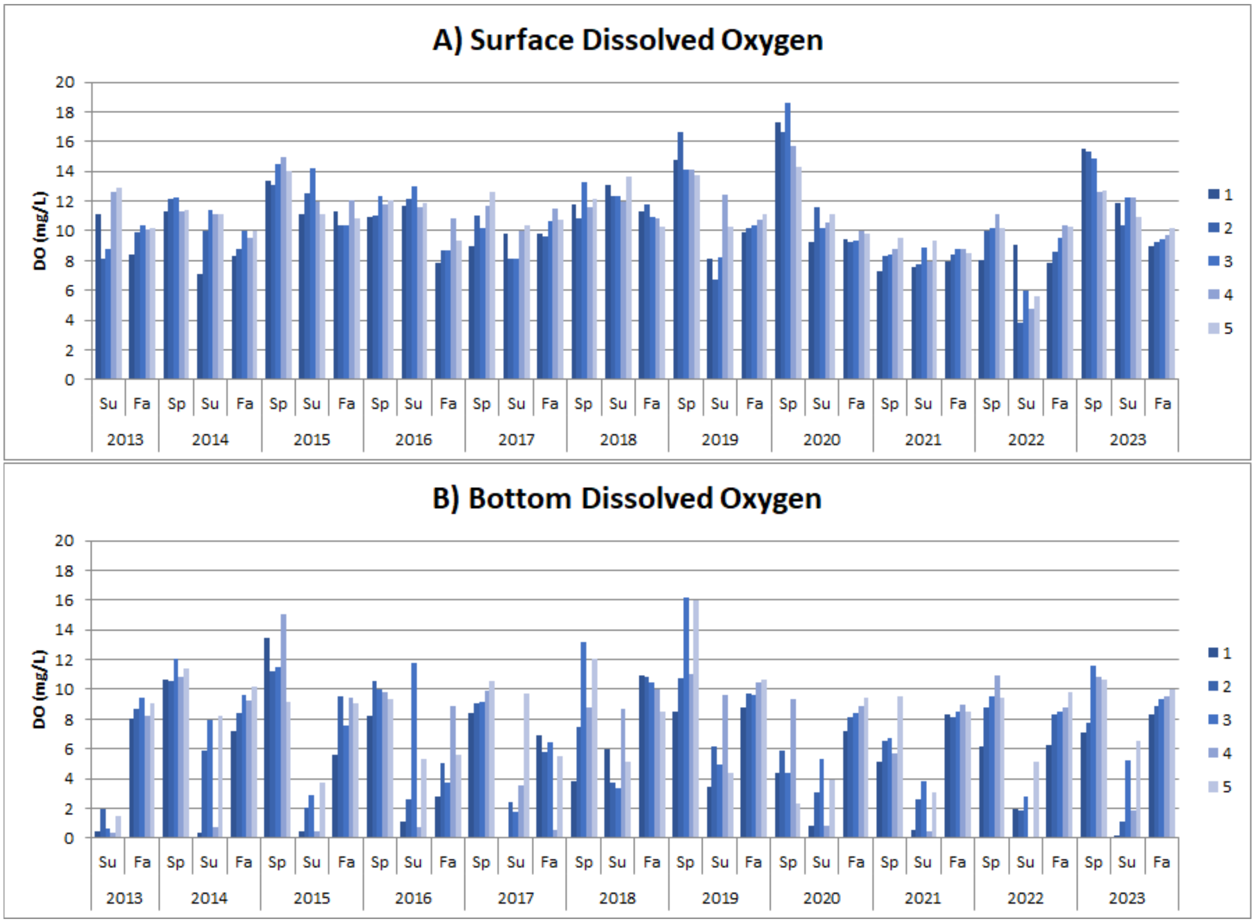

Figure 3. Dissolved Oxygen: A) surface; B) near-bottom concentrations measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2023.

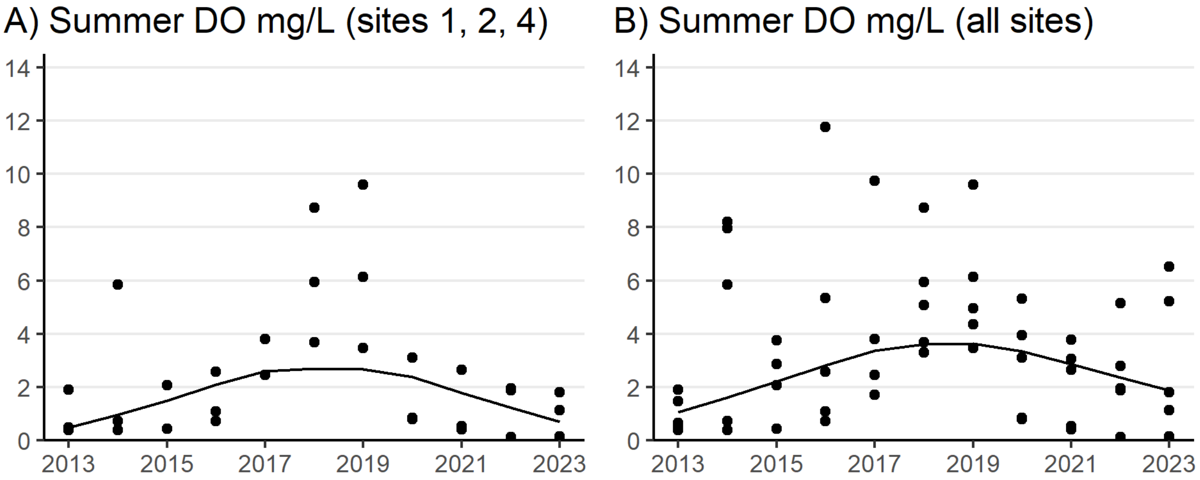

Figure 4. Locally weighted scatterplot smoothing (LOWESS) trend analyses of bottom summer DO site data from Lake Macatawa. A) Sites 1, 2, and 4 represent the main flow of Lake Macatawa via the Macatawa River watershed. B) All 5 sites, including the lake's northern Big Bay and Pine Creek Bay.

Mean surface and near-bottom SRP concentrations were considerably lower in spring and fall than in summer (Table 3), with individual sites having concentrations either below detection (<5 µg/L) or ranging 5-13 µg/L at all sites (Fig. 5A). Summer SRP concentrations ranged 15-68 µg/L, and the highest concentrations were found at the near-bottom at sites 1 and 5, possibly due to P release from the sediment at these sites (Figure 5B). The low SRP concentrations at the surface in summer likely reflect uptake by the actively growing algal community. Mean TP concentrations followed similar seasonal patterns at both sampling depths, with summer concentrations exceeding spring and fall, and the highest observed 2023 value was 235 µg/L at Site 1 surface in summer (Table 3, Figure 5C). This very high surface TP concentration at Site 1 quickly dissipated at the other 4 downlake sites, the TP concentrations were still high. Indeed, all surface TP samples except for one spring sample exceeded the TP TMDL limit of 50 µg/L for Lake Macatawa (Figure 5C).

Similar to phosphorus, chl *a* concentrations peaked in summer compared to other seasons and were highest at surface sampling depths, with the highest concentration of 241 µg/L being found at Site 1, closest to the Macatawa River inflow (Figure 5E). Indeed, all surface chl *a* samples exceeded the 22 µg/L chl *a* TMDL limit for Lake Macatawa.

Microcystin concentrations were tested at all seasons, sites, and depths and reached an observed maximum of 0.96 µg/L, below World Health Organization and Environmental Protection Agency guidelines for recreational waters (20 µg/L and 2 µg/L, respectively; data not shown). Although generally similar across sampling depths, 2023 microcystin concentrations in Lake Macatawa saw a strong seasonal trend, being lowest in spring (0.04-0.17 µg/L), increasing throughout the lake in summer (0.12-0.76 µg/L), and reaching up to 0.97 µg/L in fall (data not shown). Fall sampling also showed a strong spatial trend across sites with the western downstream end closest to Lake Michigan having relatively high concentrations (sites 4+5; 0.70-0.97 µg/L), central sites being midrange (sites 2+3; 0.26-0.37 µg/L), and the eastern end of the lake closest to the watershed having the lowest concentrations (Site 1; 0.09-

0.13 µg/L; data not shown). However, all these concentrations remain well below regulatory guidelines, only reaching half of the stricter 2 µg/L recreational guideline from EPA.

Nitrate concentrations varied seasonally, being lowest in the summer and highest in fall, when they reached 2.6-2.8 mg/L at Sites 1 and 2 (Table 3, Figure 6A). Mean surface ammonia concentrations were lowest in spring and higher in summer and fall, with concentrations at Sites 1 and 2 being up to 1 mg/L greater than at the remaining downstream sites (Figure 6C). Near-bottom ammonia concentrations were <0.5 mg/L and were highest in summer (Table 3, Figure 5D). Mean TKN concentrations ranged <3 mg/L, were higher in surface than near-bottom depths, and decreased seasonally from spring through fall (Table 3, Figures 6E-F). These data suggest that N release from bottom sediments in summer were influencing P much more than N.

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 2023 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.

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	Surface	5	6 (3)	91 (23)	0.85 (0.17)	0.18 (0.23)	2.12 (0.60)	43 (16)	0.12 (0.04)
	Bottom	5	3 (1)	62 (19)	0.74 (0.10)	0.01 (0.01)	1.59 (0.46)	37 (24)	0.11 (0.05)
Summer	Surface	5	24 (27)	172 (49)	0.17 (0.12)	0.57 (0.57)	2.07 (0.46)	113 (80)	0.56 (0.15)
	Bottom	5	21 (12)	130 (36)	0.08 (0.04)	0.22 (0.15)	1.44 (0.72)	61 (34)	0.34 (0.19)
Fall	Surface	5	6 (5)	100 (15)	2.02 (0.62)	0.46 (0.38)	1.81 (0.60)	47 (9)	0.50 (0.36)
	Bottom	5	3 (0)	76 (22)	0.73 (0.46)	0.05 (0.06)	1.03 (0.21)	48 (9)	0.46 (0.31)

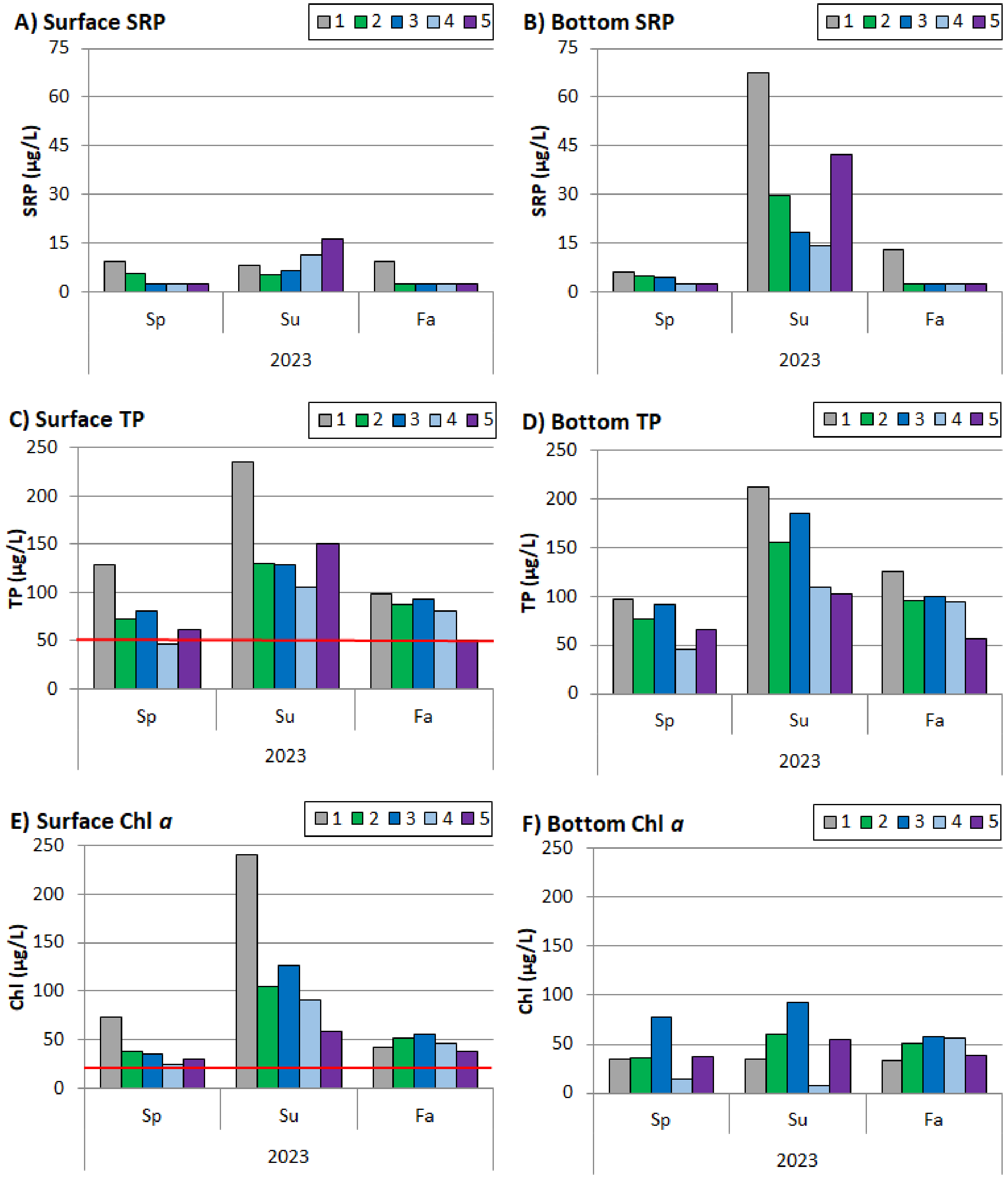

Figure 5. Soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); and chlorophyll *a* ([chl *a*]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2023. The red horizontal line on surface TP (C) indicates the interim total maximum daily load (TMDL) 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.

