PROJECT CLARITY
2022 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 includes wetland restoration, in-stream remediation, Best Management Practices (BMPs), and community education is being implemented as part of a multimillion-dollar public-private partnership. The project is expected to have many economic, social, and ecological benefits – while achieving 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 of less than 100 µg/L have been observed the past four years and but in 2022, the 5-site mean TP concentration backslid to above 100 µg/L, as reported below. This concentration exceeds the TMDL target and is more than sufficient to stimulate significant algal blooms (Steinman et al. 2018). Remediation projects and BMPs are focused on key areas in the watershed; Project Clarity is focused on reducing sediment and phosphorus loads, and working to meet the TMDL target for Lake Macatawa.

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 2022, 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 backsliding from 2021 in total phosphorus, chlorophyll *a*, and water clarity compared to 2021. However, when evaluated over the 3-year periods of pre-restoration vs. the past three years, improvements are evident in all three parameters. Bioavailable P (soluble reactive phosphorus: SRP) continues to show increases, however;

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. Even with the improvements when assessed over these 3-year increments, 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 2022 (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 2020 – fall 2022) sampling events were incorporated in the rank sum test, pooling data from all sites (1-5).

Statistical significance was set with α = 0.05 and testing was performed in SigmaPlot v.14.0 (Systat Software, Inc.).

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, 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 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 mean 2022 water column seasonal mean depth at Lake Macatawa long-term monitoring locations.

Site	Latitude	Longitude	Depth (m)
1	42.7913	-86.1194	8.1
2	42.7788	-86.1525	5.5
3	42.7872	-86.1474	4.0
4	42.7755	-86.1822	10.5
5	42.7875	-86.1820	4.7

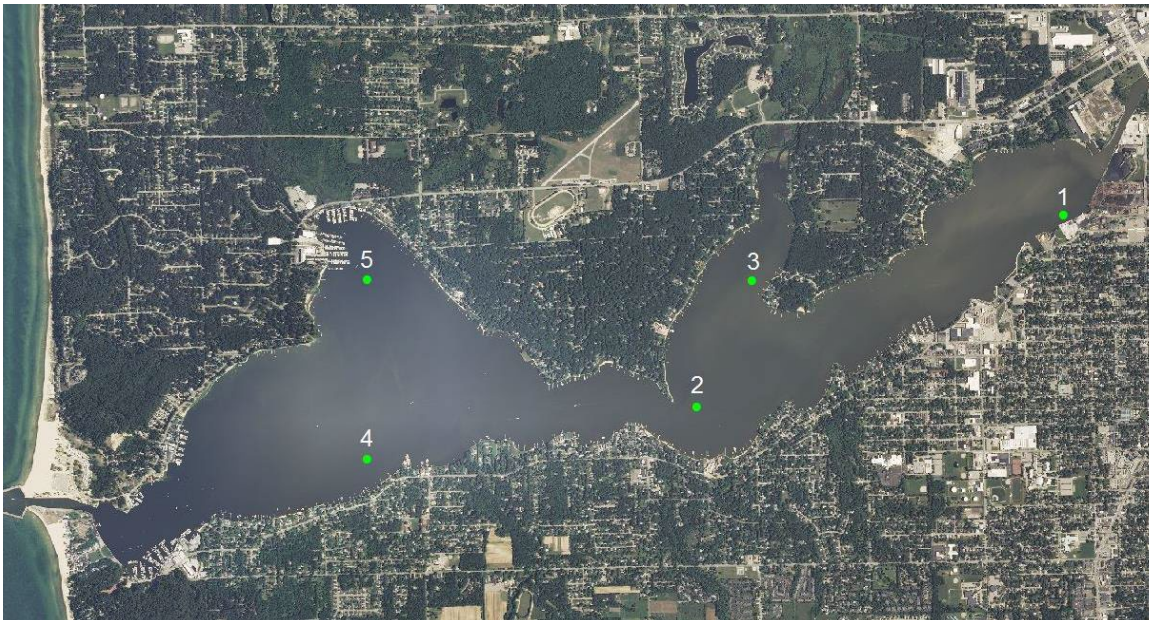

Figure 1. Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring.

2.3 Macatawa Watershed Phosphorus – Precipitation Analysis

P concentrations in Lake Macatawa 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 water bodies (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. In Lake Macatawa, the relationship between lake TP and precipitation has not been clear-cut. Previous attempts to analyze annual precipitation against annual mean TP resulted in trendless data with low statistical power

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. 2021), 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 2013-2022 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 2022 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 2022

Water quality followed seasonal trends seen in previous years of Lake Macatawa sampling (Table 2). Dissolved oxygen was well-mixed in the spring and fall, with DO concentrations generally ranging 8-11 mg/L at all sites while bottom DO was within ~1 mg/L of surface DO at all sites (Table 2). Summer DO was more variable, with surface DO ranging ~4-8 mg/L at the 5 sampling sites, and the lowest concentrations found in the middle of the lake at site 2 (Fig. 2). Summer DO concentrations near the lake bottom decreased further and ranged 0.12-2 mg/L at sites 1, 2, and 4 in the thalweg of the lake (lowest value at site 4 near the Lake Michigan channel) and ~3-5 mg/L in the northern bays (Fig. 2). Examination of DO data over the 10-yr measurement period reveals that DO usually declines in summer in Lake Macatawa, although the surface decline in 2022 was larger than has been observed in the past

(Fig. 3A). In addition, the bottom DO decline measured at site 4 is consistent with observations from previous years (Fig. 3B).

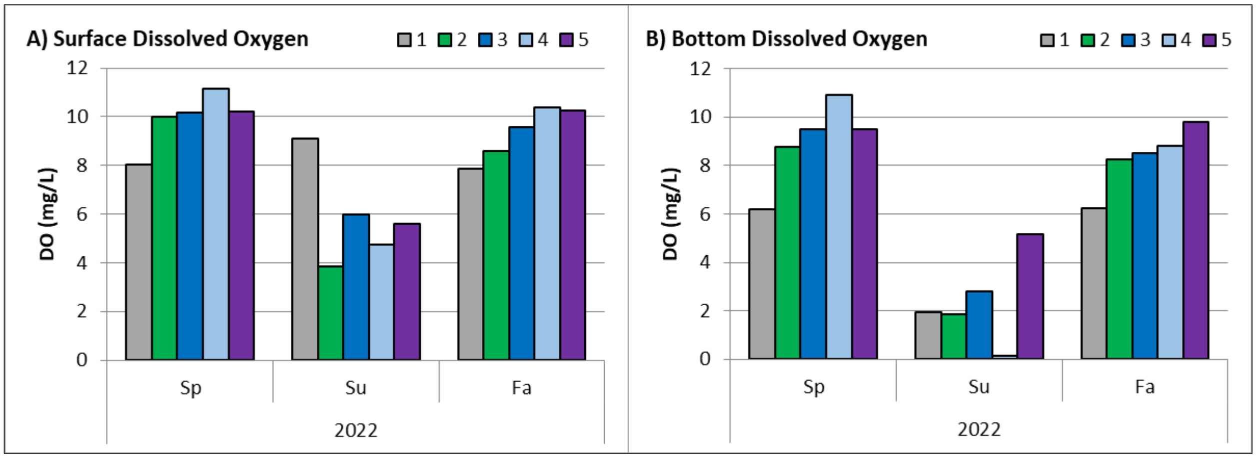

Figure 2. Dissolved Oxygen: A) surface; B) near-bottom concentrations measured at the 5 monitoring stations in Lake Macatawa during 2022.

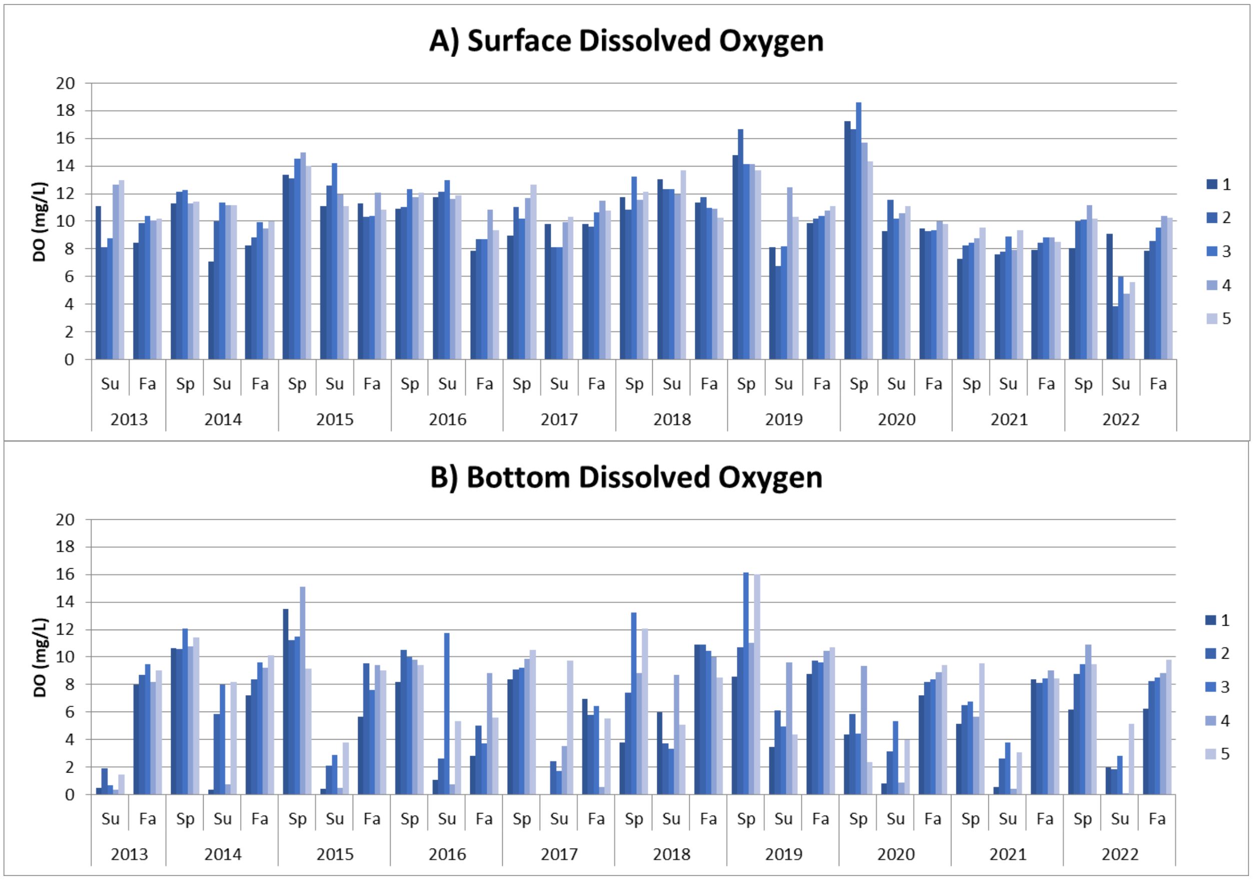

Figure 3. Dissolved Oxygen: A) surface; B) near-bottom concentrations measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2022.

Multiyear LOWESS (locally weighted scatterplot smoothing) analysis of summer DO in bottom depth samples shows that 2022 continued a recent multiyear decrease from 2018-19's recent higher DO values; this fit improves when considering only sites 1, 2, and 4 (3-site R^2 = 0.38) the main flow of Lake Macatawa, as opposed to including all 5 sites (5-site R^2 = 0.16, Fig. 4B). More variable conditions in the embayments (sites 3 and 5) likely account for the poorer fit when all 5 sites are considered.