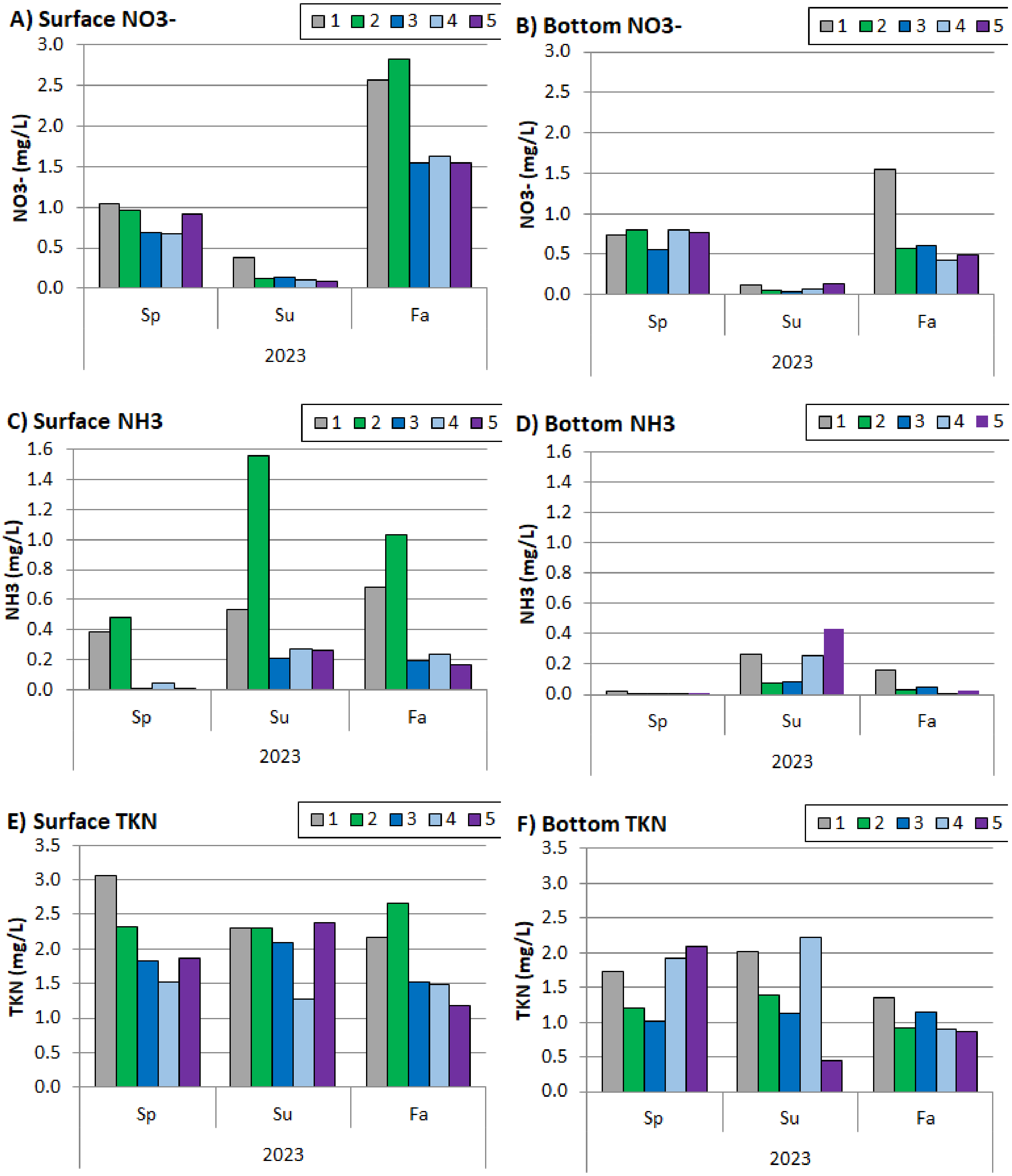

Figure 6. Nitrate ([NO_3^-]: A, B); ammonia ([NH_3]: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2023. Note scales change on y-axes.

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), which is influenced by: 1) the lake's hydraulic residence time (those with shorter residence times respond faster); 2) the quantity, quality, and location of implemented management interventions in the watershed (cf. Fales et al. 2016, Steinman et al. 2018; Iavorivska et al. 2021); and 3) the importance of internal nutrient loading in 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, this monitoring effort helps establish baselines and allows the evaluation of trends.

SRP concentrations were comparable to previous years and lowest in the spring (Table 4; Figure 7A, B). Surface and near-bottom TP concentration peaks in summer 2023 were high compared to other post-restoration years, although concentrations on average were lower than the previous summer spike in 2022 (Table 4; Figure 7C, D). Likewise, chl *a* continued to peak in summer, and 2023 had the highest chl *a* concentrations measured to date in the post-restoration monitoring period (Table 4, Figure 8A, B). Water clarity continued to show signs of improvement compared to pre-restoration conditions but has generally declined from 2021, which was the clearest year on record in the post-restoration era (Figure 8C).

No pre-restoration data exists for any of the nitrogen forms measured in this study (nitrate, ammonia, TKN); however, the long-term trends appear to be stable or slightly improved in most ways. A nitrate spike (relative to other sites) that was previously seen during fall sampling at Site 1 at bottom depth was detected again in 2023 but has continued to decrease since 2021 and was recorded within the concentration range of other fall samples (Figure 9B). Ammonia showed no changes at surface depth, but near-bottom samples in 2023 were some of the lowest on record (Figure 9C, D). TKN concentrations were similar to previous years, and bottom depth sites that had TKN spikes in 2022 returned to more normal concentrations for Lake Macatawa in 2023 (Figure 9E, F).

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 2021 – fall 2023) to assess changes over time (Fig. 10). SRP post-restoration remains significantly greater than the pre-restoration at both depths (Fig. 10A, B). Mean TP and chl *a* (which in 2022 and previous report years showed a significant improvement from pre-restoration condition) now show no significant differences between pre- and post-restoration monitoring periods (Figures 10C-F). Although chl *a* was not different, water clarity as measured by Secchi disk depth has significantly improved in the post-restoration era (i.e., clarity extended to a greater depth; Figure 10G).

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 2023). Data are color coded for readability. 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	8	12 (18)	97 (52)	1.30 (0.44)	0.27 (0.24)	1.81 (0.32)	52 (27)	0.7 (0.3)
	Bottom	Pre	2	3 (1)	98 (30)	ND	ND	ND	24 (3)	
		Post	8	12 (18)	96 (54)	1.21 (0.45)	0.43 (0.30)	1.70 (0.51)	36 (14)	
Summer	Surface	Pre	3	6 (3)	110 (66)	ND	ND	ND	67 (39)	0.4 (0.1)
		Post	8	15 (20)	95 (49)	0.46 (0.65)	0.32 (0.16)	1.57 (0.32)	67 (31)	0.8 (0.2)
	Bottom	Pre	3	17 (18)	107 (49)	ND	ND	ND	32 (13)	
		Post	8	23 (30)	105 (55)	0.41 (0.50)	0.52 (0.25)	1.56 (0.45)	34 (15)	
Fall	Surface	Pre	3	10 (12)	134 (23)	ND	ND	ND	63 (43)	0.4 (0.1)
		Post	8	8 (5)	76 (14)	1.07 (0.73)	0.42 (0.22)	1.46 (0.31)	50 (22)	0.6 (0.1)
	Bottom	Pre	3	11 (13)	158 (19)	ND	ND	ND	61 (35)	
		Post	8	16 (16)	88 (16)	1.12 (0.75)	0.36 (0.24)	1.37 (0.32)	43 (12)	

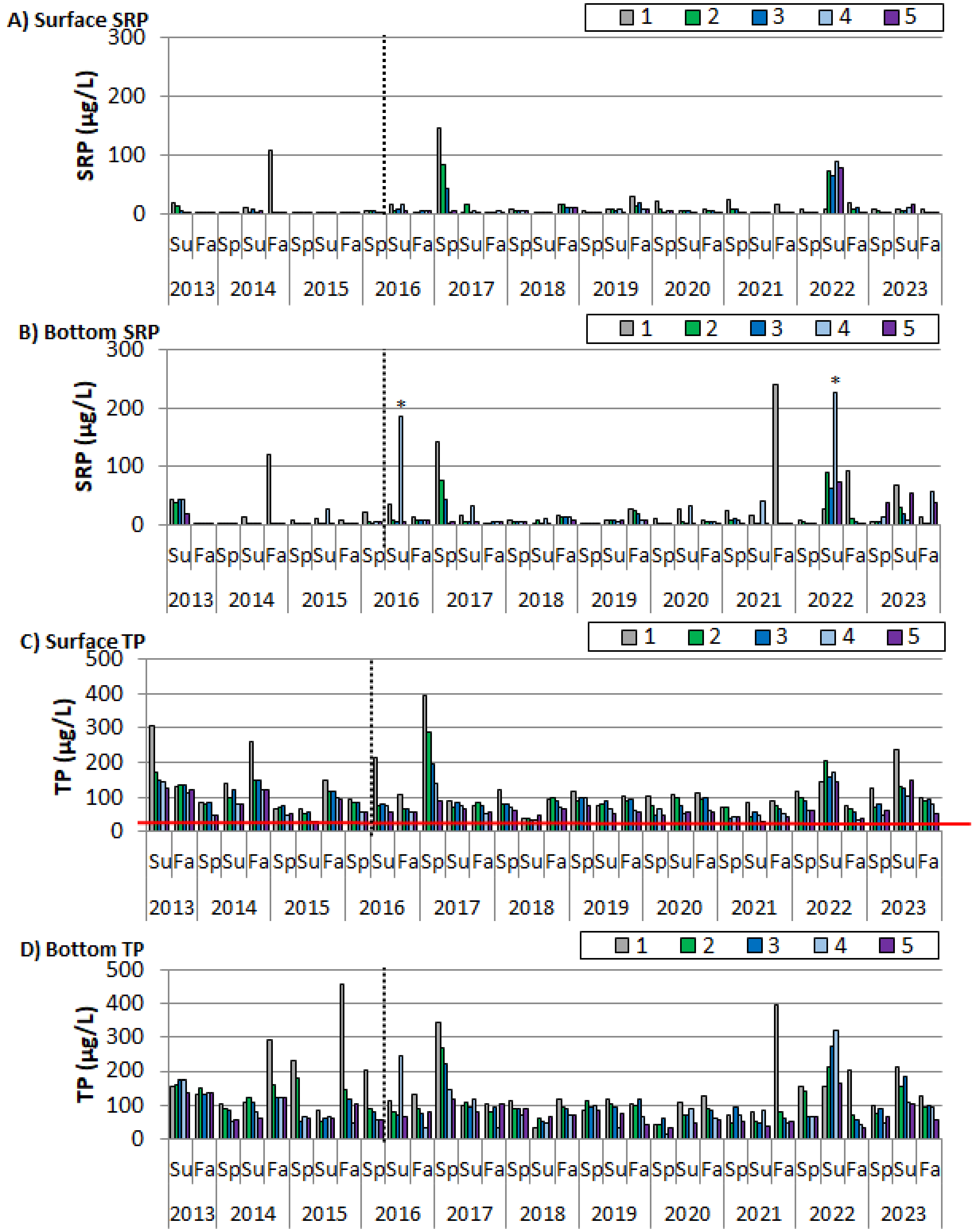

Figure 7. Soluble reactive phosphorus ([SRP]: A, B) and total phosphorus ([TP]: C, D) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2023. The red horizontal lines on surface TP (C) indicate the interim total daily maximum load (TMDL) goal of 50 µg/L (Walterhouse 1999). Note scales change

on y-axes. 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.

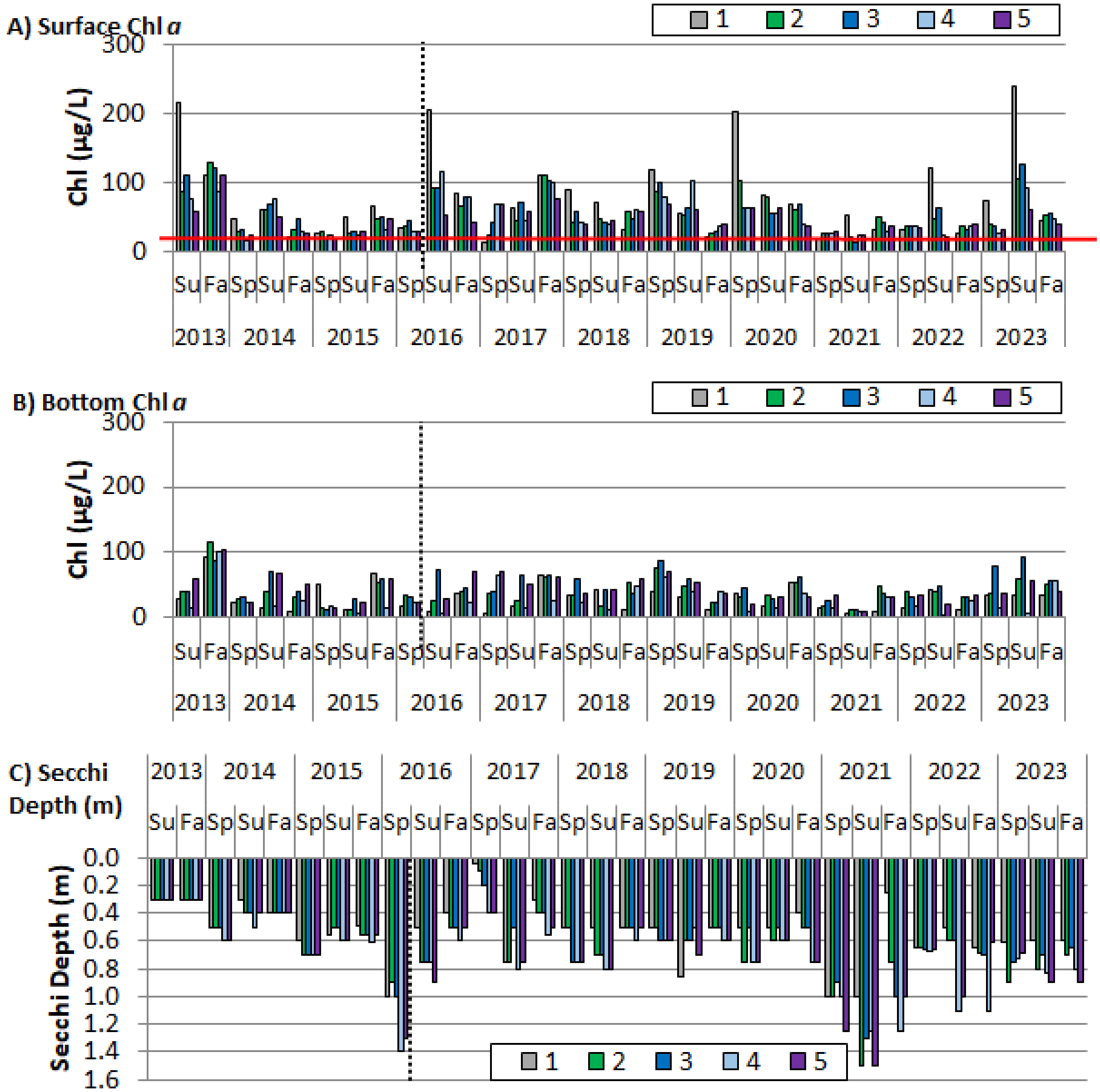

Figure 8. Chlorophyll *a* ([chl *a*]: A, B); and Secchi disk depth: (C) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2023. The red horizontal line on surface chl (A) indicates the hypereutrophic boundary of 22 µg/L used by EGLE to assess chl *a* in Lake Macatawa (Holden 2014). Note scales change on y-axes. Vertical dotted lines represent approximate restoration construction completion dates for Middle Macatawa and Haworth wetlands.

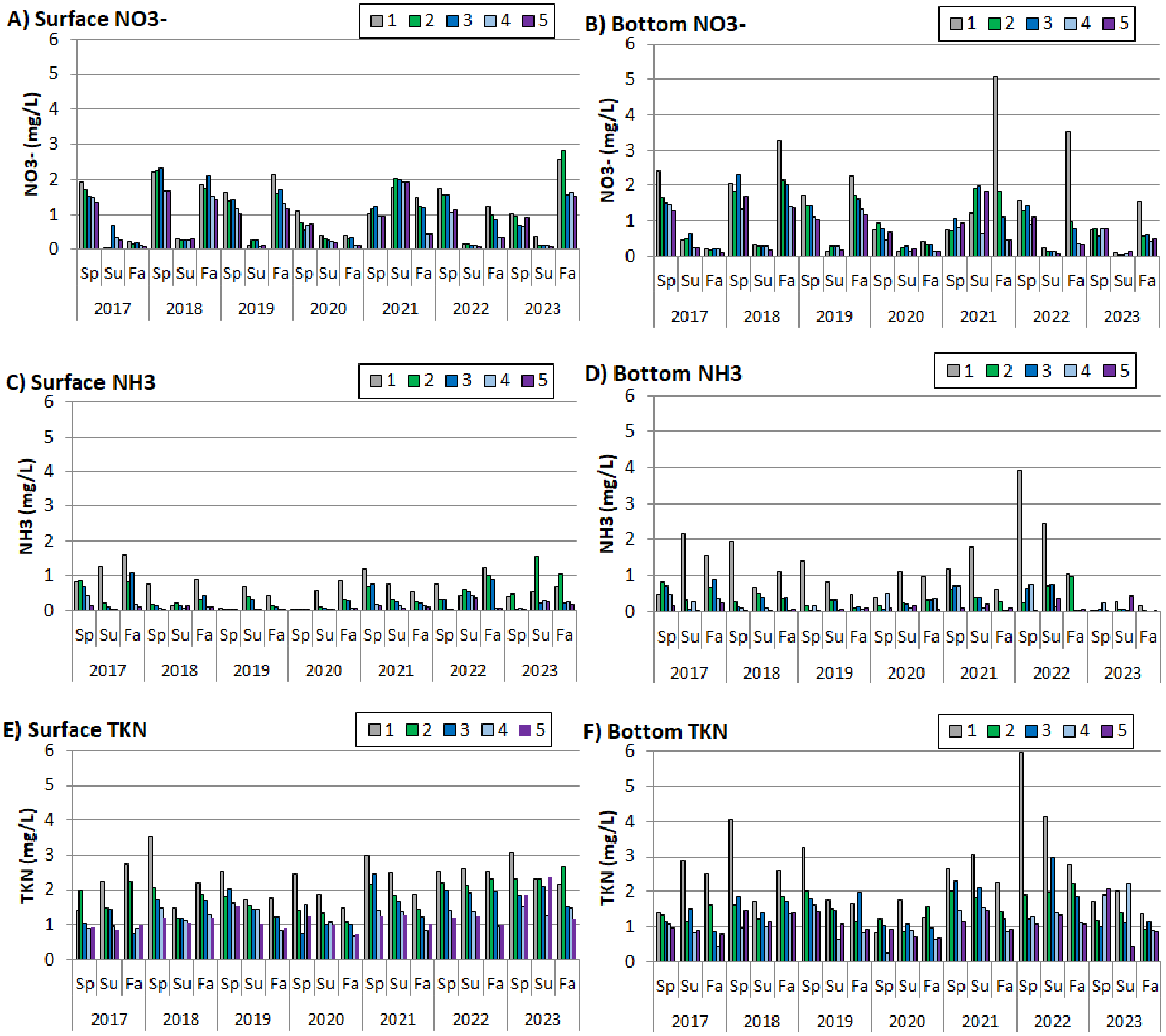

Figure 9. Nitrate ($[NO_3^-]$: A, B); ammonia ($[NH_3]$: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2017 through 2023. Note scales change on y-axes.

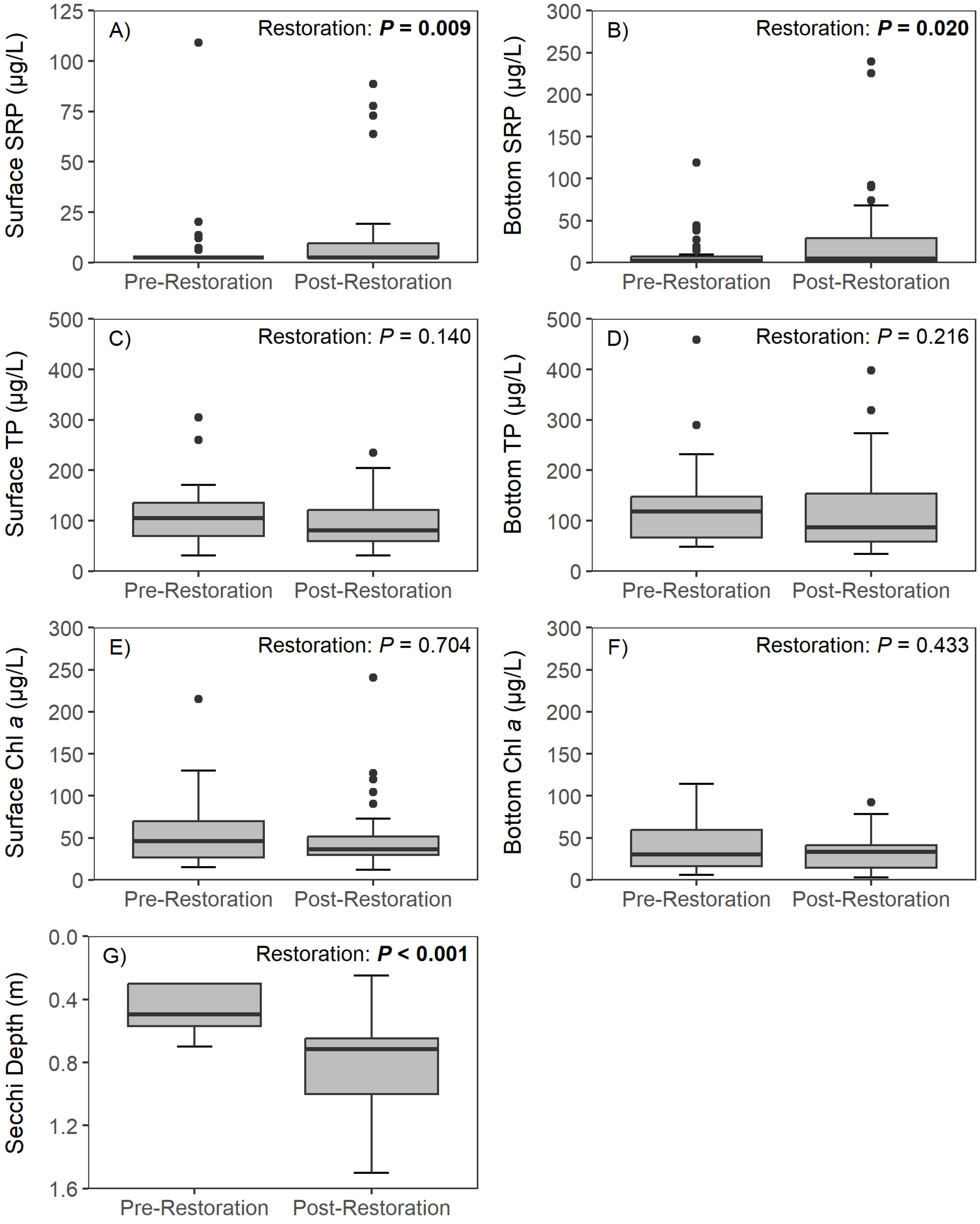

Figure 10. Box plots of soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); chlorophyll *a* ([chl *a*]: E, F; and Secchi disk depth: G) levels measured at the 5 monitoring stations in Lake Macatawa during all pre-restoration sampling dates (summer 2013 – fall 2015) and an equal and seasonally corresponding number of post-restoration sampling dates (summer 2021 – fall 2023). 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. P-values are results of Mann-Whitney rank sum tests of pre- vs. post-restoration data; bold values indicate statistical significance (α = 0.05). Note scales change on y-axes.

3.3 Lake Macatawa Precipitation-Phosphorus Relationship

Phosphorus 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.

Using the best-fit precipitation periods determined in previous years' analyses (Hassett et al. 2023), surface SRP and TP values were regressed upon precipitation totals in the period preceding each sampling event (2 months for SRP, 1 day for TP; Fig. 11). The results support a weak but statistically significant underlying relationship between precipitation and P content of the lake.

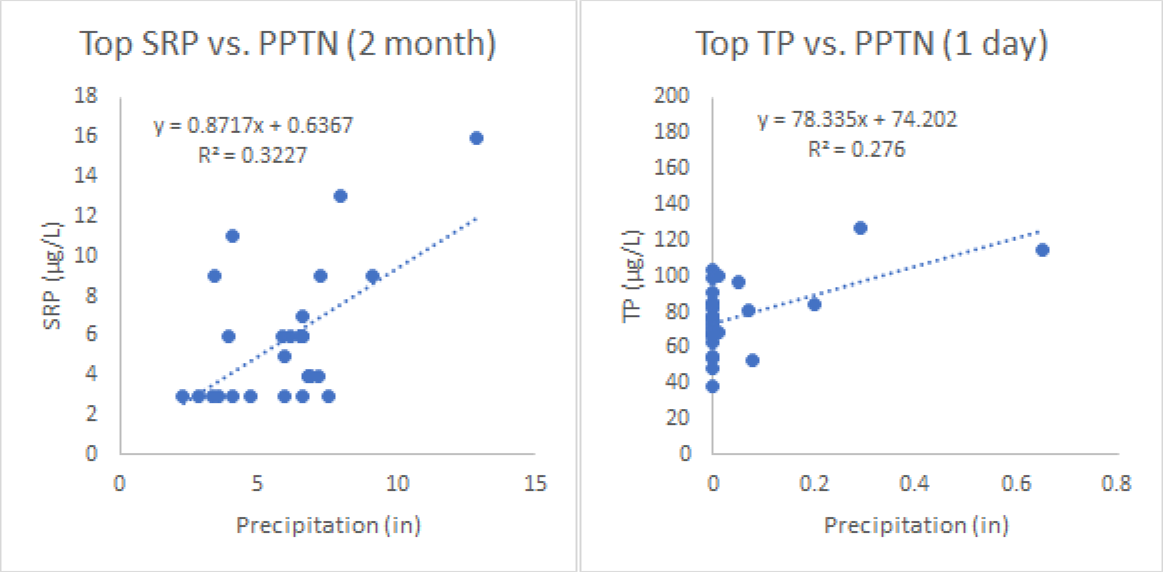

Figure 11. Linear regressions plotting annual precipitation vs. mean soluble reactive phosphorus (SRP) and total phosphorus (TP) concentrations in Lake Macatawa. Surface SRP and TP data are lake-wide means of seasonal 2013-2023 AWRI sampling events. Precipitation data sources were provided by the National Climatic Data Center/National Centers for Environmental Information (2013-2023; NOAA).