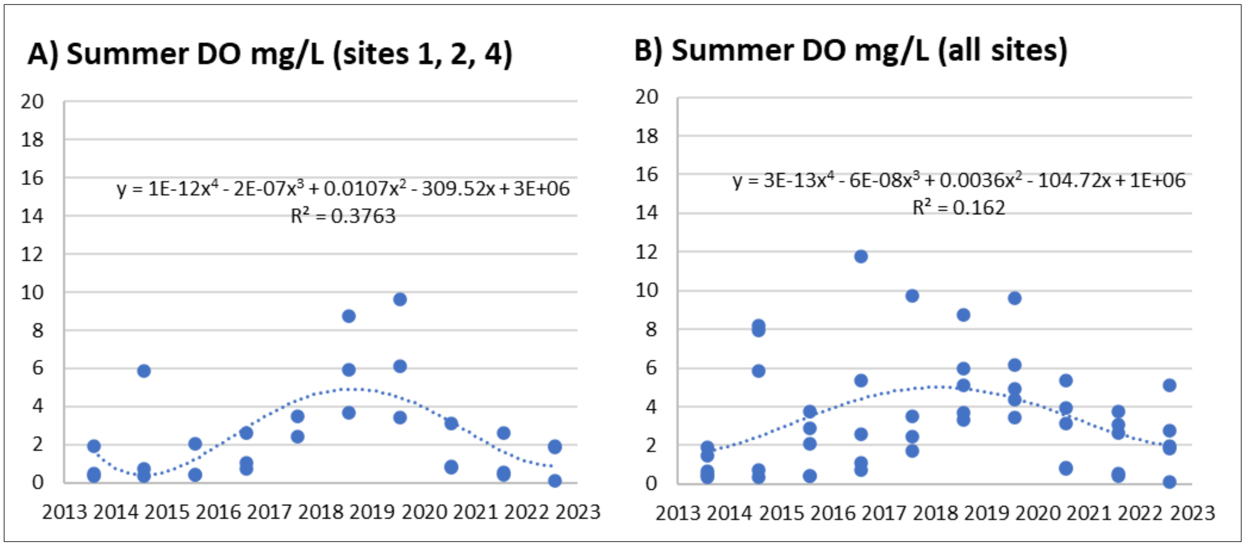

Figure 4. Locally weighted scatterplot smoothing (LOWESS) trend analyses of bottom summer DO site data from Lake Macatawa. A) Sites 1, 2, and 4 represent the main flow of Lake Macatawa via the Macatawa River watershed. B) All 5 sites, including the lake's northern Big Bay and Pine Creek Bay.

Mean specific conductivity ranged from 515 to 565 µS/cm at all sites and depths, being somewhat lower in summer than spring or fall (Table 2). These values are higher than we generally find in other drowned river mouth lakes in our region (e.g., Mona Lake: 411-447 µS/cm; Steinman et al. 2006) and indicative of Lake Macatawa having an excess of dissolved ions entering from the watershed. The 2022 conductivity readings were similar to our prior measurements (Appendix A, Fig. A1).

Mean turbidity was more variable among seasons and depths, with the highest values in spring and a trend toward higher values with depth (Table 2). The anomalously high mean bottom reading in fall may have been due to disturbance of the bottom sediment when deploying the sonde. The turbidity readings were generally similar to the measurements we have taken since 2013 (Appendix A, Fig. A2).

Secchi disk depths were less than 1m regardless of season (Table 2). Spring Secchi disk data were not available due to lost data and instead were modeled using all surface site water quality data from Project Clarity history (2013-2022) and forward stepwise linear regression to identify parameters deemed statistically significant for predicting Secchi disk depth. The final model incorporated turbidity (P=0.001), chlorophyll (P=0.011), and cyanobacteria density (P<0.001) with a final model R^2=0.54 and modeled spring Secchi depths ranging 0.64-0.67 m across all 5 sites (Table 3).

Table 2. Lake-wide means (1 SD) of select general water quality parameters recorded during 2022 monitoring year. Data are shaded for readability. Dates of sampling events: 5/24/2022; 7/27/2022; 10/28/2022. "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 (NTU)	Secchi Depth (m)
Spring	Surface	5	16.99 (0.87)	9.91 (1.14)	548 (85)	16.9 (6.5)	0.7 (0)
	Middle	5	16.73 (0.99)	9.42 (1.37)	542 (90)	18.7 (8.8)	
	Bottom	5	16.36 (1.24)	8.97 (1.74)	560 (157)	22.1 (6.7)	
Summer	Surface	5	25.58 (0.55)	5.85 (1.99)	515 (55)	10.0 (4.6)	0.8 (0.2)
	Middle	5	25.26 (0.47)	3.83 (1.39)	517 (59)	10.3 (4.6)	
	Bottom	5	24.72 (0.85)	2.37 (1.83)	536 (96)	10.6 (3.8)	
Fall	Surface	5	11.36 (0.28)	9.33 (1.08)	565 (90)	7.5 (2.0)	0.7 (0.3)
	Middle	5	11.14 (0.17)	8.85 (1.26)	563 (85)	8.4 (3.0)	
	Bottom	5	10.98 (0.19)	8.32 (1.30)	553 (71)	29.6 (31.8)	

Mean surface and near bottom SRP concentrations were generally low in spring and fall (Table 3), with individual sites having concentrations either below detection (<5 µg/L) or ranging 5-12 µg/L at all sites (Fig. 5A), with a notable exception of site 1 (closest to the Macatawa River) in fall 2022, which reached 92 µg/L in the near-bottom sample (Fig. 5B). Summer SRP concentrations were higher with means of 63 and 96 µg/L (Table 3) and reached a maximum of 225 µg/L at site 4 near-bottom (Fig. 5B).

Mean TP concentrations followed SRP seasonal patterns and exceeded the 50 µg/L TMDL threshold on every sampling date (Table 3). Bottom concentrations at individual sites ranged over nearly an order of magnitude from 35-320 µg/L (Fig. 5D).

Notably, the highest summer SRP and TP concentrations were observed in the near-bottom sample of site 4, the deepest site and closest to Lake Michigan. This site also had the lowest observed DO concentration (0.12 mg/L), as noted above. Additionally, we observed a strong algal bloom was occurring in Lake Macatawa prior to our arrival at 10:00 AM on July 27, 2022, accompanied by several dead and decomposing fish, as well as visible accumulations of algae on the shorelines and throughout the lake that day (Fig. 6). Microbial respiration associated with the decomposition of dying algae consumes dissolved oxygen in the water column and can lead to fish kills; these low oxygen levels may also be a driver for the release of phosphorus otherwise bound to iron in lake sediments into the water column (Mortimer 1941).

NO_3^- varied seasonally, being lowest in the summer and generally highest in the spring, ranging <2 mg/L except for a fall bottom spike of 3.5 mg/L at site 1 closest to the river (Table 3; Figures 7A, B). Mean NH_3 increased seasonally throughout the monitoring year (Fig. 7C), except for site 1 bottom sample spikes which declined over the year (~1 mg/L; Table 3; Fig. 7D). Interestingly, whereas deep site 4 had the highest SRP concentrations, suggesting low DO and internal phosphorus loading may be occurring, a similar phenomenon was not observed for ammonia, which can be released from sediments under hypoxic/anoxic conditions (Yang et al. 2020).

The Redfield ratio is often used as a potential indicator of whether N or P is limiting algal growth in aquatic ecosystems. There is debate as to whether the total nutrient or dissolved (bioavailable form) nutrient should be used to calculate the ratio. Using the total forms (TN:TP), and comparing that against the optimal Redfield Ratio, which is 7.23:1 (by weight), the surface water ratios in Lake Macatawa changed by season: 38.1 in spring; 12.0:1 in summer; and 27.6 in fall. Hence, these ratios suggest that the phytoplankton in Lake Macatawa are likely P-limited in spring and fall, and co-limited by N and P in summer.

Mean chl *a* concentrations ranged from 27 to 54 µg/L with higher concentrations near the surface than near-bottom (Table 3). These means exceeded EGLE's hypereutrophic threshold of 22 µg/L (Fig. 5E). Near bottom chl *a* concentrations at individual sites ranged 3-47 µ/L and site 4's bottom summer samples had the lowest chl concentration of the year (Table 3; Fig. 5F).

Microcystin concentrations were tested at all seasons, sites, and depths and were one or more orders of magnitude below World Health Organization and Environmental Protection Agency guidelines for recreational waters (20 µg/L and 2 µg/L, respectively). Microcystin concentrations remained ≤0.1 µg/L throughout most 2022 samples except for one detection at 0.19 µg/L at site 5 on the western side of Lake Macatawa at the near-bottom depth during spring sampling. However, this concentration remains well below regulatory guidelines.

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 2022 monitoring year. Data are shaded for readability. See Table 2 for dates of sampling events. Note different units for the analytes. Spring Secchi depth was modeled. "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	4 (3)	86 (24)	1.42 (0.29)	0.29 (0.30)	1.86 (0.55)	34 (3)	0.016 (0.011)
	Bottom	5	4 (2)	98 (45)	1.27 (0.26)	0.90 (1.69)	2.29 (2.08)	27 (11)	0.059 (0.075)
Summer	Surface	5	63 (31)	166 (24)	0.13 (0.03)	0.46 (0.10)	1.86 (0.56)	54 (41)	0 (0)
	Bottom	5	96 (76)	225 (70)	0.15 (0.06)	0.98 (0.83)	2.36 (1.19)	30 (19)	0.021 (0.033)
Fall	Surface	5	9 (7)	55 (18)	0.76 (0.41)	0.65 (0.55)	1.76 (0.73)	34 (5)	0.010 (0.011)
	Bottom	5	23 (39)	81 (70)	1.19 (1.33)	0.59 (0.45)	1.81 (0.73)	27 (9)	0.003 (0.007)

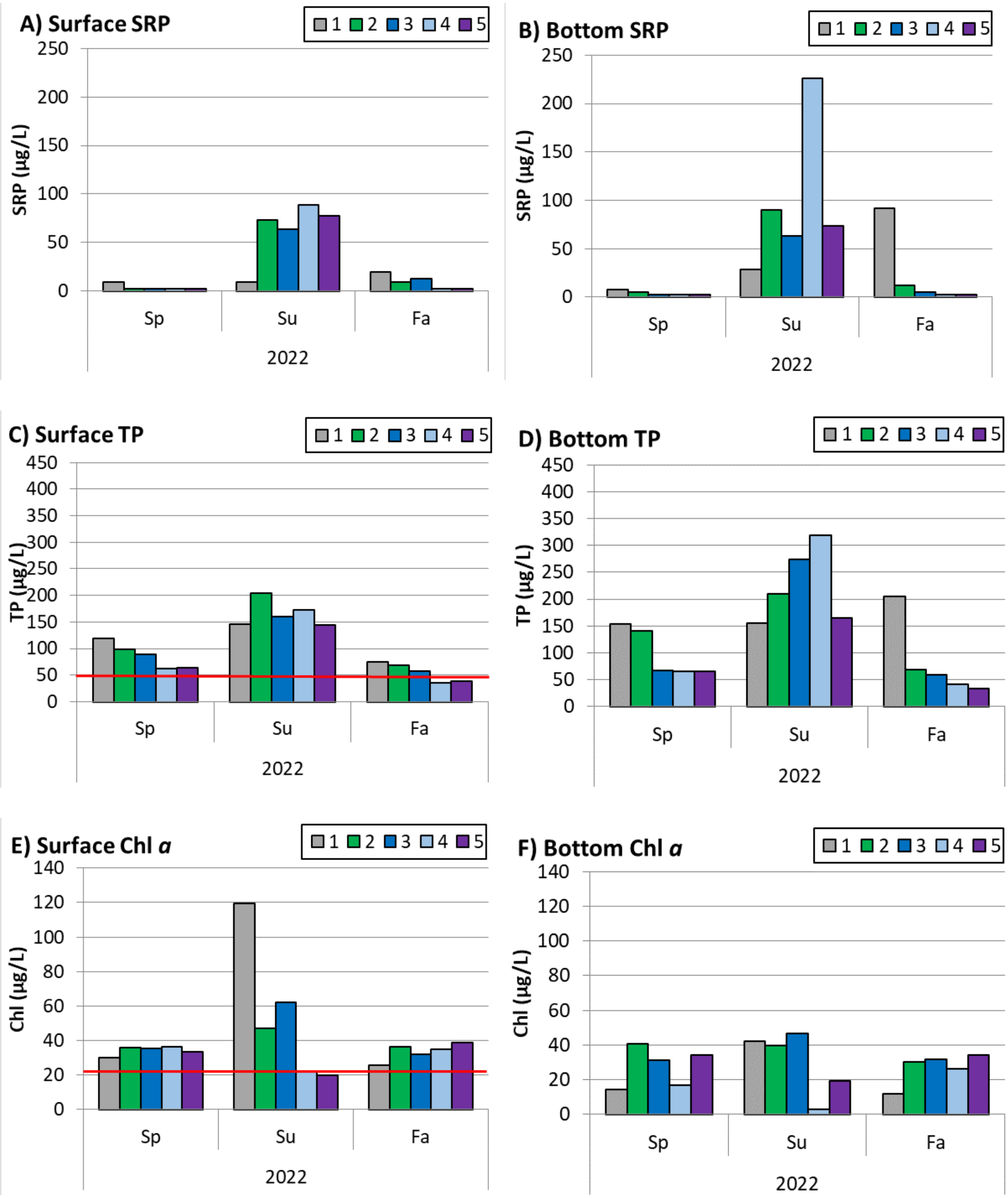

Figure 5. Soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); and chlorophyll *a* ([chl *a*]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2022. The red horizontal line on surface TP (C) indicates the interim total maximum daily load (TMDL) 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.