4. Summary

During the 10 years since Project Clarity has been initiated, there has been a tremendous amount of work undertaken in the watershed to restore the system, implement best management practices, and educate the stakeholders about the watershed. These activities have collectively improved water quality in the localized 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. The impacts on Lake Macatawa 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).

A lag time is consistent with the results from the 2023 water quality study in Lake Macatawa, which revealed mixed results. The high TP and chl a concentrations in 2023 continued to show some of the backsliding we observed in 2022, compared to the 2021 data. The 2023 summer spike in TP was similar to the one observed in 2022. While bottom TP concentrations were elevated (~200 µg/L), these were somewhat lower than what we measured in 2022, and also modest compared to other local lakes experiencing internal phosphorus loading, where TP concentrations can reach over 1,000 µg/L (Steinman et al. 2004, 2009). Summer chl *a* concentrations were quite elevated, and indicative of bloom conditions. On the other hand, SRP concentration, the bioavailable form of P in the water, declined from the 2022 increase.

Our pre- vs. post-restoration (2013-15 vs. 2021-23) data comparison of 3 critical water quality indicators (TP, chl *a*, and water clarity) indicated increasing surface and bottom SRP concentrations, non-statistically significant differences in TP concentration, and improving water clarity. As noted last year, increases in dissolved inorganic phosphorus (SRP) values have increased significantly over time; this is the bioavailable form of P, so its increase is of concern. It is unclear if this increase is related to soil tillage practices in the watershed, as has been observed in the Maumee River watershed in Lake Erie (Daloglu et al. 2012; Jarvie et al. 2017). We recommend the agricultural community evaluate their tillage practices and continue the implementation of BMPs wherever and whenever possible.

The fall nitrate and ammonia spikes in bottom waters were present in 2023 but much smaller than what we measured in 2021 and 2022. It is unclear if this reduction is due to changes in agricultural practices (e.g., planting of cover crops) or weather conditions; regardless, it is a welcome reversal. Utilization of the computational SWAT model for the Macatawa watershed (Iavorivska et al. 2021) can help producers identify appropriate agricultural practices to reduce nitrogen and phosphorus runoff from the watershed.

As is the case in all of our reports, we recommend that the results from any one year be viewed with caution; with only 3 sampling dates per year, it is very possible that results from one site or data can overinflate its importance. Hence, the 2023 water quality data need to be evaluated in light of multiyear trends; although the past year's results suggest a lack of progress, when assessed over multiple years there is overall improvement in Lake Macatawa water quality. Nonetheless, it is clear that the current phosphorus and chlorophyll concentrations are well above what should be observed in a "healthy" lake, although the low microcystin concentrations are a positive sign. Current management efforts need to be maintained and additional measures should be considered. We caution once again that it can take decades for actions in the watershed to result in improvements in a lake.

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 improvement, but still are 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. 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, Yellow Perch catch in 2023 was among the lowest in 10 years of monitoring in Lake Macatawa (lowest for fyke netting and second lowest for boat electrofishing). Other common fish species in those 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).

We conclude with a list of recommendations for the ODC and partners to consider as Project Clarity enters its second decade of planning, implementation, and management; these mostly repeat what we have presented previously, as the need for each of them is still relevant:

- Although the current monitoring program provides important baseline information from which to assess Lake Macatawa water quality trends across time and space, grab samples taken only 3× per year leaves information gaps and may create a biased picture of lake status. We recommend again investigating the installation of a monitoring observatory in the lake, which can provide near real-time data on a continuous basis throughout the time it is deployed. There are scaled-down models that can provide basic water quality information, which can be supplemented by the monitoring data currently collected, as reflected in this report.

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

- The current monitoring program does not analyze two important biotic components in the lake: algal taxonomic composition, and aquatic vegetation biomass and taxonomic composition. The phytoplankton community structure can provide important information on water quality. The 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.

- The 2023 data are consistent with the 2022 data suggesting nutrient release from the sediments may be important, especially in the deeper sites where dissolved oxygen is most likely to be depleted. There has not been a rigorous analysis of internal nutrient loading from sediments in Lake Macatawa. As recommended last year, a lake management plan, including actions, timelines, and costs, should be developed that includes a comprehensive nutrient budget.

- Finally, we recommend re-examining the feasibility of a public works program to treat Macatawa River inflow before it enters Lake Macatawa. In January 2017, Progressive AE delivered their Feasibility Study Final Report to ODC. Their preliminary findings concluded that a centralized alum injection facility may provide an effective means of reducing pollutant levels in the Macatawa watershed, but several critical obstacles impacted feasibility (Progressive AE

2017). A more detailed report that evaluates these obstacles, examines other inactivants besides alum (e.g., Phoslock), and updates the financing, should be considered.

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, and Natalie Huisman 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

2023

Prepared: February 2024

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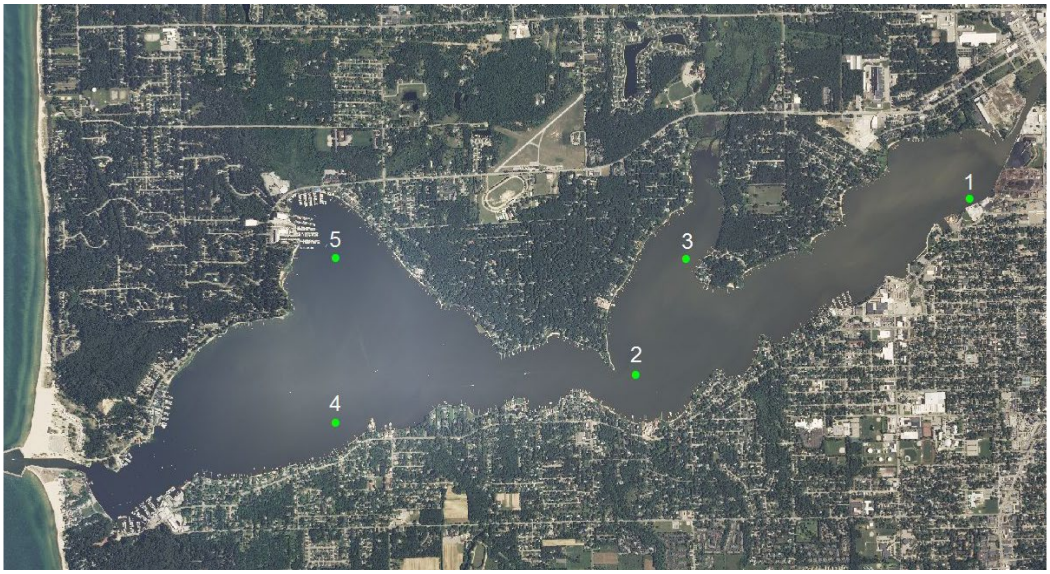
Introduction

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).

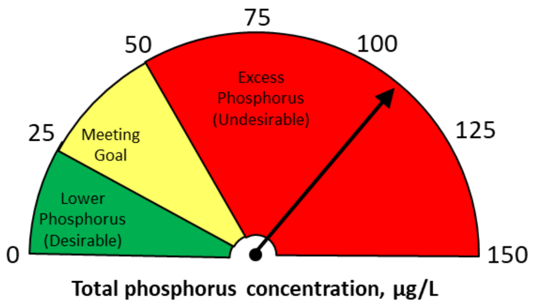


Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring. Dashboard indicators were calculated based on data from Sites 1, 2, and 4.

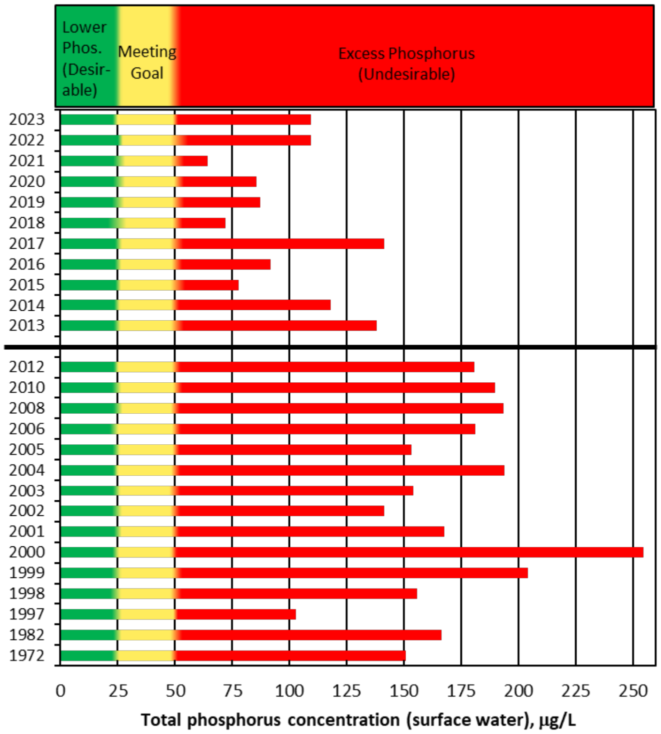
Total Phosphorus

2023 Mean Concentration: 110 µg/L
Target Concentration: 50 µg/L

Current status (2023)



Historical Status (1972*; 1982-2012†; 2013-2023‡)



*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).

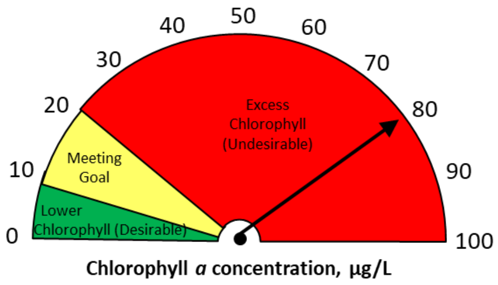
Lake Macatawa has a history of extremely high TP concentrations (i.e., > 100 µg/L), placing it in the past in the "hypereutrophic" trophic state. As a result of this nutrient enrichment, the State of Michigan established an interim target TP concentration of 50 µg/L in Lake Macatawa. Thus, the TP dashboard 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 2023 status for the total phosphorus indicator remains **Undesirable** from 2022, indicating that the average TP concentration in 2023 exceeded the water quality goal. Although the highest 2023 concentrations were found in summer, high concentrations in spring (47-128 µg/L) and fall (81-99 µg/L) show that phosphorus is a year-round problem for Lake Macatawa, and that water quality benefits from activities implemented in the watershed have not yet reached the lake.

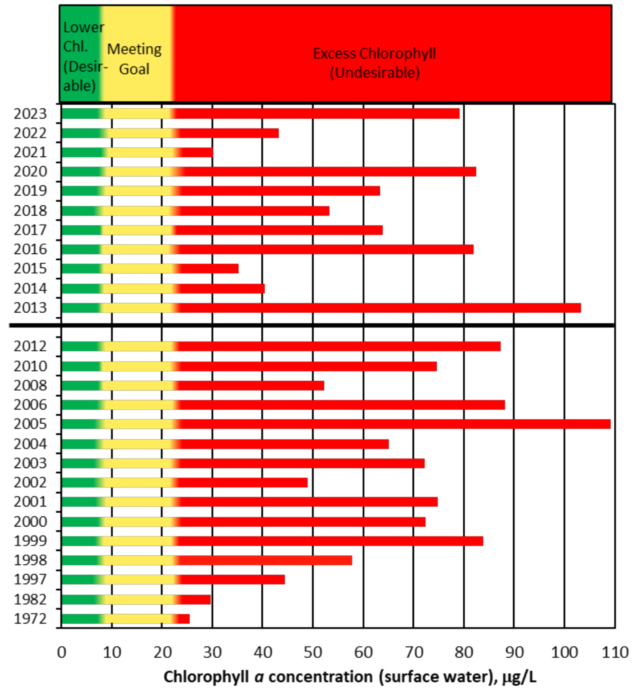
Chlorophyll *a*

2023 Mean Concentration: 79 µg/L
Target Concentration: 22 µg/L

Current status (2023)



Historical Status (1972*; 1982-2012†; 2013-2023‡)



*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.

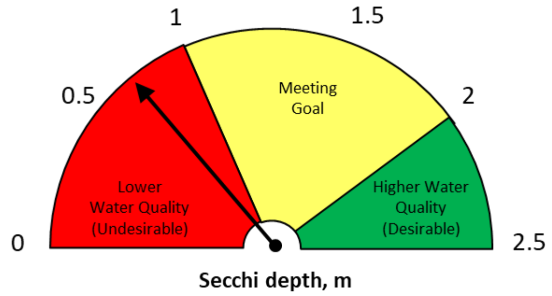
Lake Macatawa has a history of excess algal biomass and high chlorophyll *a* concentrations, typically exceeding the “hypereutrophic” threshold commonly used by EGLE (22 µg/L) in its assessments of the lake. The chlorophyll *a* dashboard shows that the concentration will meet the water quality goal once 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 4× the restoration goal for Lake Macatawa. Although TP concentrations in 2022 and 2023 are similar, mean 2023 chlorophyll *a* concentration is nearly double that of 2022. Indeed, 2023 seems to be the latest in a series of chlorophyll spikes that has occurred every 3-4 years in recent Project Clarity sampling history.

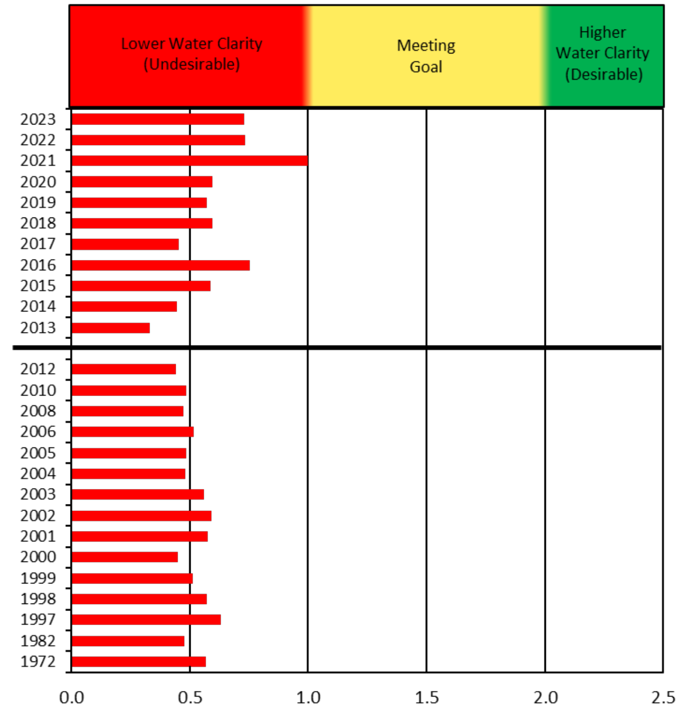
Secchi Disk Depth (Water Clarity)

2023 Mean Depth: 0.73 m (~2.4 ft)
Target Depth: 1 m (~3.3 ft)

Current status (2023)



Historical Status (1972*; 1982-2012†; 2013-2023‡)



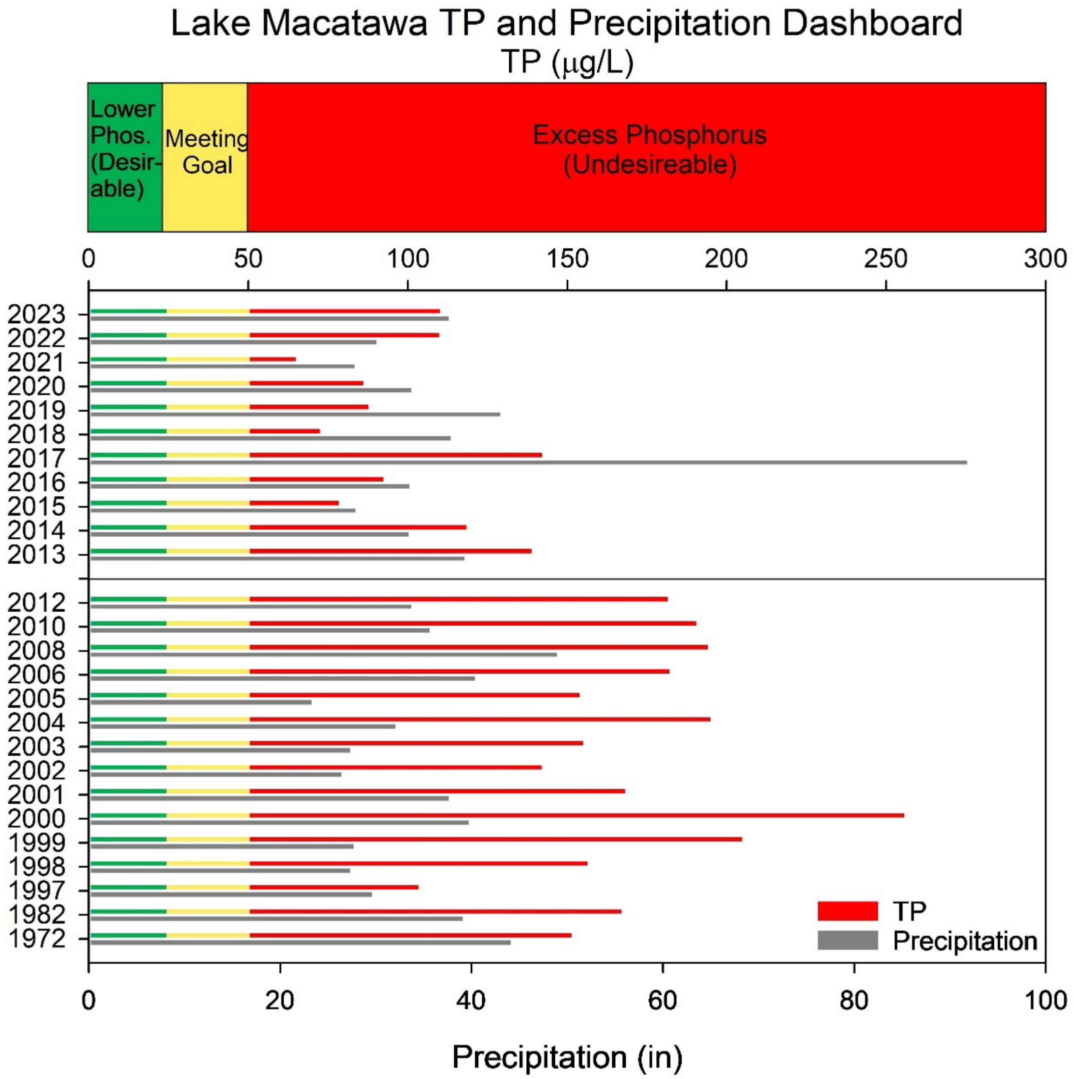
*U.S. EPA; †EGLE; ‡AWRI

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 extremely 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**, meaning that the average Secchi depth remains similar to last year and currently does not meet the criteria of the water quality goal. However, the water clarity is still slightly improved compared to recent sampling years.

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. As a consequence, 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 2022, 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 by considering only the rainfall in the previous day instead of the entire year and is statistically significant (for 2013-2023, $R^2 = 0.32$; $p = 0.003$). 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.

Appendix B. Long-Term Fish Monitoring of Lake Macatawa: Results from Year 10 (2023)

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27 February 2024

An Annual Report to the Outdoor Discovery Center

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Introduction

This study was initiated to provide critical information on littoral fish populations in Lake Macatawa that will be used 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 tenth year (2023) of sampling was to continue to characterize the littoral fish assemblage. We made comparisons with previous 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 began to assess patterns in the data over time. However, the true value of this fish monitoring effort will come as we continue to accumulate data so that we can examine how the littoral fish assemblage responds to restoration activities in the watershed over relatively long time scales.

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 23 September 2023 during daylight hours (i.e., between 0900 and 1300) and fished for about 26.9 h (range = 24.0-29.8 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 21 September 2023. All previous nighttime electrofishing surveys were conducted during 5-22 September (2014-2022). 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 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 6600 multi-parameter data 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 2023 (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. The mean water depth at fyke nets was 83 cm (Table 2), which was similar to the long-term mean water depth of 91 cm (range = 83-104 cm; *n* = 10 years) at fyke nets. Mean water temperature during fyke netting (20.6 °C; Table 2) was similar to conditions during nighttime boat electrofishing (21.9 °C; Table 3). The long-term mean water temperature during fyke netting was 22.2 °C (range = 18.3-25.5 °C; *n* = 10 years) and nighttime boat electrofishing was 21.9 °C (range = 19.2-24.2 °C; *n* = 10 years). We were unable to estimate percent macrophyte cover at sites during fyke netting (because of a lack of water clarity), although we were able to visually estimate percent macrophyte cover during nighttime electrofishing: 50% at site #1, 75% at site #2, 80% at site #3, and 35% at site #4. The percent macrophyte cover in 2023 appeared similar to recent years (Figure 2B). 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 (21.8 NTU, *n* = 12 nets) in 2023 greater than the long-term mean (17.1 NTU, *n* = 120 nets; Figure 3) during 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 2,693 fish comprising 26 species in Lake Macatawa during 2023 sampling surveys (Table 4). The total catch in 2023 was above the long-term mean of 1,507 fish (SD = 597, *n* = 10 years), but the number of fish species captured was similar to the long-term mean of 27 species (SD = 2.7, *n* = 10 years; Figure 4). The most common fishes in the combined catch (i.e., fyke netting and boat electrofishing) were Gizzard Shad (20%), Bluegill (15%), Alewife (14%), Brook Silverside (11%), Round Goby (9%), Emerald Shiner (6%), and Spotfin Shiner (5%), which composed 79% of the total catch (Figure 5A). Five of the 26 species captured during 2023 were non-native to the Great Lakes basin (Bailey et al. 2004)—Alewife, Goldfish, Common Carp, White Perch, and Round Goby—which composed 27% of the total catch, although most of the non-native fishes were Alewife, Round Goby, and White Perch (Table 4). For comparison, we captured 1,092 fishes comprising 27 species in Muskegon Lake during autumn 2023 (with sampling effort in terms of sites and gear similar to the sampling reported here for Lake Macatawa). Four of the 27 species in Muskegon Lake were non-native to the Great Lakes basin—Alewife, Common Carp, White Perch, and Round Goby—which composed 19% of the catch (82% of non-native fish species captured in Muskegon Lake in autumn 2023 were Round Goby). Rock Bass—associated with excellent biotic integrity (Cooper et al. 2018)—composed about 9% of the catch in Muskegon Lake during autumn 2023, whereas this species was not captured in Lake Macatawa during 2023.

In fyke netting, Gizzard Shad (17%), Bluegill (17%), Alewife (15%), Brook Silverside (12%), and Round Goby (10%) were the most common fishes in the catch, composing 71% of all fish captured (Figure 5B). The most common species in the catch at each site were Bluegill and Gizzard Shad at sites #1 and #2, Alewife and Round Goby at site #3, and Brook Silverside and Emerald Shiner at site #4 (Table 5). The number of fish captured also varied among sites, with the most fish captured at site #1 and the least at sites #2 and #4 (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). The relative abundance (i.e., percentage of a fish species in the total catch for a given year) in 2023 was similar to recent years (particularly 2020 and 2022), although Alewife was a larger component and Yellow Perch a smaller component of the catch (Figure 7).

In boat electrofishing, the most common fishes captured were Gizzard Shad (32%), White Perch (16%), Alewife (10%), Largemouth Bass (8%), and Yellow Perch (7%), which composed 73% of the total catch (Figure 5C). The most common species in the catch were Gizzard Shad and White Perch at sites #1 and #2, Largemouth Bass and White Perch at site #3, and Gizzard Shad and Alewife at site #4 (Table 6). Total catch also varied among sites in 2023, with the highest catch at site #4 and lowest catch at site #1 (Figure 6B). Compared with previous boat electrofishing surveys, the most common species in the catch varied among years (Figure 8). In 2023, Gizzard Shad and Alewife were more common and Yellow Perch was less common in the catch than most previous years (Table 4; Figure 8).

The observations reported here can be used to characterize the littoral fish assemblage of Lake Macatawa. As we continue to build this time series of observations, we will be able to make more robust inferences about the littoral fish assemblage of Lake Macatawa (in terms of assessing the baseline, evaluating change over time, and comparing abiotic and biotic variables with other drowned river mouth lakes in the region) and better identify likely mechanisms driving spatiotemporal patterns. A current graduate student in the Ruetz Lab (Maria Scarborough) is planning to compare and contrast spatiotemporal patterns of littoral fish assemblages in Lake Macatawa and Muskegon Lake as part of her thesis research, allowing for more robust statistical analyses of the data reported here than has been undertaken in this report. Nevertheless, after 10 years of fish monitoring, there are both positive and negative indicators of Lake Macatawa's ecological health. 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, Yellow Perch catch in 2023 was among the lowest in 10 years of monitoring in Lake Macatawa (lowest for fyke netting and second lowest for boat electrofishing). 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 10 years of sampling, 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).

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Table 1. Locations (latitude and longitude) for each 2023 fish sampling site; coordinates are the mean of the three fyke nets and the start and end of each boat electrofishing transect. Approximate site locations are depicted in Figure 1.

			Electrofishing			
	Fyke Netting		Start		End	
Site	Lat (°)	Long (°)	Lat (°)	Long (°)	Lat (°)	Long (°)
1	42.79592	-86.12125	42.79561	-86.12046	42.79518	-86.12344
2	42.79007	-86.14386	42.79040	-86.14449	42.78773	-86.14496
3	42.78620	-86.17459	42.78679	-86.17572	42.78488	-86.17319
4	42.77971	-86.19685	42.77892	-86.19746	42.78097	-86.19447

Table 2. Mean ± 1 standard error (*n* = 3) of environmental variables at fish sampling sites in Lake Macatawa. Water quality measurements were made during fyke netting on 23 September 2023 with a YSI sonde.

Site	Depth (cm)	Water Temperature (˚C)	Dissolved Oxygen (mg/L)	Dissolved Oxygen (%)	Specific Conductivity (uS/cm)	Turbidity (NTU)	pH	Chlorophyll *a* (ug/L)
1	92 ± 5	20.05 ± 0.02	4.99 ± 0.12	55.1 ± 1.4	742 ± 5	18.9 ± 1.3	7.41 ± 0.01	60.6 ± 1.0
2	86 ± 3	20.92 ± 0.03	13.12 ± 0.09	146.9 ± 0.9	503 ± 0	23.7 ± 1.9	8.81 ± 0.01	103.2 ± 0.8
3	84 ± 3	20.40 ± 0.17	9.79 ± 0.06	109.0 ± 0.7	432 ± 0	14.1 ± 0.9	8.88 ± 0.01	36.2 ± 0.9
4	68 ± 3	21.06 ± 0.04	10.37 ± 0.07	116.5 ± 0.6	423 ± 0	30.5 ± 4.1	8.90 ± 0.01	30.6 ± 1.5

Table 3. Water quality variables at fish sampling sites in Lake Macatawa. Water quality measurements were made during nighttime boat electrofishing on 21 September 2023 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	22.57	17.40	201.30	601	9.1	9.01	117.5
2	22.44	20.55	236.40	484	10.4	9.29	87.6
3	22.29	13.27	152.40	419	7.0	9.15	25.6
4	20.18	11.79	130.20	408	8.8	9.06	27.0

Table 4. Number and total length (TL; mean, minimum, and maximum) of fish captured at four sites by fyke netting (n = 12 nets) on 24 September and boat electrofishing (n = 4 transects) on 21 September 2023 in Lake Macatawa. Total is the total catch combined for both gear.