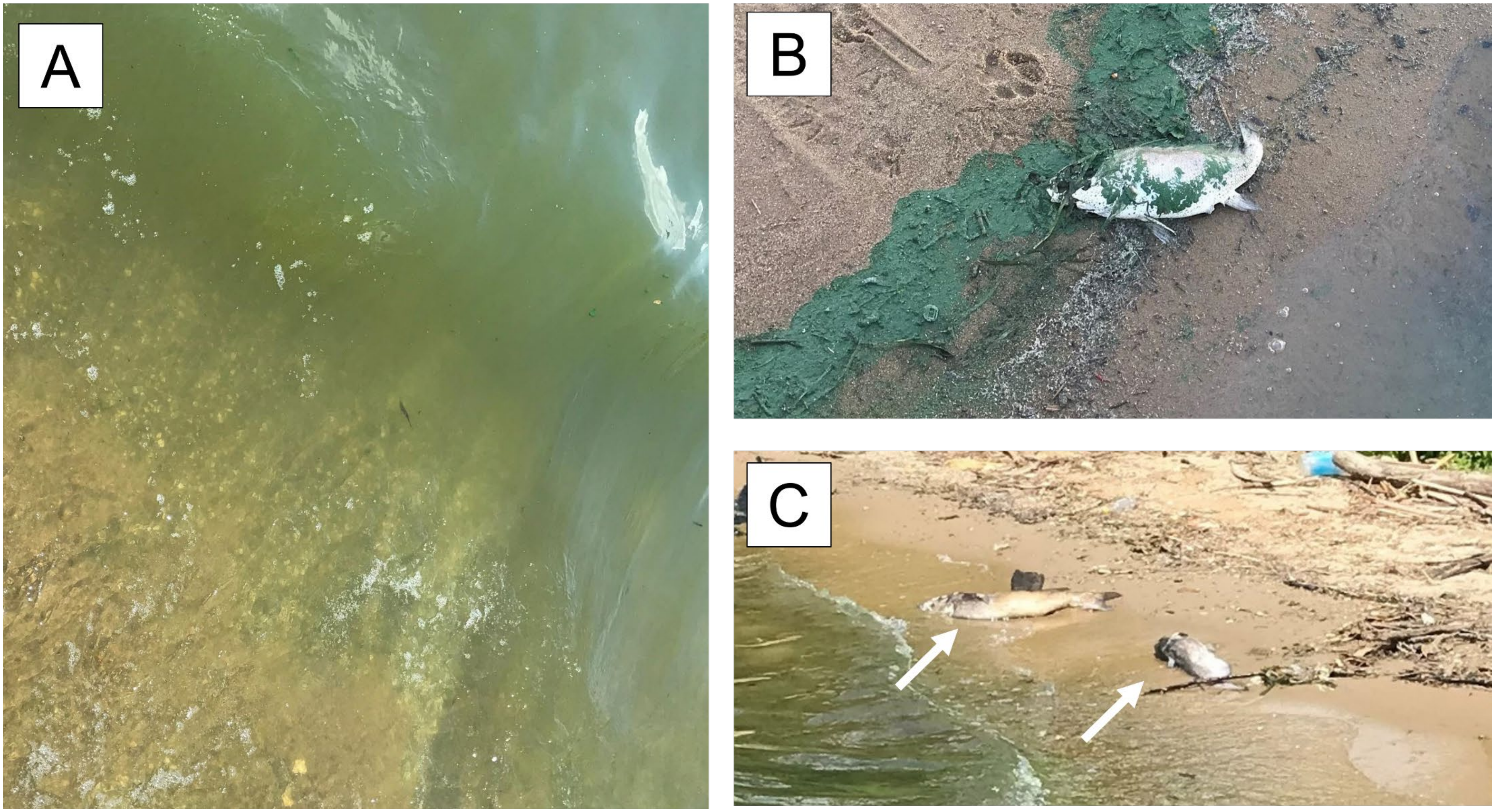

Figure 6. Photos of 7/27/2022 algae bloom and fish kill taken near Dunton Park boat launch. (A) Wave on boat launch concrete ramp showing water clarity at 12:30 PM. (B) Fish kill found at boat ramp at 9:54 AM covered in algae. (C) Two additional fish (noted by arrows) on shoreline west of boat ramp at 12:30 PM.

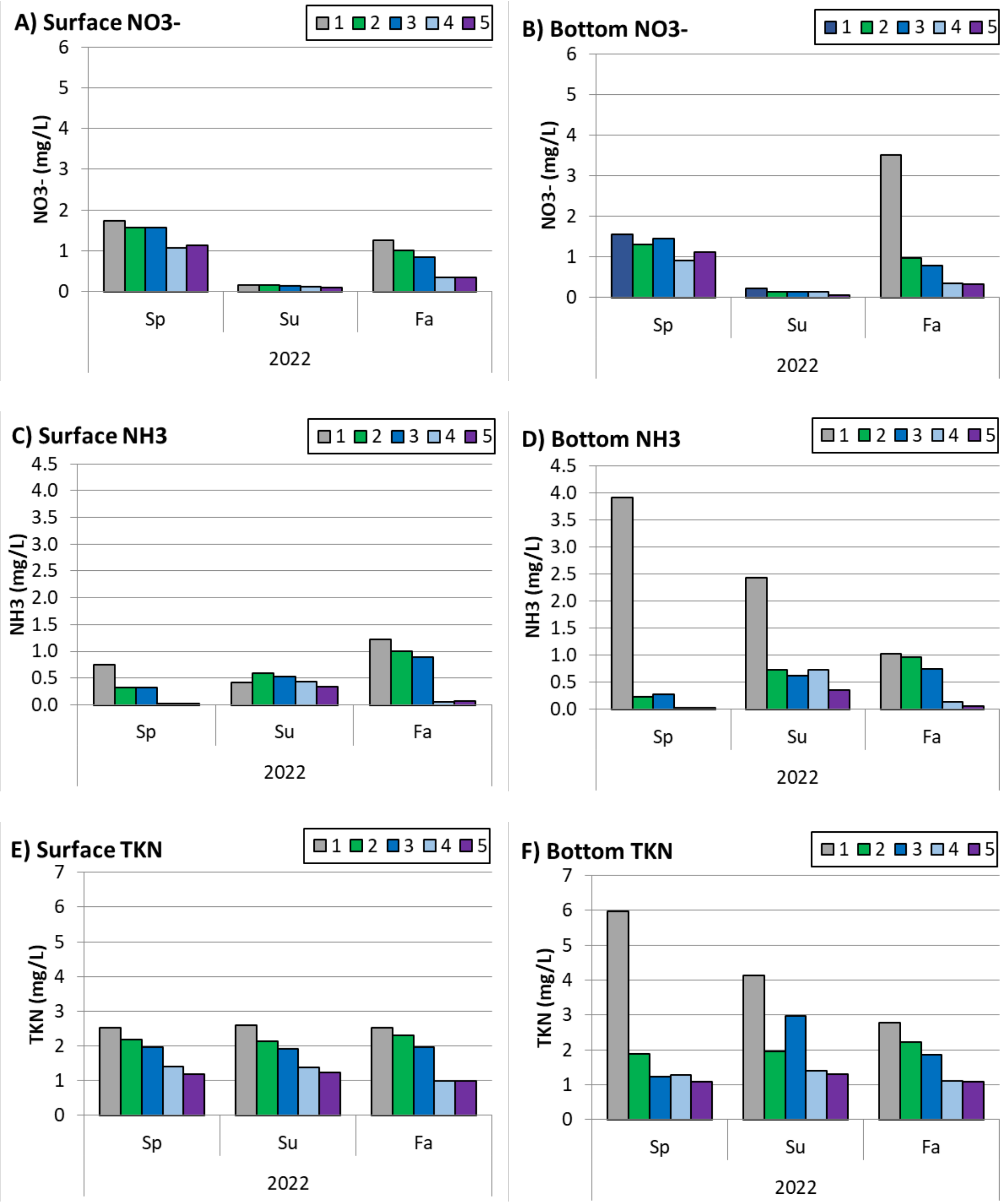

Figure 7. Nitrate ($[NO_3^-]$: A, B); ammonia ($[NH_3]$: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2022. Note scales change on y-axes.

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); 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. This year's restoration analyses exclude data collected from 2016 to 2019, representing years immediately following major restoration construction activities, and which may have resulted in greater release of P.

SRP surface concentrations in spring and fall were low and comparable to prior years (Table 4); however, summer surface SRP levels were elevated in summer 2022 (Fig. 8). The elevated summer SRP in the near-bottom waters may be related to phosphorus release from the sediments, and if the water column is well-mixed, and is often the case in shallow Lake Macatawa, the bottom SRP may be transported into the surface waters, thereby accounting for the high SRP in both strata.

Overall, mean surface TP concentrations have increased in the spring following the start of Project Clarity, and have declined substantially in the summer and fall (Table 4). However, in 2022, elevated summer TP concentrations (similar to SRP) were greater than in past years (Fig. 8), and are likely related to the algal bloom that occurred during July sampling. Normally, one would expect an algal bloom to draw down SRP, as the bioavailable P is taken up by the algae and transformed into particulate phosphorus (measured as part of TP). However, if the internal loading from the sediment is very strong, it can override the P uptake, at least in the short term. Mean bottom TP concentrations in 2022 were similar pre- vs. post-restoration in spring and summer, and declined almost 70 µg/L in fall, although the mean concentration was still 90 µg/L, which is still almost twice the interim TMDL goal of 50 µg/L.

Pre- vs. post-restoration mean chl *a* concentrations showed similar patterns for surface and bottom collections, consistent with Lake Macatawa being well-mixed (Table 4). Mean spring chl *a* concentrations have doubled following restoration, tracking the increase in TP, have changed little in summer, and have declined 20 to 30% in fall (Table 4). When examined by individual site and season, the chl a concentrations in 2022 appear to be fairly similar to past years (Fig. 9). Site 1 in summer had elevated chl a concentrations, but this site has had periodic summer chlorophyll spikes in the past (2013 and 2016; Fig. 9). Secchi disk depth remains poor, and although it declined a bit from 2021, is slightly improved from the 2016-2020 period (Fig. 9).

The long-term trends in the three N forms that we measure (nitrate, ammonia, TKN) indicate that surface N in 2022 was very similar to prior years (Fig. 10A, C, E). However, the bottom waters showed N spikes at site 1 that appear to be a new occurrence (Fig. 10B, D, F). The spring and fall nitrate spikes may be due to fertilizer runoff after applications, which is quickly assimilated or denitrified in the system, resulting in a significant drop by site 2 (Fig. 10B). Ammonia usually makes up a significant fraction of TKN (the rest is organic N), so it is not surprising they have similar responses (Fig. 10D, F); their spring and summer spikes in Fig. 10 may be due to internal release from sediments, as this site is relatively deep where hypoxia/anoxia could form. Alternatively, reduced forms of N fertilizer runoff may contribute to high levels due to the site's proximity to the Macatawa River inlet. The site's NH_3

concentrations decline relatively quickly as one moves downlake, suggesting uptake or nitrification in this system.

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 2022). 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	7	13 (19)	98 (56)	1.37 (0.43)	0.29 (0.26)	1.76 (0.32)	53 (29)	0.7 (0.3)
	Bottom	Pre	2	3 (1)	98 (30)	ND	ND	ND	24 (3)	
		Post	7	13 (19)	100 (57)	1.29 (0.44)	0.50 (0.25)	1.72 (0.56)	36 (16)	
Summer	Surface	Pre	3	6 (3)	110 (66)	ND	ND	ND	67 (39)	0.4 (0.1)
		Post	7	14 (22)	84 (41)	0.51 (0.70)	0.27 (0.12)	1.48 (0.26)	60 (26)	0.8 (0.2)
	Bottom	Pre	3	17 (18)	107 (49)	ND	ND	ND	32 (13)	
		Post	7	23 (32)	102 (58)	0.46 (0.52)	0.57 (0.24)	1.58 (0.49)	30 (11)	
Fall	Surface	Pre	3	10 (12)	134 (23)	ND	ND	ND	63 (43)	0.4 (0.1)
		Post	7	8 (5)	73 (11)	0.91 (0.65)	0.41 (0.24)	1.40 (0.29)	51 (24)	0.6 (0.1)
	Bottom	Pre	3	11 (13)	158 (19)	ND	ND	ND	61 (35)	
		Post	7	17 (16)	90 (16)	1.18 (0.79)	0.41 (0.22)	1.42 (0.31)	42 (13)	

We also compared the three years of pre-restoration water quality data with an equal and seasonally corresponding number of the most recent post-restoration sampling dates to assess changes over time (Fig. 11). SRP post-restoration period remains significantly greater than the pre-restoration at both depths (Fig. 11A, B). In contrast, mean TP, chl *a*, and Secchi depth continue be significantly improved from pre-restoration (Figures 11C-G).

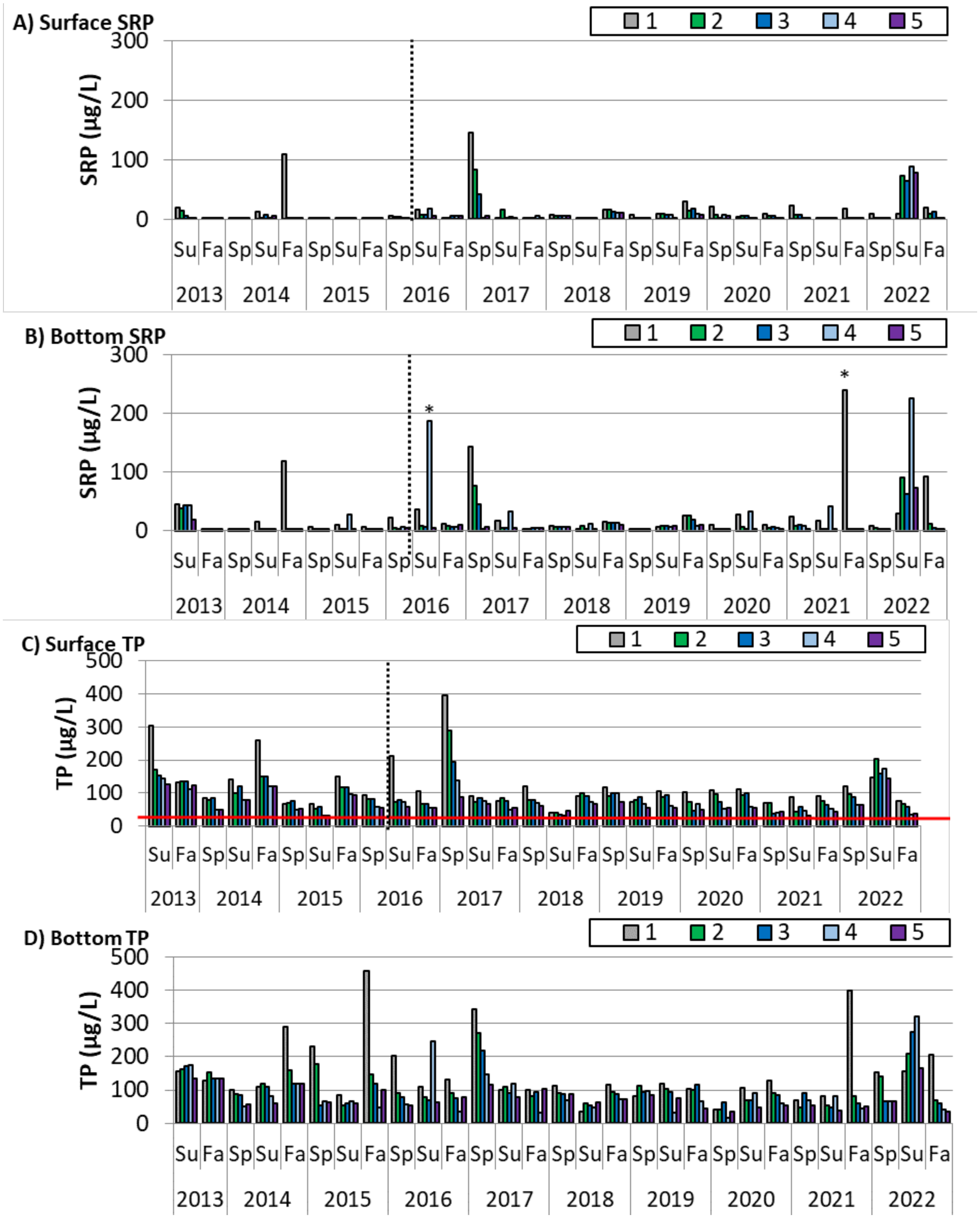

Figure 8. Soluble reactive phosphorus ([SRP]: A, B) and total phosphorus ([TP]: C, D) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2022. The red horizontal lines on surface TP (C) indicate the interim total daily maximum load (TMDL) goal of 50 µg/L (Walterhouse 1999). 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.

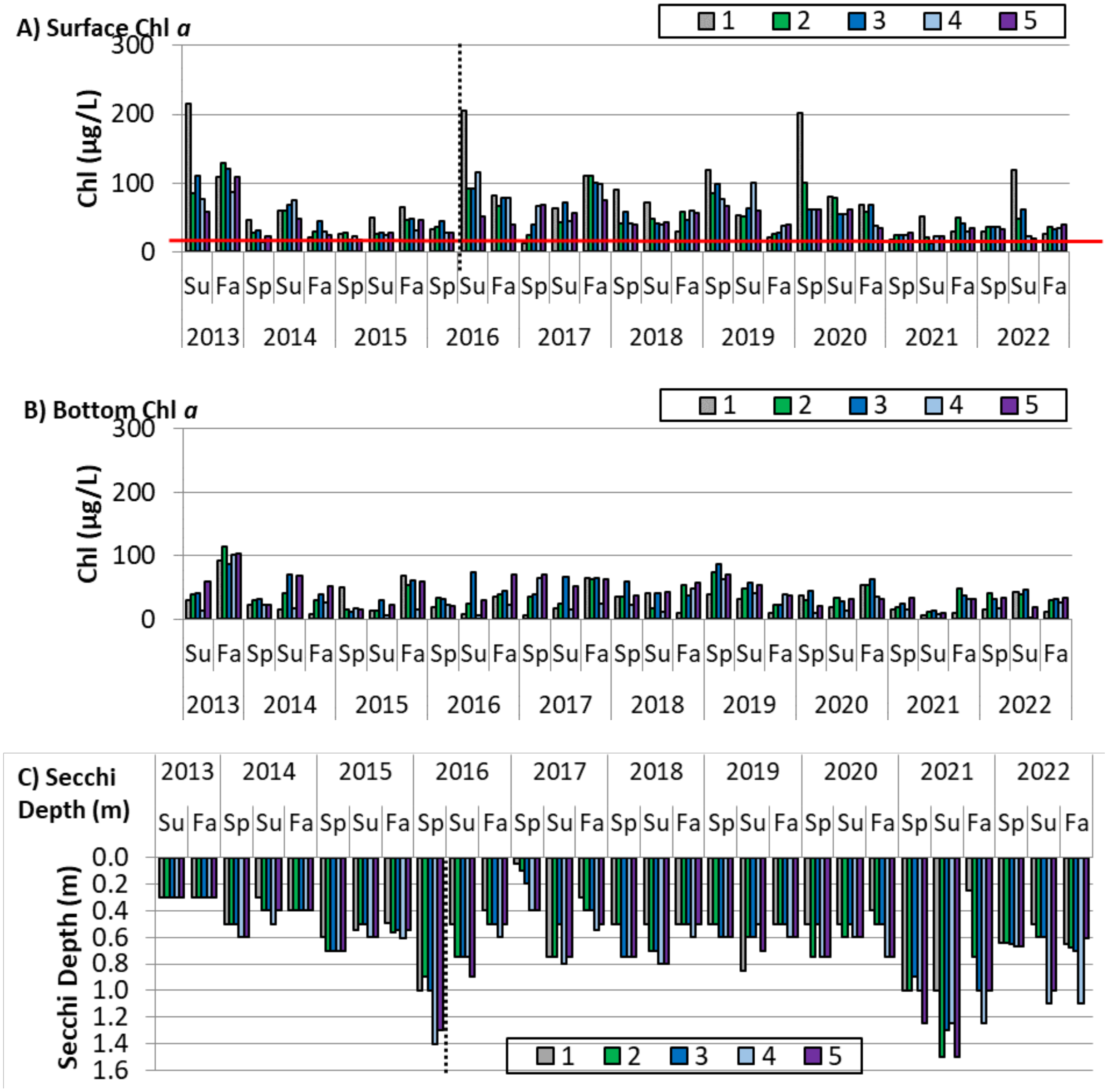

Figure 9. Chlorophyll *a* ([chl *a*]: A, B); and Secchi disk depth: (C) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2022. The red horizontal line on surface chl (A) indicates the hypereutrophic boundary of 22 µg/L used by EGLE to assess chl *a* in Lake Macatawa (Holden 2014). Note scales change on y-axes. Vertical dotted lines represent approximate restoration construction completion dates for Middle Macatawa and Haworth wetlands.

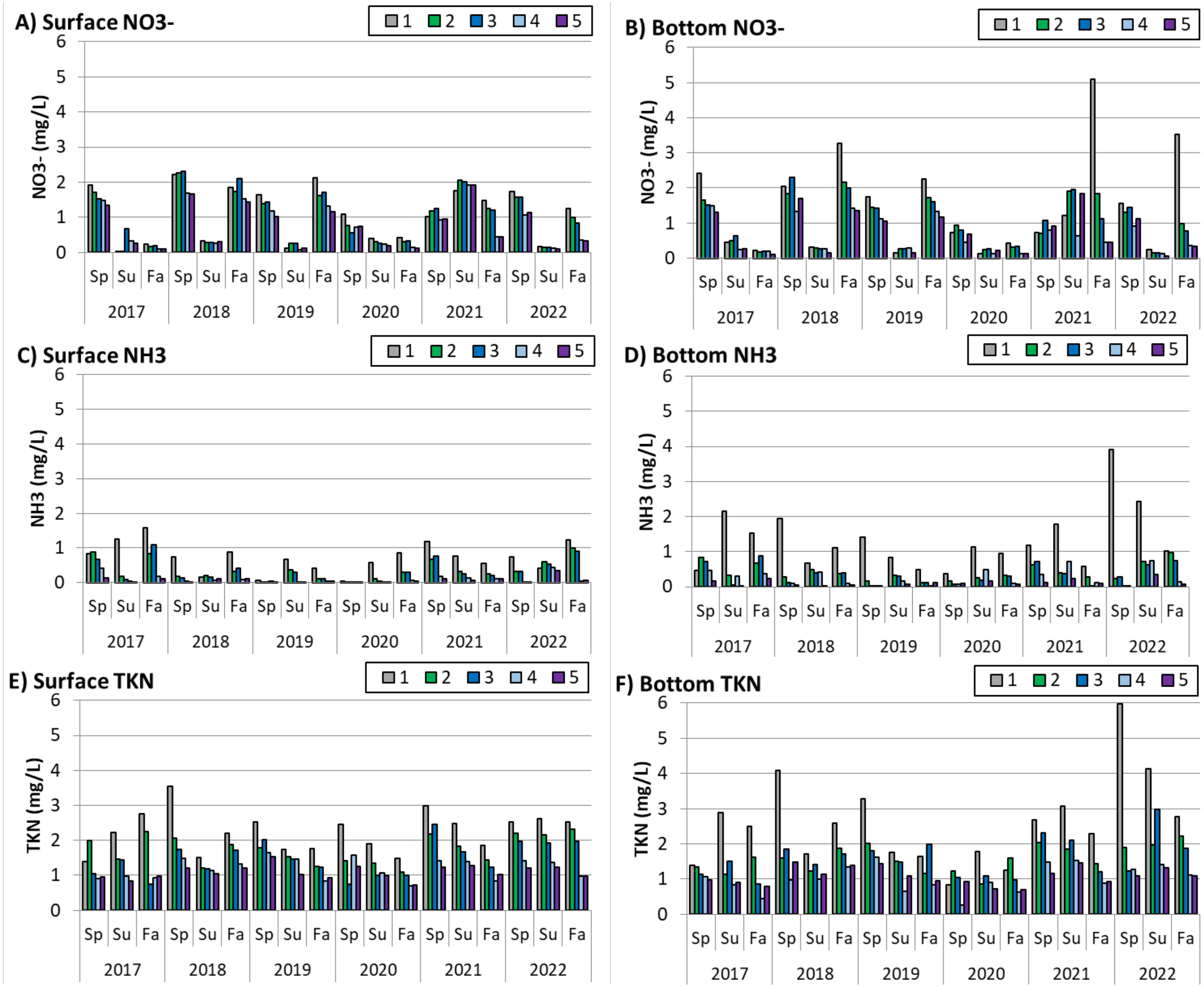

Figure 10. Nitrate ([NO_3^-]: A, B); ammonia ([NH_3]: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2017 through 2022. Note scales change on y-axes.