			Fyke netting				Electrofishing			
				TL (cm)				TL (cm)		
Common name	Scientific name[a]	Total	Count	Mean	Min	Max	Count	Mean	Min	Max
Alewife	*Alosa pseudoharengus* [b]	381	342	8.5	3.3	11.2	39	9.2	7.3	10.9
Bowfin	*Amia calva*	5	3	54.6	40.6	65.6	2	49.2	46.4	51.9
Freshwater Drum	*Aplodinotus grunniens*	2	1	42.4	--	--	1	18.9	--	--
Goldfish	*Carassius auratus* [b]	2	0	--	--	--	2	21.0	13.2	28.8
White Sucker	*Catostomus commersonii*	12	1	43.1	--	--	11	37.0	18.9	50.5
Bloater	*Coregonus hoyi*	2	2	6.2	5.7	6.7	0	--	--	--
Spotfin Shiner	*Cyprinella spiloptera*	134	134	5.8	2.6	10.6	0	--	--	--
Common Carp	*Cyprinus carpio* [b]	9	1	39.0	--	--	8	60.8	44.3	76.0
Gizzard Shad	*Dorosoma cepedianum*	530	398	10.6	5.9	19.5	132	11.8	8.1	15.8
Banded Killifish	*Fundulus diaphanus*	55	47	6.2	3.1	9.2	8	8.5	7.0	10.7
Channel Catfish	*Ictalurus punctatus*	4	4	54.2	50.6	62.9	0	--	--	--
Brook Silverside	*Labidesthes sicculus*	284	283	6.8	3.6	9.1	1	6.0	--	--
Pumpkinseed	*Lepomis gibbosus*	40	33	9.0	4.3	17.5	7	14.0	10.9	19.5
Bluegill	*Lepomis macrochirus*	404	388	5.2	2.5	8.1	16	11.6	5.0	19.0
Largemouth Bass	*Micropterus salmoides*	110	77	11.4	5.1	38.7	33	15.7	6.3	44.1
White Perch	*Morone americana* [b]	96	31	8.1	6.2	20.1	65	17.7	7.6	29.6
Round Goby	*Neogobius melanostomus* [b]	231	221	6.5	2.2	13.4	10	8.9	6.5	13.3
Golden Shiner	*Notemigonus crysoleucas*	53	44	9.2	5.2	15.1	9	12.7	8.6	18.3
Emerald Shiner	*Notropis atherinoides*	166	149	8.4	3.6	11.6	17	9.4	7.8	17.4
Spottail Shiner	*Notropis hudsonius*	107	94	8.1	4.6	11.7	13	10.2	8.0	12.7
Yellow Perch	*Perca flavescens*	34	6	15.9	10.6	19.0	28	18.6	15.3	23.5
Bluntnose Minnow	*Pimephales notatus*	22	22	6.0	4.6	8.0	0	--	--	--
Fathead Minnow	*Pimephales promelas*	3	3	6.0	5.0	6.5	0	--	--	--
Black Crappie	*Pomoxis nigromaculatus*	2	1	25.5	--	--	1	26.6	--	--
Western Blacknose Dace	*Rhinichthys obtusus*	1	1	9.0	--	--	0	--	--	--
Walleye	*Sander vitreus*	4	0	--	--	--	4	48.3	22.5	72.0
	Total	2693	2286				407			

[a] Scientific names are based on Bailey et al. (2004).

[b] Species classified as non-native to Michigan (Bailey et al. 2004).

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 24 September 2023. Site locations are depicted in Figure 1.

	Site # 1				Site # 2				Site # 3				Site # 4			
		TL (cm)				TL (cm)				TL (cm)				TL (cm)		
Common Name	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max
Alewife	0	--	--	--	2	9.6	9.6	9.6	328	8.5	3.3	11.2	12	8.3	6.0	9.8
Bowfin	0	--	--	--	0	--	--	--	0	--	--	--	3	54.6	40.6	65.6
Freshwater Drum	0	--	--	--	0	--	--	--	0	--	--	--	1	42.4	--	--
White Sucker	0	--	--	--	1	43.1	--	--	0	--	--	--	0	--	--	--
Bloater	0	--	--	--	0	--	--	--	1	5.7	--	--	1	6.7	--	--
Spotfin Shiner	51	5.6	3.8	9.6	28	7.6	4.9	10.6	4	8.6	7.1	10.4	51	4.7	2.6	8.0
Common Carp	0	--	--	--	0	--	--	--	1	39.0	--	--	0	--	--	--
Gizzard Shad	246	9.5	7.1	19.5	134	12.6	9.2	17.7	11	9.6	5.9	14.3	7	11.8	7.1	14.5
Banded Killifish	2	6.6	6.2	7.0	5	6.9	5.5	8.0	16	6.7	5.2	9.2	24	5.7	3.1	8.0
Channel Catfish	1	51.9	--	--	1	50.6	--	--	1	51.4	--	--	1	62.9	--	--
Brook Silverside	44	7.6	6.0	8.8	46	7.0	5.0	9.1	53	7.0	5.2	8.5	140	6.4	3.6	8.2
Pumpkinseed	7	10.1	5.1	16.8	24	9.0	5.2	17.5	1	4.3	--	--	1	4.8	--	--
Bluegill	298	5.1	2.5	8.1	77	5.4	2.6	7.4	5	4.4	2.6	5.6	8	4.8	3.8	6.1
Largemouth Bass	30	13.0	5.1	38.4	35	11.8	7.0	38.7	2	9.0	7.9	10.0	10	8.5	6.1	11.6
White Perch	1	6.5	--	--	7	8.0	7.5	8.6	21	7.6	6.2	16.9	2	14.0	7.9	20.1
Round Goby	34	5.4	2.3	10.2	38	6.8	2.2	9.5	80	6.6	2.4	11.0	69	6.8	3.1	13.4
Golden Shiner	5	8.7	8.2	9.5	14	8.2	5.2	10.0	18	9.7	8.3	11.5	7	10.4	7.4	15.1
Emerald Shiner	3	9.8	7.8	11.0	0	--	--	--	59	9.0	6.1	11.5	87	7.9	3.6	11.6
Spottail Shiner	15	8.0	6.9	9.1	28	8.3	6.4	11.7	35	8.2	4.7	11.4	16	7.6	4.6	11.5
Yellow Perch	0	--	--	--	2	15.5	15.0	16.0	4	16.1	10.6	19.0	0	--	--	--
Bluntnose Minnow	5	7.1	6.0	8.0	8	6.1	4.6	8.0	0	--	--	--	9	5.3	4.6	6.6
Fathead Minnow	0	--	--	--	2	6.5	6.5	6.5	0	--	--	--	1	5.0	--	--
Black Crappie	0	--	--	--	0	--	--	--	0	--	--	--	1	25.5	--	--
Western Blacknose Dace	0	--	--	--	0	--	--	--	0	--	--	--	1	9.0	--	--
Total	742				452				640				452			

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 21 September 2023. Site locations are depicted in Figure 1.

	Site #1				Site #2				Site #3				Site #4			
		TL (cm)				TL (cm)				TL (cm)				TL (cm)		
Common name	Count	Mean	Min	Max	Count	Mean	Min	Max	Count	Mean	Min	Max	Count	Mean	Min	Max
Alewife	0	--	--	--	1	7.3	--	--	8	8.9	7.5	10.0	30	9.4	8.0	10.9
Bowfin	0	--	--	--	0	--	--	--	1	46.4	--	--	1	51.9	--	--
Freshwater Drum	1	18.9	--	--	0	--	--	--	0	--	--	--	0	--	--	--
Goldfish	0	--	--	--	0	--	--	--	1	13.2	--	--	1	28.8	--	--
White Sucker	2	19.7	18.9	20.4	0	--	--	--	6	39.7	30.6	44.0	3	43.0	39.0	50.5
Common Carp	5	60.4	44.3	76.0	0	--	--	--	3	61.3	54.8	70.0	0	--	--	--
Gizzard Shad	15	13.0	8.9	15.8	58	12.0	8.7	14.2	18	11.6	8.2	15.3	41	11.2	8.1	14.4
Banded Killifish	0	--	--	--	0	--	--	--	3	8.6	7.3	10.3	5	8.4	7.0	10.7
Brook Silverside	0	--	--	--	0	--	--	--	1	6.0	--	--	0	--	--	--
Pumpkinseed	6	13.1	10.9	15.2	0	--	--	--	0	--	--	--	1	19.5	--	--
Bluegill	11	12.5	7.9	19.0	0	--	--	--	4	8.8	5.0	13.3	1	13.1	--	--
Largemouth Bass	5	16.7	11.5	23.8	1	38.7	--	--	23	12.6	8.2	31.0	4	26.5	6.3	44.1
White Perch	15	17.6	7.6	28.9	10	17.3	15.4	18.6	23	17.5	7.7	29.6	17	18.3	15.2	27.5
Round Goby	0	--	--	--	1	13.3	--	--	1	12.6	--	--	8	7.8	6.5	8.7
Golden Shiner	3	14.5	13.7	15.1	2	12.4	9.7	15.1	1	9.0	--	--	3	12.2	8.6	18.3
Emerald Shiner	4	8.3	7.8	8.8	7	10.1	7.9	17.4	1	10.3	--	--	5	9.2	8.1	11.7
Spottail Shiner	4	9.9	8.0	11.7	1	8.8	--	--	2	9.7	9.3	10.0	6	10.7	8.5	12.7
Yellow Perch	3	16.1	15.3	17.3	2	18.8	18.3	19.3	12	19.2	15.7	23.5	11	18.6	16.5	20.4
Black Crappie	0	--	--	--	1	26.6	--	--	0	--	--	--	0	--	--	--
Walleye	2	56.5	41.0	72.0	1	22.5	--	--	1	57.7	--	--	0	--	--	--
Total	76				85				109				137			

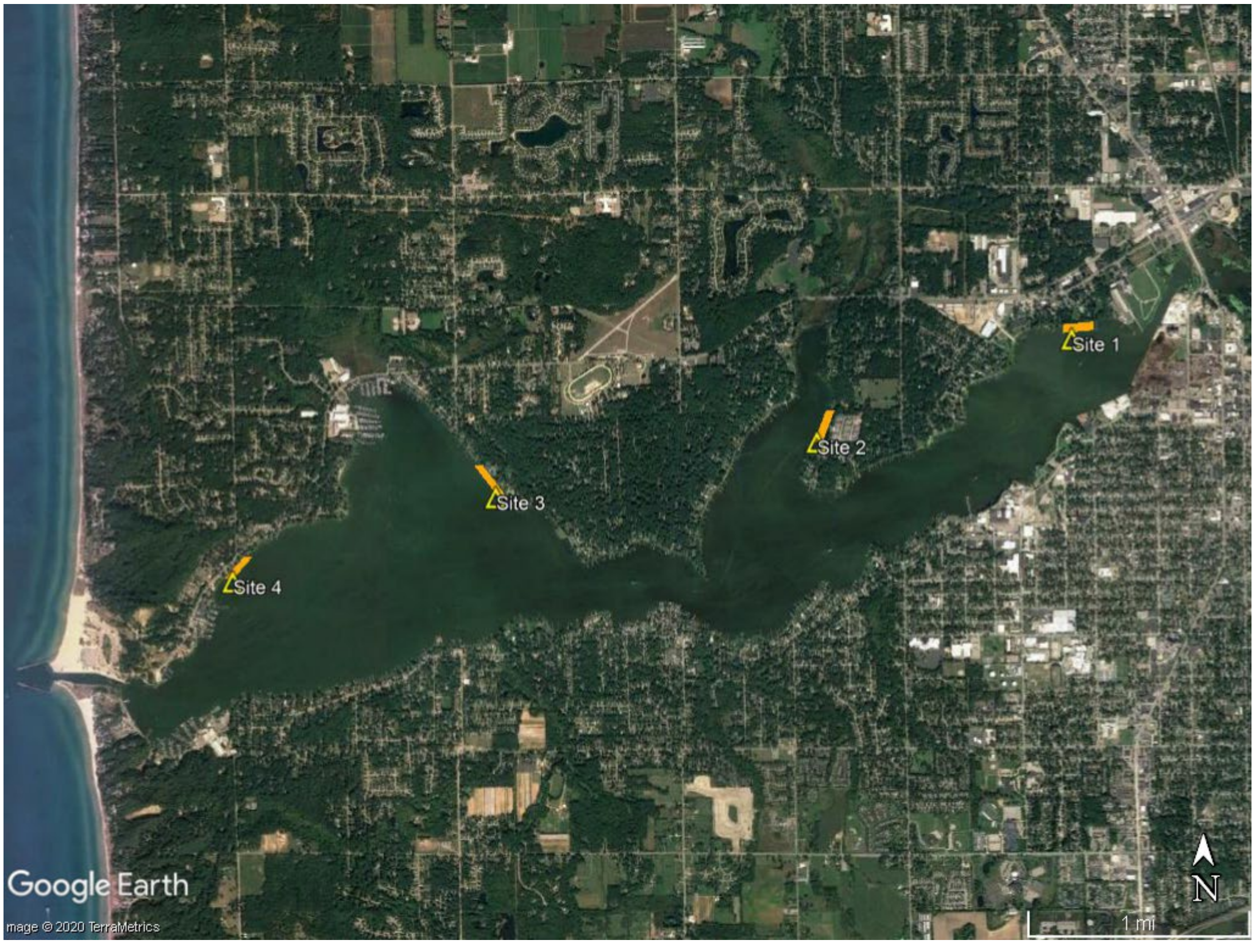

Figure 1. Map of Lake Macatawa (Ottawa County, Michigan) showing fish sampling sites (triangles). The orange transects depict approximately where boat electrofishing was conducted at each site. Site #1 is closest to the Macatawa River and site #4 is closest to Lake Michigan. Note that riparian vegetation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