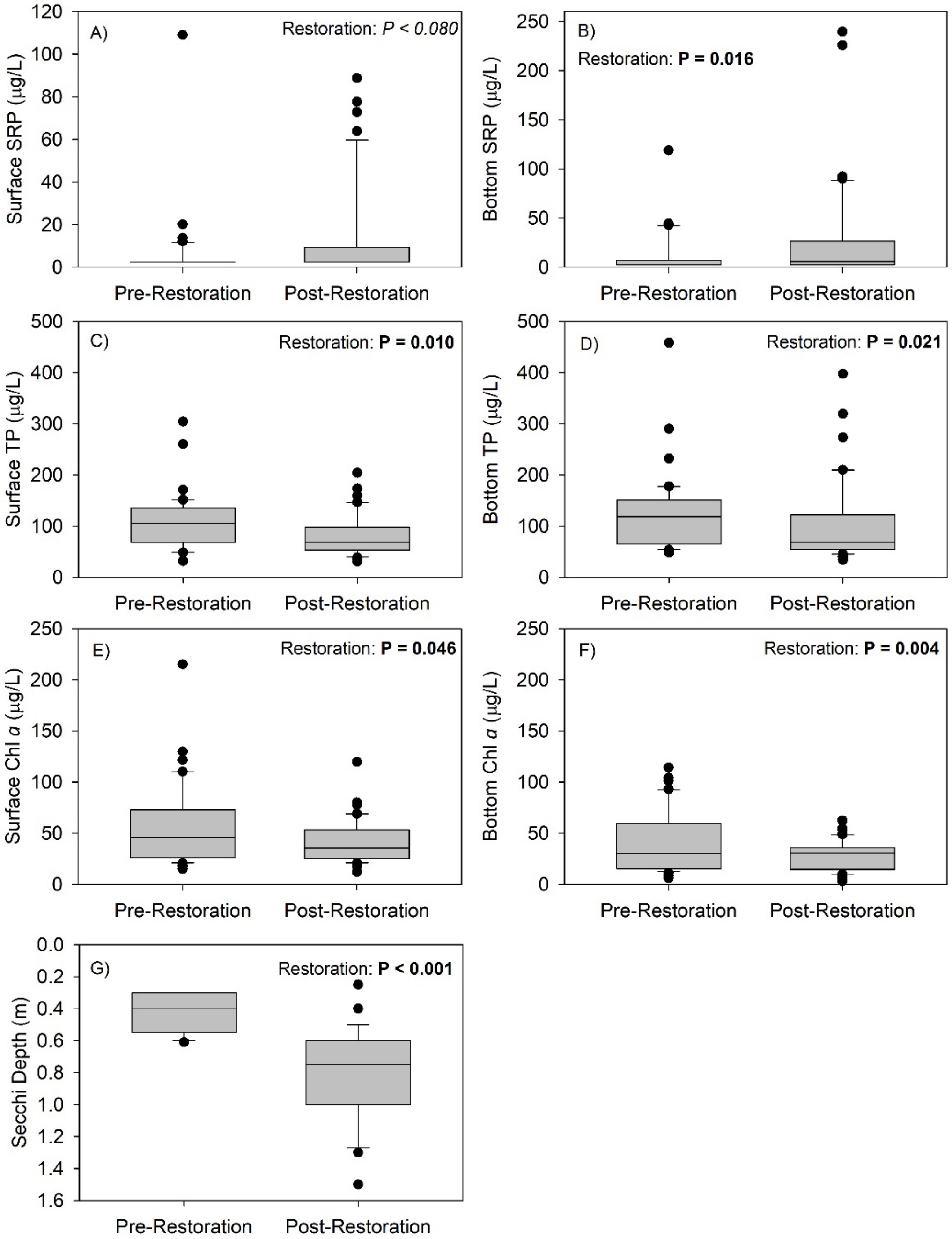

Figure 11. Box plots of soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); chlorophyll *a* ([chl *a*]: E, F; and Secchi disk depth: G) levels measured at the 5 monitoring stations in Lake Macatawa during all pre-restoration sampling dates (summer 2013 – fall 2015) and an equal and seasonally corresponding number of post-restoration sampling dates (summer 2020 – fall 2022). 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. 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, whereby phosphorus can be transported in the dissolved form or as attached to sediment particles. 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. The large P concentrations measured in the lake during summer 2022 during an algal bloom was not associated with a high precipitation event during either the preceding day or 2 months and as such stood out as outliers in our precipitation analysis (Fig. 12; this was also verified by Grubb's test for Outliers). Removing this outlier improved the R^2 values of both relationships (Fig. 13; SRP-PPTN and TP-PPTN: R^2=0.32). This suggests that there is a weak but statistically significant underlying relationship between precipitation and P content in the lake, but at times, other factors may override this relationship, such as internal loading from the sediments.

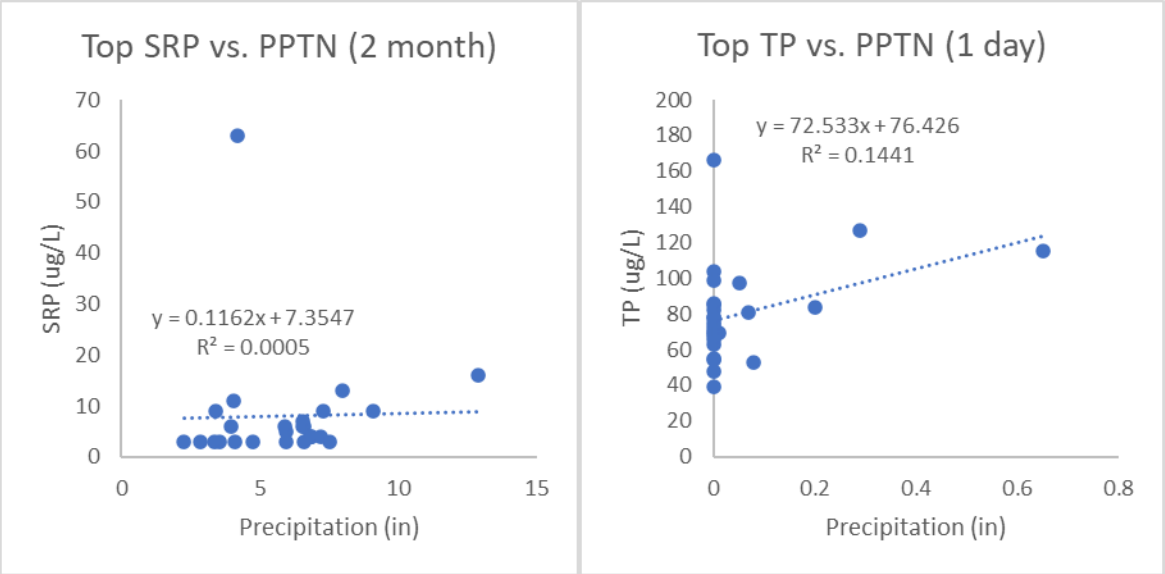

Figure 12. Linear regressions plotting annual precipitation vs. mean soluble reactive phosphorus (SRP) and total phosphorus (TP) concentrations in Lake Macatawa. Summer 2022 was determined to be an outlier resulting in low R^2 values.

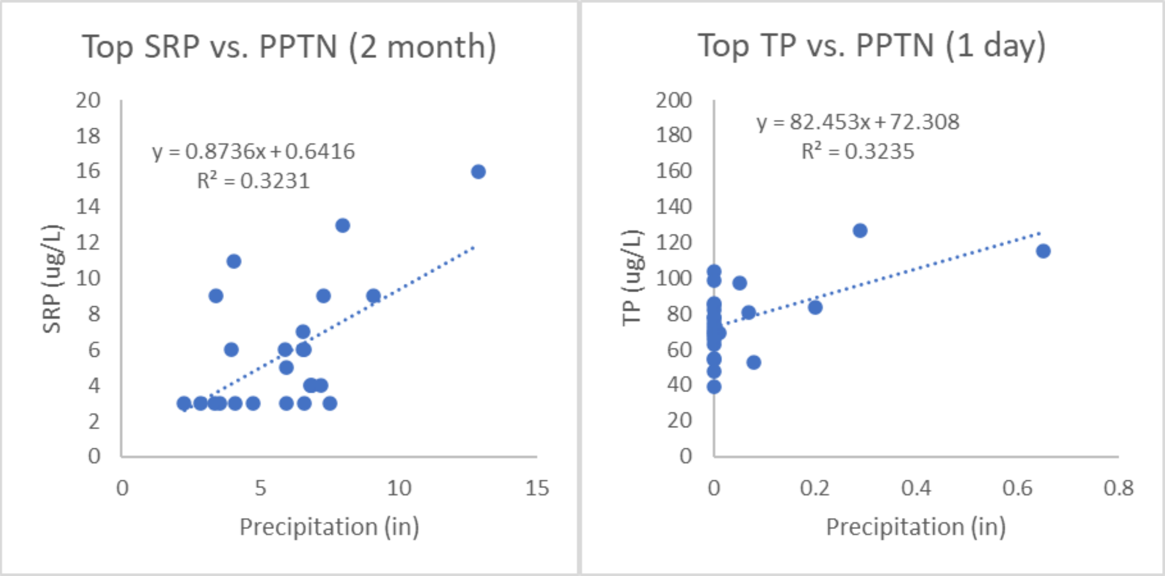

Figure 13. Linear regressions plotting annual precipitation vs. mean soluble reactive phosphorus (SRP) and total phosphorus (TP) concentrations in Lake Macatawa. Surface SRP and TP data are lake-wide means of seasonal 2013-2022 AWRI sampling events. Precipitation data sources were provided by the National Climatic Data Center/National Centers for Environmental Information (2013-2022; NOAA).

4. Summary

The 2022 water quality in Lake Macatawa showed backsliding compared to the 2021 data. The increase in TP may be somewhat anomalous as our summer sampling occurred during an algal bloom, which will concentrate phosphorus levels. Indeed, when 3-yr increments of pre- (2013-2015) vs. post-restoration (2020-2022) measurements, TP (as well as chlorophyll *a* and water clarity) shows improvement. Nonetheless, all 3 critical indicators (TP, chl a, and water clarity) indicated declining water quality in 2022 vs. 2021. As we have observed the past few years, dissolved 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. We recommend the agricultural community evaluate their tillage practices and continue the implementation of BMPs wherever and whenever possible.

Similar to what we observed in 2021, nitrate levels in spring and fall, especially at Site 1 closest to the Macatawa River inflow, are higher than in the past. Nitrate, similar to SRP, is in the dissolved form and readily taken up by algae. Utilization of the computational SWAT model for the Macatawa watershed (Iavorivska et al. 2020) can help producers identify appropriate agricultural practices to reduce nitrogen and phosphorus runoff from the watershed.

We caution that the 2022 water quality data need to be evaluated in light of multiyear trends; hence, 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, and the 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 additional data (Appendix A), Lake Macatawa dashboard (Appendix B), and results from the long-term fish monitoring study on Lake Macatawa (Appendix C).

The Lake Macatawa Dashboard (Appendix B) 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 littoral fish assemblage showed both positive and negative indicators of Lake Macatawa's ecological health. Yellow perch, bluegill, and pumpkinseed were common species captured in fish surveys, and they are indicators of good water quality. However, other common fish species in surveys, such as gizzard shad and spotfin shiner, are often associated with poor water quality. The near absence of rock bass in the catch also likely indicates poor water quality. In the 9 years of sampling, rock bass was captured in only one year (2021).

We conclude with a list of recommendations for the ODC and partners to consider as Project Clarity nears the end of its first decade of planning, implementation, and management:

- 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.

- Although we have observed overall improvements in water quality, the 2022 data indicate this improvement is neither linear nor guaranteed in the future. Continued maintenance and implementation of GAAMPs (generally accepted agricultural management practices) are needed. Utilization of the SWAT model developed for the Lake Macatawa watershed can provide 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—for example, is the lake developing more 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 2022 data suggest that 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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6. References

Abell, J.M., Özkundakci, D., Hamilton, D.P., and P. Reeves P. 2020. Restoring shallow lakes impaired by eutrophication: Approaches, outcomes, and challenges. Critical Reviews in Environmental Science and Technology. https://doi.org/10.1080/10643389.2020.1854564.

APHA. 1992. Standard Methods for Examination of Water and Wastewater. 18th Edition. American Public Health Association. Baker, D.B., L.T. Johnson, R.B. Confesor Jr, J.P. Crumrine, T. Guo, and N.F. Manning. 2019. Needed: Early term adjustments for Lake Erie phosphorus target loads to address western basin cyanobacterial blooms. Journal of Great Lakes Research 45: 203-211.

Brennan, A.K., C.J. Hoard, J.W. Duris, M.E. Ogdahl, and A.D. Steinman. 2016. Water quality and hydrology of Silver Lake, Oceana County, Michigan, with emphasis on lake response to nutrient loading (No. 2015-5158). US Geological Survey.

Fales, M., Dell, R., Herbert, M.E., Sowa, S.P., Asher, J., O'Neil, G., Doran, P.J. and Wickerham, B. 2016. Making the leap from science to implementation: Strategic agricultural conservation in Michigan's Saginaw Bay watershed. Journal of Great Lakes Research 42(6): 1372-1385.

Hassett, M., M. Oudsema, E. Kindervater, and A. Steinman. 2021. Project Clarity: 2020 Annual Monitoring Report. Available at: https://www.gvsu.edu/cms4/asset/DFC9A03B-95B4-19D5-F96AB46C60F3F345/project_clarity_2020_annual_report_final.pdf

Holden, S. 2014. Monthly water quality assessment of Lake Macatawa and its tributaries, AprilSeptember 2012. Michigan Department of Environmental Quality, Water Resources Division. MI/DEQ/WRD-14/005.

Jarvie, H.P., Johnson, L.T., Sharpley, A.N., Smith, D.R., Baker, D.B., Bruulsema, T.W. and Confesor, R. 2017. Increased soluble phosphorus loads to Lake Erie: Unintended consequences of conservation practices?. Journal of Environmental Quality 46(1): 123-132.

Michalak, A.M., E.J. Anderson, D. Beletsky, S. Boland, N.S. Bosch, et al. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proceedings of the National Academy of Sciences 110: 6448-6452. MWP (Macatawa Watershed Project). 2012. Macatawa Watershed Management Plan. Macatawa Area Coordinating Council, Holland, Michigan.

Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. I. Journal of Ecology 29: 280-329.

Progressive AE. 2017. Macatawa Watershed Alum Injection System Preliminary Engineering Feasibility Study Report. Prepared for Outdoor Discovery Center, Holland, MI.

Steinman, A., Rediske, R., Denning, R., Nemeth, L., Chu, X., Uzarski, D., Biddanda, B. and Luttenton, M. 2006. An environmental assessment of an impacted, urbanized watershed: the Mona Lake Watershed, Michigan. Archiv für Hydrobiologie 166(1): 117-144.

Steinman, A., Abdimalik, M., Ogdahl, M.E. and M. Oudsema, M. 2016. Understanding planktonic vs. benthic algal response to manipulation of nutrients and light in a eutrophic lake. Lake and Reservoir Management 32: 402-409.

Steinman, A.D., Hassett, M. and Oudsema, M. 2018. Effectiveness of best management practices to reduce phosphorus loading to a highly eutrophic lake. International Journal of Environmental Research and Public Health 15(10), 2111.

Steinman, A.D. and B. Spears (Editors). 2020. Internal Phosphorus Loading: Causes, Case Studies, and Management. Publisher: J. Ross Publishing, Boca Raton, FL. 466 pp. U.S. EPA. 1993. Methods for Chemical Analysis of Inorganic Substances in Environmental Samples. EPA600/4-79R-93-020/100. Walterhouse, M. 1999. Total Maximum Daily Load for Phosphorus in Lake Macatawa, January 20, 1999. MDEQ Submittal to U.S. Environmental Protection Agency.

Yang, C., Yang, P., Geng, J., Yin, H. and Chen, K. 2020. Sediment internal nutrient loading in the most polluted area of a shallow eutrophic lake (Lake Chaohu, China) and its contribution to lake eutrophication. Environmental Pollution 262, 114292.

7. Appendices

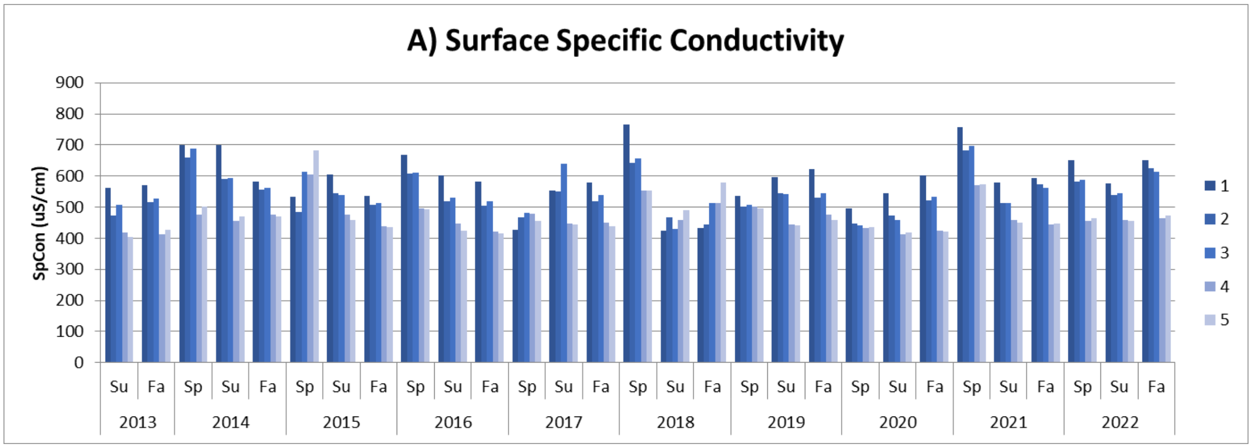
Appendix A. Specific conductivity and turbidity data: 2013-2022

Appendix B. Lake Macatawa Dashboards

Appendix C. Long-Term Fish Monitoring of Lake Macatawa

Appendix A.

Fig. A1. Specific conductivity measurements. A) surface readings; B) near-bottom readings.



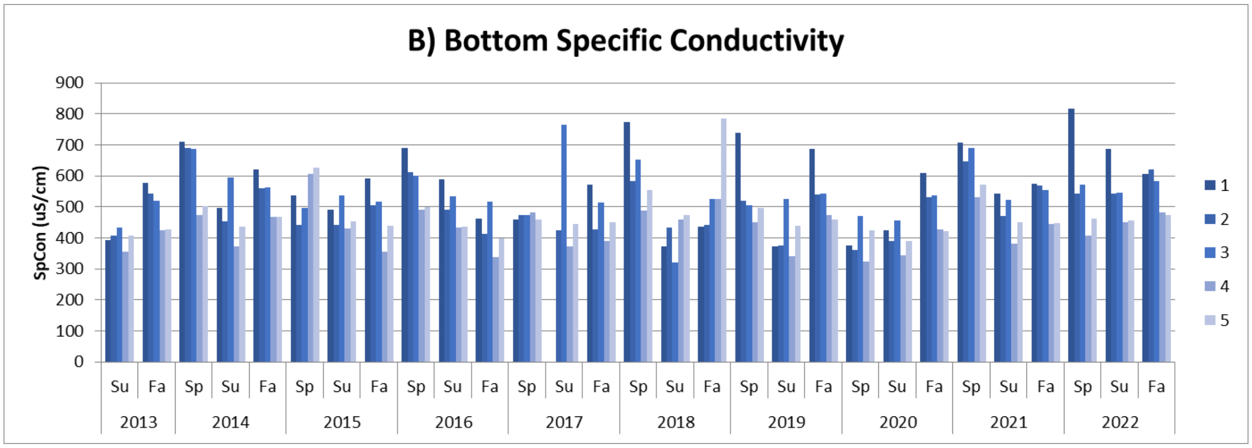
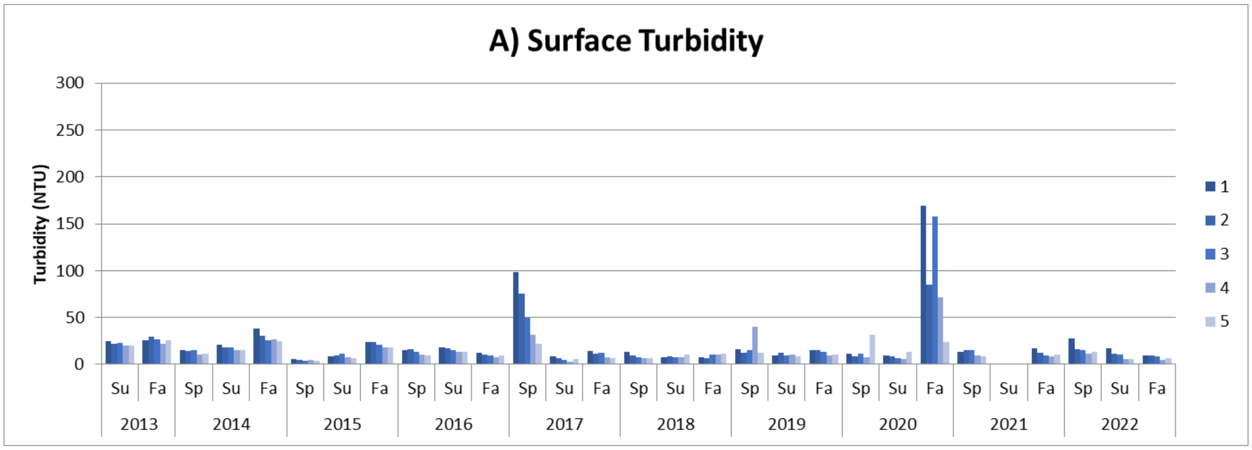
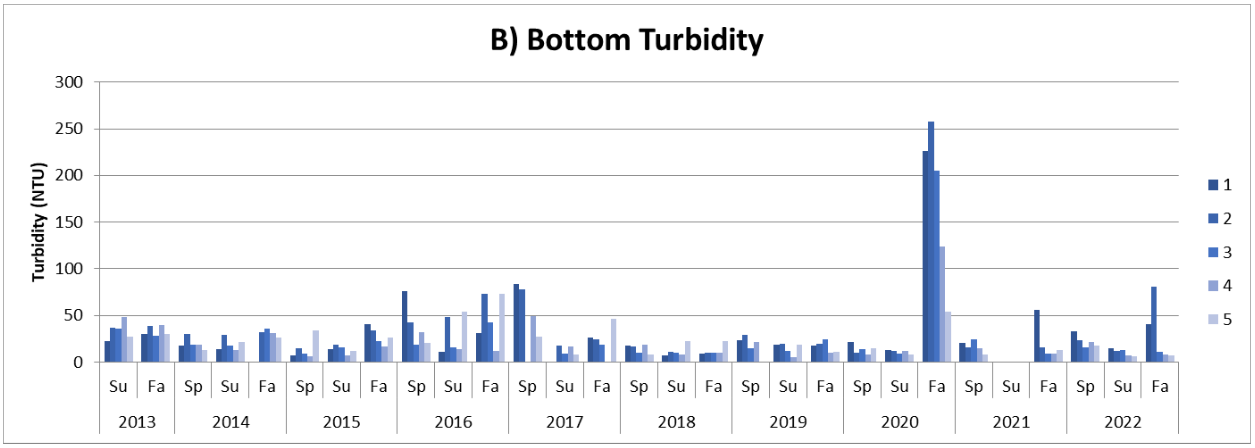


Fig. A2. Turbidity measurements. A) surface readings; B) near-bottom readings.