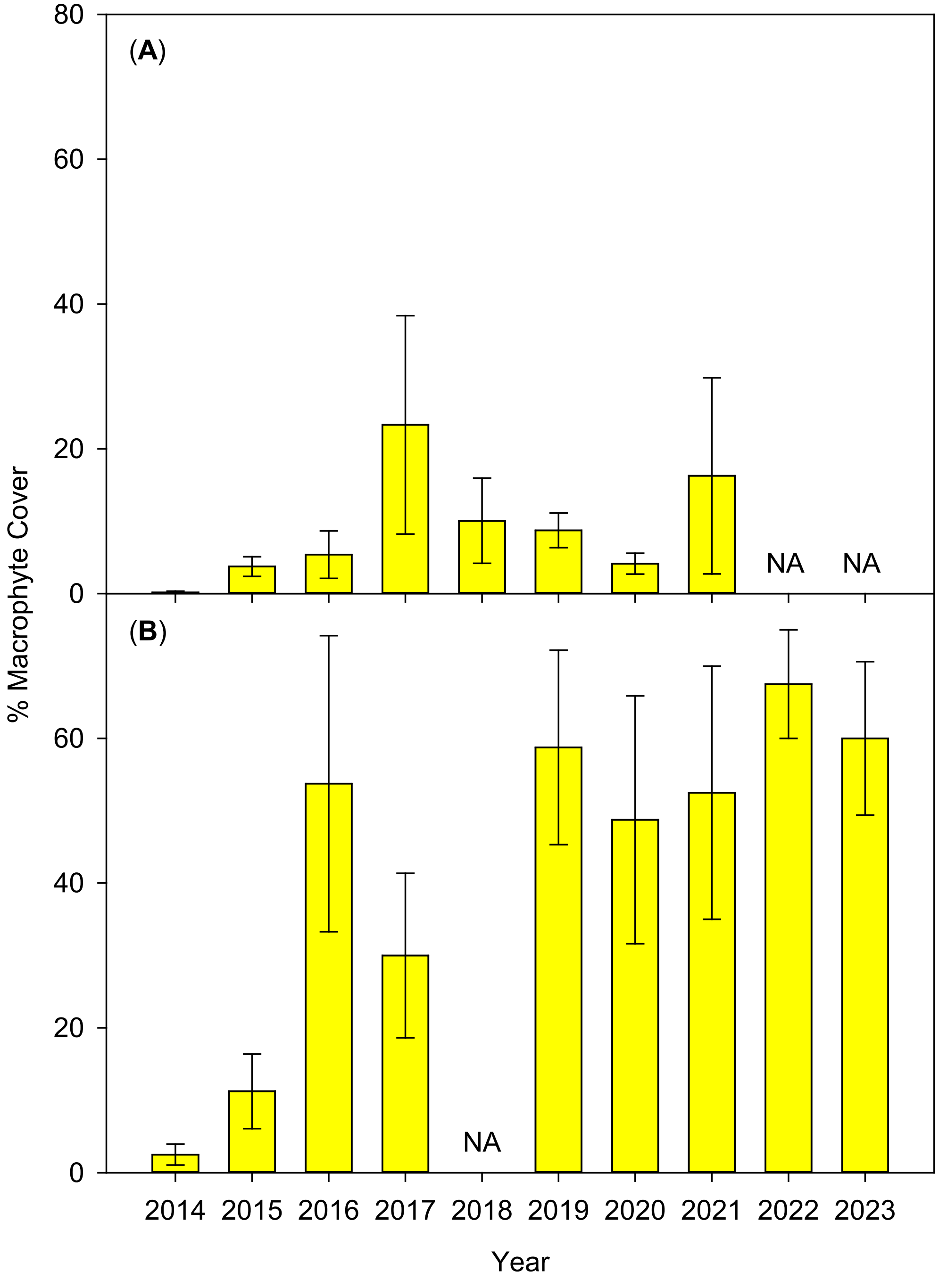

Figure 2. Mean (±1 standard error) percent macrophyte cover visually estimated at (**A**) fyke net locations and (**B**) boat electrofishing transects in Lake Macatawa (*n* = 4 sites per year; however, the *n* = 2 sites for 2021 and 2022 boat electrofishing because of poor visibility). Note that the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

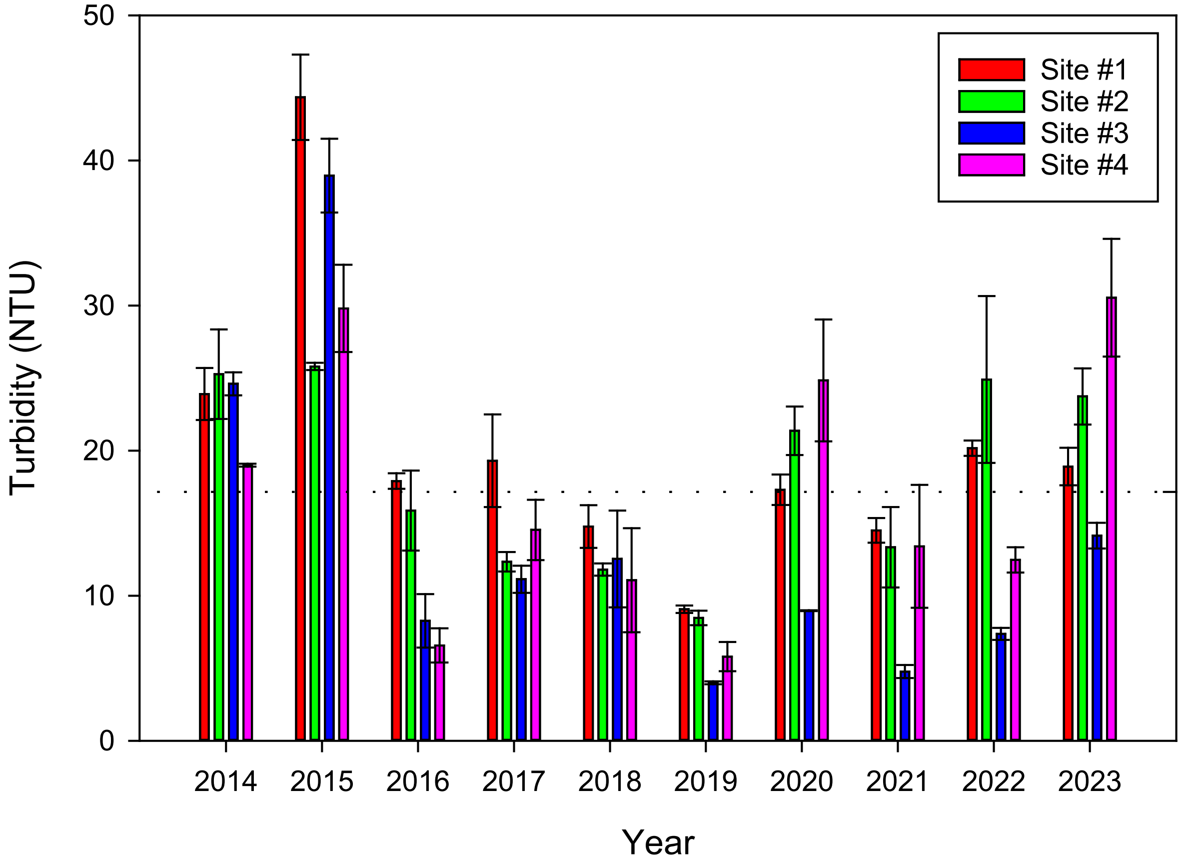

Figure 3. Mean (±1 standard error) turbidity measured during fyke netting in Lake Macatawa (*n* = 3 nets per site). Dashed line is the long-term mean (*n* = 10 years).

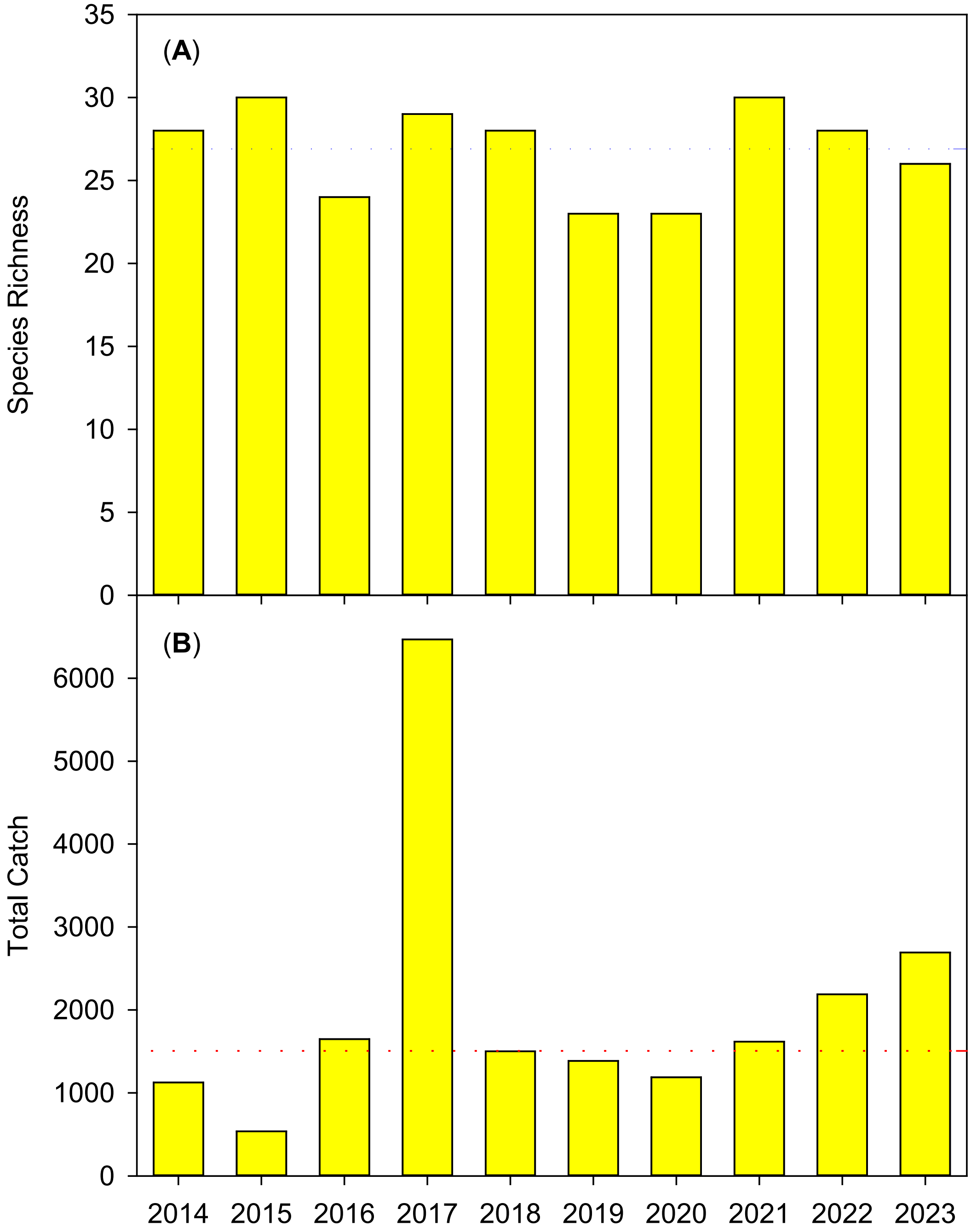

Figure 4. (**A**) Number of fish species captured (dashed blue line is long-term mean; *n* = 10 years) and (**B**) total number of fish captured using both fyke netting and boat electrofishing each year in Lake Macatawa (dashed red line is long-term mean; *n* = 10 years). *Note*: the long-term mean total 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.