Appendix B. Lake Macatawa Dashboards

Lake Macatawa Water Quality Dashboard

2022

Prepared: February 2023

Michael C. Hassett
Alan D. Steinman, Ph.D.

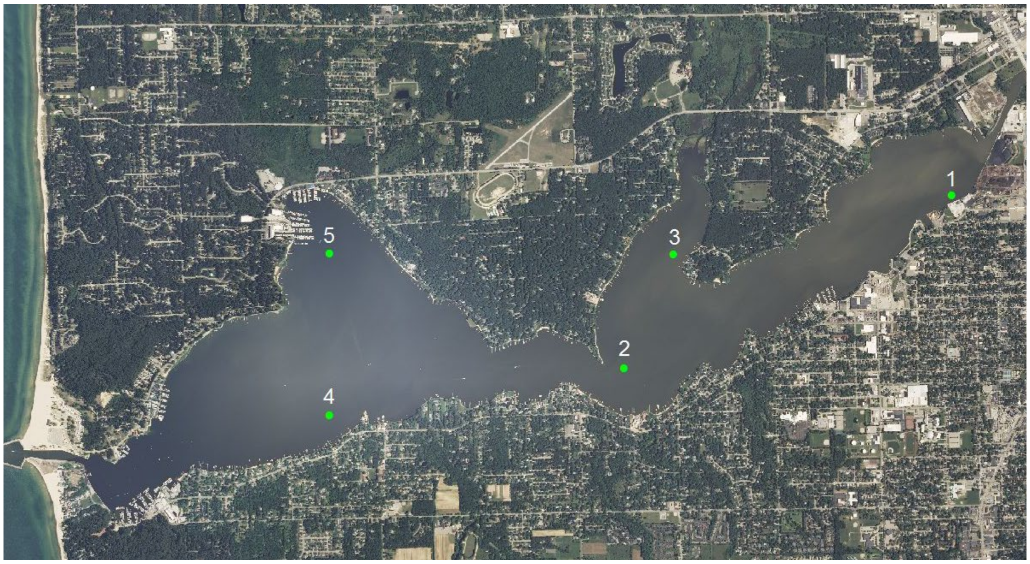
GRAND VALLEY
STATE UNIVERSITY
ROBERT B. ANNIS
WATER RESOURCES INSTITUTE

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). Data are also collected for Sites 3 and 5 (northern bays) and are available in the full annual report but are excluded from the dashboard because they are more heavily influenced by local conditions in the bay and can bias the dashboard readings.

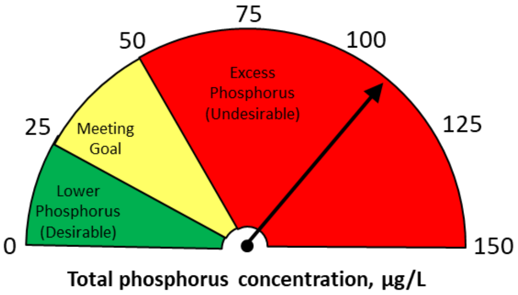


Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring. Dashboard indicators were calculated based on data from Sites 1, 2, and 4.

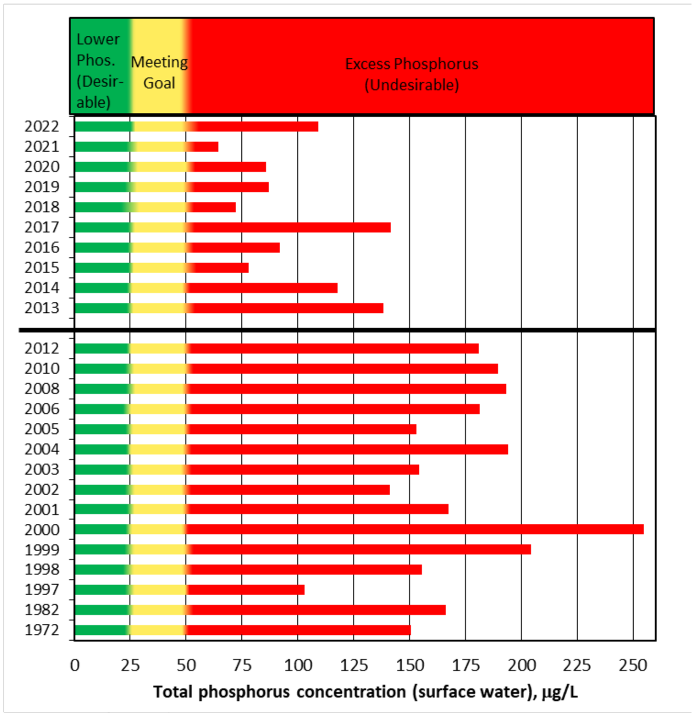
Total Phosphorus

2022 Mean Concentration: 109 µg/L
Target Concentration: 50 µg/L

Current status (2022)



Historical Status (1972*; 1982-2012†; 2013-2022‡)



*U.S. EPA; †EGLE; ‡AWRI

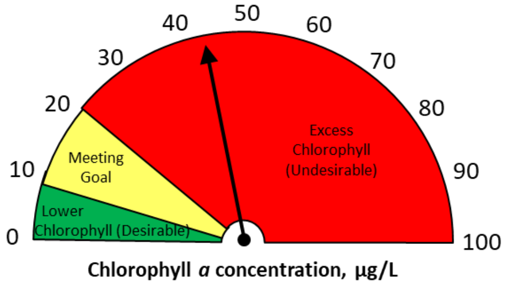
Phosphorus (P) is an essential element for living organisms. In many freshwater systems, P is the element that limits algal growth. However, when it becomes too abundant, it can help stimulate undesirable algal blooms. Phosphorus comes in many forms; we selected Total Phosphorus (TP) as the dashboard 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.

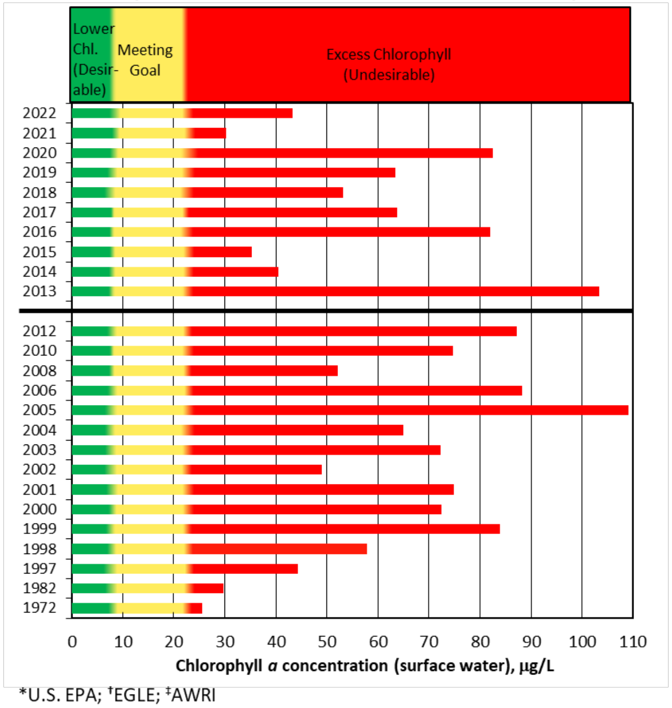
The current status for the total phosphorus indicator is **Undesirable**, indicating that the average TP concentration in 2022 exceeded the water quality goal and represents a reversal from the past four years. Although high summer TP was likely a result of an algae bloom and low dissolved oxygen, spring and fall mean TP also exceeded the 50 µg/L restoration goal.

Chlorophyll *a*

2022 Mean Concentration: 43 µg/L
Target Concentration: 22 µg/L



Current status (2022)



Historical Status (1972*; 1982-2012†; 2013-2022‡)

*U.S. EPA; †EGLE; ‡AWRI

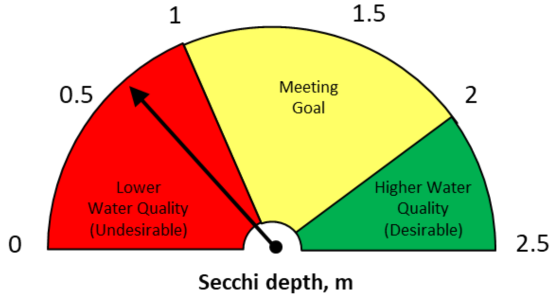
Chlorophyll *a* is the green pigment found in photosynthetic plants and algae. Measuring chlorophyll *a* is a relatively simple way to estimate the amount of algal biomass present in lake water, although it has some limitations. First, chlorophyll *a* does not provide information on whether or not the 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.

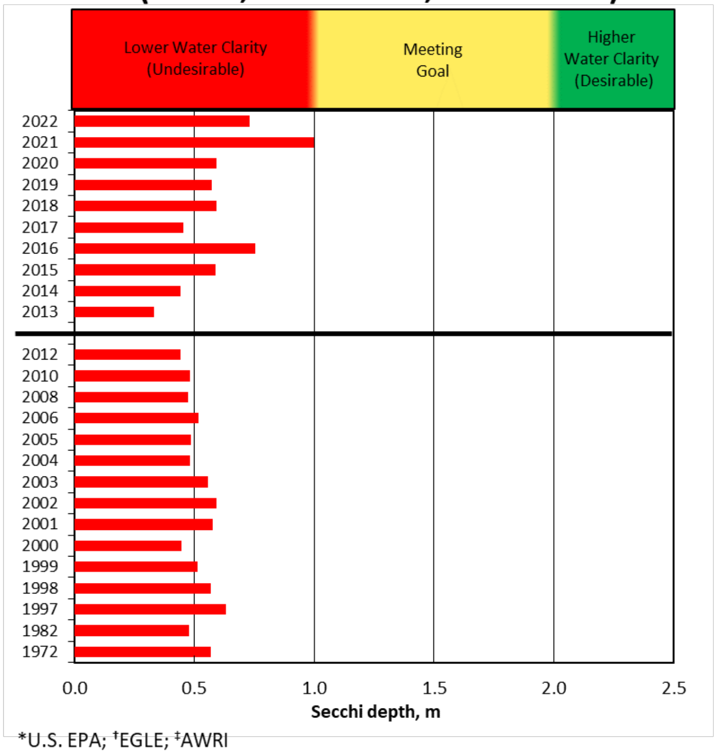
The current status for the chlorophyll *a* indicator is **Undesirable** due in part to the algae bloom in July 2022; although the dashboard reflects an increase compared to 2021, chlorophyll *a* levels remained lower than the 2016-2020 concentrations.

Secchi Disk Depth (Water Clarity)

2022 Mean Depth: 0.73 m (~2.4 ft)
Target Depth: 1 m (~3.3 ft)



Current status (2022)



Historical Status (1972*; 1982-2012[†]; 2013-2022[‡])

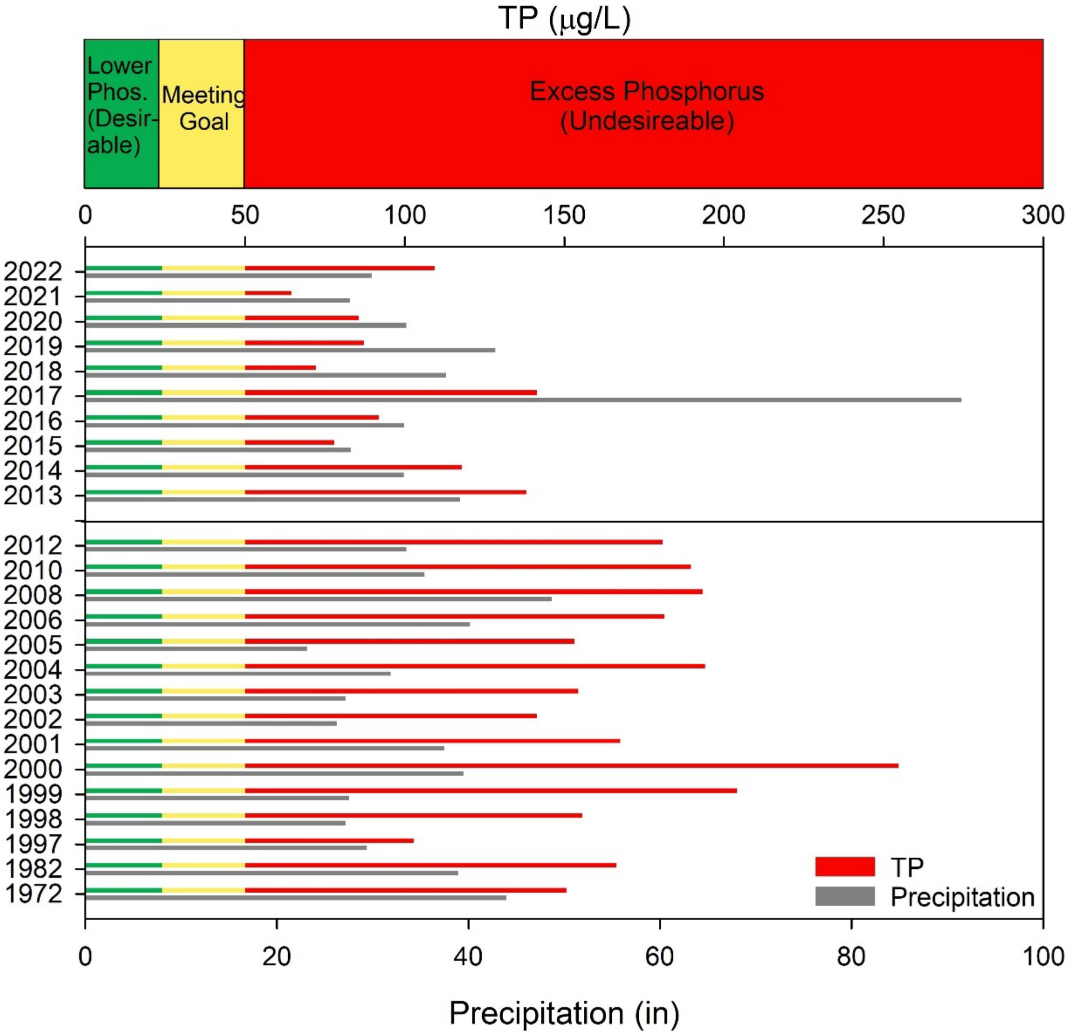
*U.S. EPA; [†]EGLE; [‡]AWRI

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, suspended sediment, or dissolved organic matter?).

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 slightly worsened from last year and currently does not meet the criteria of the water quality goal. However, the water clarity is still improved compared to prior 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 statistically 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 2013-2022, $R^2 = 0.32$; $p = 0.003$). 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 non-monitored season.

Appendix C.

Long-Term Fish Monitoring of Lake Macatawa: Results from Year 9 (2022)

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27 February 2023

An Annual Report
to the
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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 ninth year (2022) 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 begin to assess patterns in the data over time. However, the true value of this fish monitoring effort will come as we continue to accumulate more data so that we can examine how the littoral fish assemblage responds 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. 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). 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 19 September 2022 during daylight hours (i.e., between 0900 and 1400) and fished for about 26.9 h (range = 23.3-28.6 h). Except for 2021 when poor weather conditions delayed sampling into October, fyke nets had been previously set 4-16 September (2014-2020), which was similar to 2022. 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 22 September 2022. All previous nighttime electrofishing surveys were conducted during 5-14 September (2014-2021). 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 2022 (Tables 2 and 3). The mean water depth at fyke nets was 90 cm (Table 2), which was similar to the long-term mean water depth of 92 cm (range = 84-104 cm; n = 9 years) at fyke nets. Mean water temperature during fyke netting (22.8 °C; Table 2) was similar to conditions during nighttime boat electrofishing (20.7 °C; Table 3). The long-term mean water temperature during fyke netting was 22.3 °C (range = 18.3-25.5 °C; n = 9 years) and nighttime boat electrofishing was 21.9 °C (range = 19.2-24.2 °C; n = 9 years). We were unable to estimate percent macrophyte cover at sites during fyke netting and able to estimate percent macrophyte cover only at site #3

(60%) and site #4 (75%) during nighttime electrofishing. Thus, the limited observations we were able to make during 2022 adds little in terms of assessing trends in percent macrophyte cover over time (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 (16.2 NTU, n = 12) in 2022 about the same as the long-term mean (16.6 NTU, n = 108; 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 2,188 fish comprising 28 species in Lake Macatawa during 2022 sampling surveys (Table 4). The total catch in 2022 was above the long-term mean of 1,375 fish (SD = 454, n = 9 years), but the number of fish species captured was similar to the long-term mean of 27 species (SD = 2.9, n = 9 years; Figure 4). The most common fishes in the combined catch (i.e., fyke netting and boat electrofishing) were gizzard shad (21%), brook silverside (17%), spotfin shiner (14%), bluegill (9%), round goby (8%), yellow perch (7%), and white perch (7%), which composed 83% of the total catch (Figure 5A). Six of the 28 species captured during 2022 were non-native to the Great Lakes basin (Bailey et al. 2004)—alewife, goldfish, common carp, white perch, round goby, and Chinook salmon—which composed 16% of the total catch, although most of the non-native fishes were round goby and white perch (Table 4). For comparison, we captured 1,324 fishes comprising 23 species in Muskegon Lake during autumn 2022 (with sampling effort in terms of sites and gear similar to the sampling reported here for Lake Macatawa). Four of the 23 species in Muskegon Lake were non-native to the Great Lakes basin—alewife, common carp, white perch, and round goby—which composed 7% of the catch (88% of non-native fish species captured in Muskegon Lake in autumn 2022 were round goby). Rock bass—associated with excellent biotic integrity (Cooper et al. 2018)—composed almost 11% of the catch in Muskegon Lake during autumn 2022, whereas this species was not captured in Lake Macatawa during 2022.

In fyke netting, gizzard shad (25%), brook silverside (21%), spotfin shiner (19%), round goby (11%), and bluegill (8%) were the most common fishes in the catch, composing 85% of all fish captured (Figure 5B). The most common species in the catch at each site were gizzard shad and spotfin shiner at sites #1 and #2, brook silverside at site #3, and brook silverside and gizzard shad 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 site #3 (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 2022 was similar to 2021, except that gizzard shad were a larger component of the catch (Figure 7).

In boat electrofishing, the most common fishes captured were yellow perch (23%), white perch (20%), pumpkinseed (10%), bluegill (9%), gizzard shad (8%), and brook silverside (8%), which composed 78% of the total catch (Figure 5C). The most common species in the catch were white perch and bluegill at site #1, white perch and pumpkinseed at site #2, yellow perch, brook silverside, and white perch at site #3, and yellow perch at site #4 (Table 6). Total catch also varied among sites in 2022, with the highest catch at site #2 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 2022, yellow perch and white perch were more common in the catch and gizzard shad less common than in recent (i.e., 2019-2021) years (Figure 8). Nevertheless, gizzard shad was common in fyke netting in 2022 (Figure 7), showing the value of using two types of gear when sample littoral fish assemblages (see Ruetz et al. 2007).

The observations reported here can be used to characterize the littoral fish assemblage of Lake Macatawa. After 9 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). Nevertheless, 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 9 years of sampling, rock bass was captured in only one year (2021). As we continue to build our 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.

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References

Bailey, R.M., W.C. Latta, and G.R. Smith. 2004. An atlas of Michigan fishes with keys and illustrations for their identification. Miscellaneous Publications, Museum of Zoology, University of Michigan, No. 192.

Bhagat, Y., and C.R. Ruetz III. 2011. Temporal and fine-scale spatial variation in fish assemblage structure in a drowned river mouth system of Lake Michigan. Transactions of the American Fisheries Society 140:1429-1440.

Breen, M.J., and C.R. Ruetz III. 2006. Gear bias in fyke netting: evaluating soak time, fish density, and predators. North American Journal of Fisheries Management 26:32-41.

Cooper, M.J., G.A. Lamberti, A.H. Moerke, and 9 coauthors. 2018. An expanded fish-based index of biotic integrity for Great Lakes coastal wetlands. Environmental Monitoring and Assessment 190:580 (https://doi.org/10.1007/s10661-018-6950-6).

Janetski, D.J., and C.R. Ruetz III. 2015. Spatiotemporal patterns of fish community composition in Great Lakes drowned river mouths. Ecology of Freshwater Fish 24:493-504.

Kleindl, P.M, and A.D. Steinman. 2021. Contrasting trajectories in macrophyte community development after shoreline restoration: water level obscures trends. Aquatic Botany 169:103327 (https://doi.org/10.1016/j.aquabot.2020.103327).

Liu, Q., E.J. Anderson, Y. Zhang, A.D. Weinke, K.L. Knapp, and B.A. Biddanda. 2018. Modeling reveals the role of coastal upwelling and hydrologic inputs on biologically distinct water exchanges in a Great Lakes estuary. Estuarine, Coastal and Shelf Science 209:41-55.

Michigan Department of Natural Resources (MDNR). 2011. Lake Macatawa Ottawa County. Fish Collection System (printed 6/11/2011). Accessed at http://www.the-macc.org/wp-content/uploads/History-of-Lake-Mactawa-and-Fish.pdf (on 12/1/2014).

Ogdahl, M.E., and A.D. Steinman. 2014. Factors influencing macrophyte growth and recovery following shoreline restoration activity. Aquatic Botany 120:363-370.

Radomski, P., and T.J. Goeman. 2001. Consequences of human lakeshore development on emergent and floating-leaf vegetation abundance. North American Journal of Fisheries Management 21:46-61.

Ruetz, C.R., III, D.G. Uzarski, D.M. Krueger, and E.S. Rutherford. 2007. Sampling a littoral fish assemblage: comparing small-mesh fyke netting and boat electrofishing. North American Journal of Fisheries Management 27:825-831.

Uzarski, D.G., T.M. Burton, M.J. Cooper, J.W. Ingram, and S.T.A. Timmermans. 2005. Fish habitat use within and across wetland classes in coastal wetlands of the five Great Lakes: development of a fish-based index of biotic integrity. Journal of Great Lakes Research 31(Suppl. 1):171-187.

Table 1. Locations (latitude and longitude) for each 2022 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	42.78594	-86.12134	42.79573	-86.12041	42.79562	-86.12280
2	42.79003	-86.14386	42.79033	-86.14413	42.78821	-86.14447
3	42.78607	-86.17442	42.78682	-86.17531	42.78597	-86.17409
4	42.77946	-86.19719	42.77916	-86.19762	42.78001	-86.19621

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 20 September 2022 with a YSI sonde.

Site	Depth (cm)	Water Temperature (°C)	Dissolved Oxygen (mg/L)	Dissolved Oxygen (%)	Specific Conductivity (µS/cm)	Total Dissolved Solids (g/L)	Turbidity (NTU)	pH	Chlorophyll *a* (µg/L)
1	87 ± 4	22.92 ± 0.00	9.09 ± 0.10	105.9 ± 1.2	561 ± 1	0.365 ± 0.000	20.2 ± 0.5	8.20 ± 0.01	66.5 ± 1.2
2	98 ± 3	22.71 ± 0.06	9.09 ± 0.12	105.4 ± 1.3	505 ± 0	0.328 ± 0.000	24.9 ± 5.7	8.48 ± 0.02	82.3 ± 2.2
3	83 ± 5	22.87 ± 0.01	9.60 ± 0.18	111.7 ± 2.2	431 ± 0	0.280 ± 0.000	7.4 ± 0.4	8.68 ± 0.02	20.6 ± 0.8
4	92 ± 1	22.56 ± 0.07	10.80 ± 0.19	125.0 ± 2.8	438 ± 0	0.285 ± 0.000	12.5 ± 0.9	8.74 ± 0.01	40.7 ± 7.8

Table 3. Water quality variables at fish sampling sites in Lake Macatawa. Water quality measurements were made during nighttime boat electrofishing on 22 September 2022 with a YSI sonde.

Site	Water Temperature (°C)	Dissolved Oxygen (mg/L)	Dissolved Oxygen (%)	Specific Conductivity (µS/cm)	Total Dissolved Solids (g/L)	Turbidity (NTU)	pH	Chlorophyll *a* (µg/L)
1	21.69	6.22	72.5	618	0.402	13.8	7.76	30.5
2	20.68	9.34	104.6	517	0.336	12.2	8.34	40.8
3	19.88	10.19	112.9	444	0.289	5.6	8.68	22.4
4	20.49	8.82	98.1	439	0.285	8.2	8.53	24.8

Table 4. Number and total length (TL; mean, minimum, and maximum) of fish captured by fyke netting (*n* = 12 nets) on 20 September at four sites and boat electrofishing (*n* = 4 transects) on 22 September 2022 at four sites in Lake Macatawa. Total is the total catch combined for both gear.