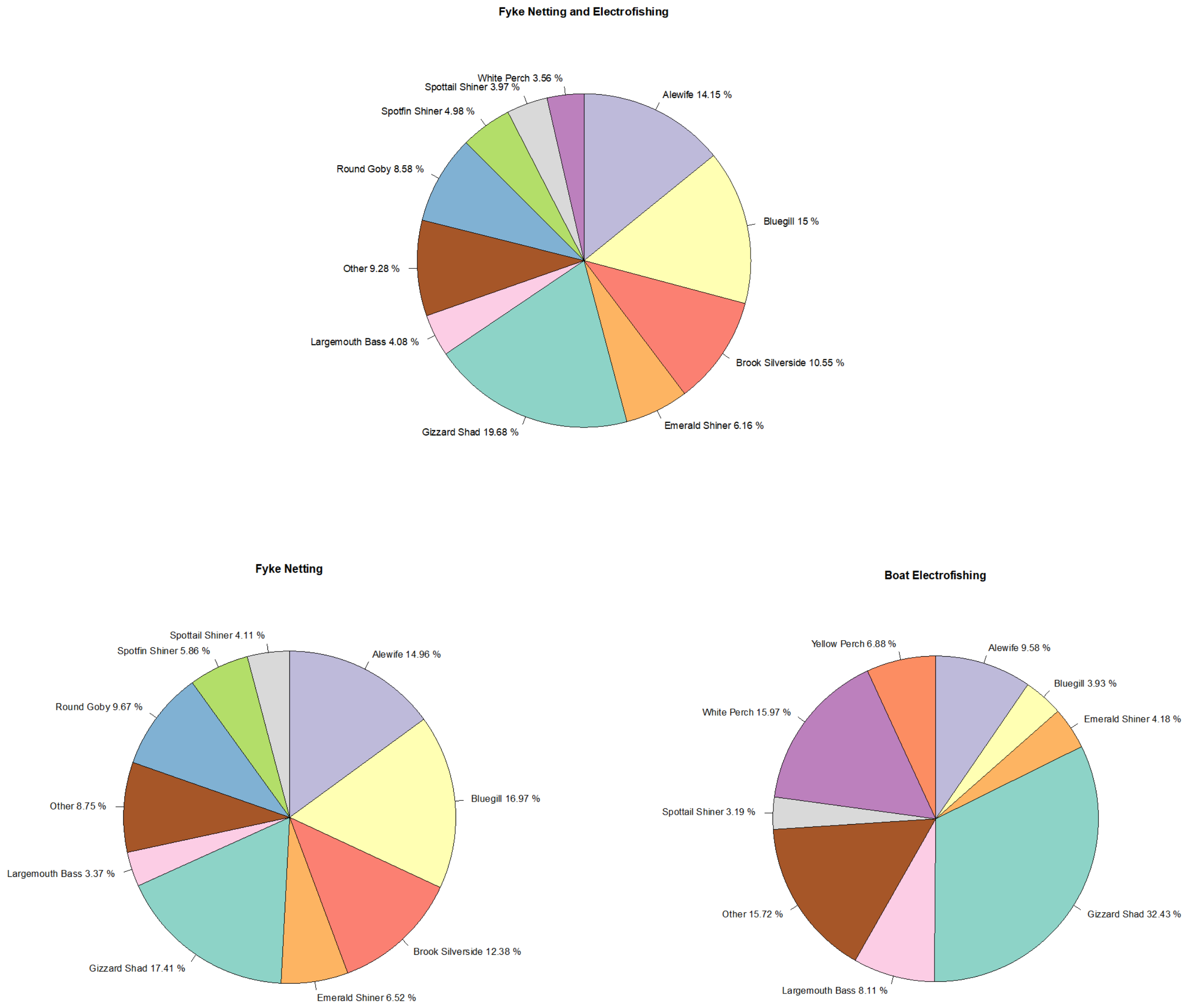

Figure 5. Fish species captured in littoral habitats of Lake Macatawa by (**A**) fyke netting and boat electrofishing (i.e., combined catch), (**B**) fyke netting (*n* = 12 nets), and (**C**) boat electrofishing (*n* = 4 transects) during September 2023. Catch data, including the species pooled in the “Other” category, are reported in Table 4.

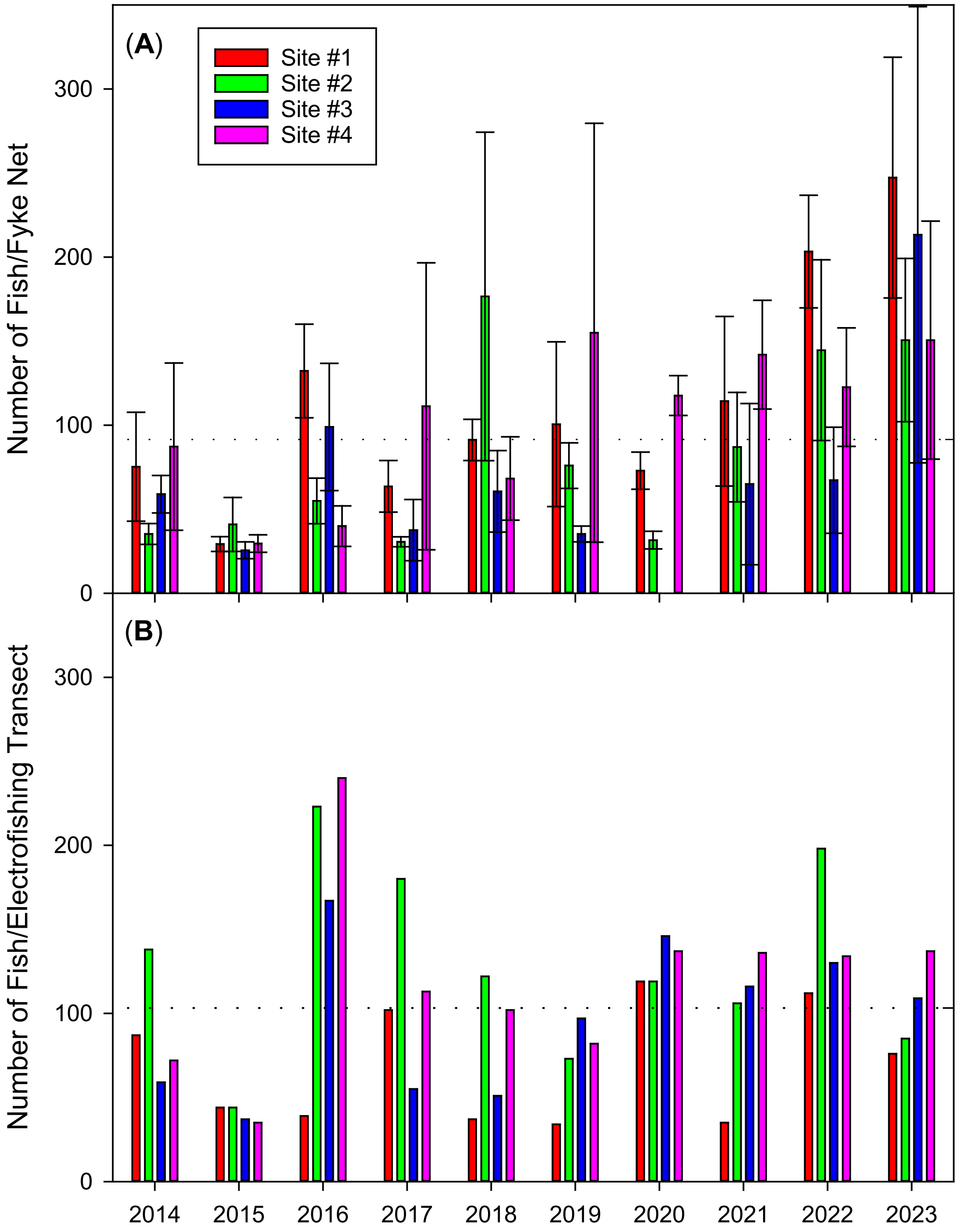

Figure 6. (**A**) Mean number (±1 standard error) of fish captured in fyke nets (*n* = 3 nets per site) and (**B**) number of fish captured during a boat electrofishing transect (*n* = 1 transect per site) in Lake Macatawa. *Note*: 5,288 Brook Silversides captured in a single fyke net at site #4 in 2017 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* = 39) and boat electrofishing (*n* = 40).

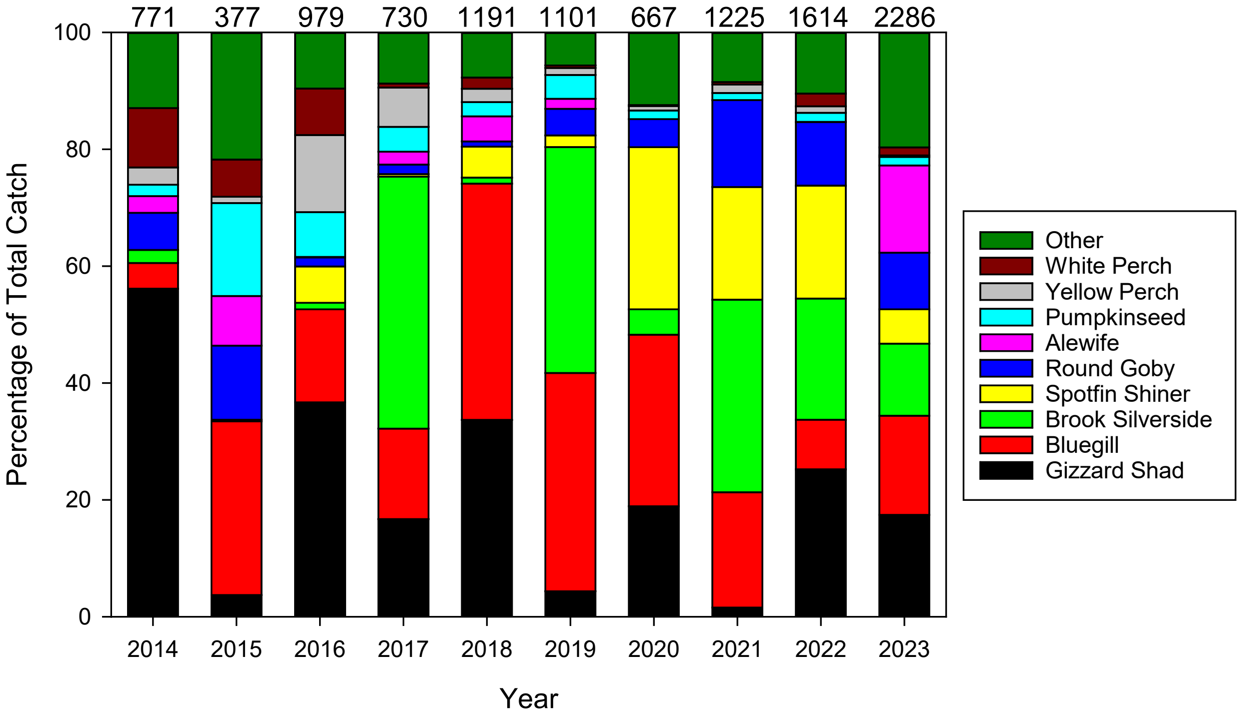

Figure 7. Fish species composition (pooled across sites) in fyke netting surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar. *Note*: 5,288 Brook Silversides captured in a single fyke net at site #4 in 2017 were excluded from the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

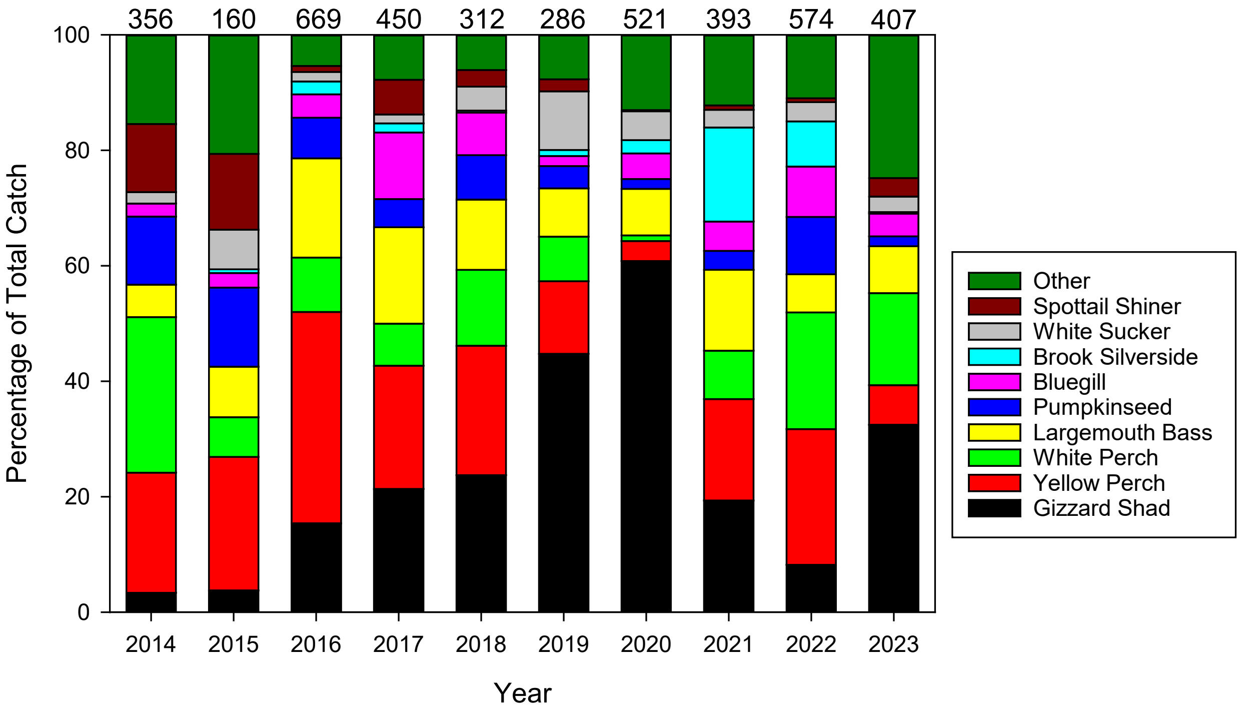

Figure 8. Fish species composition (pooled across sites) in nighttime boat electrofishing surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar.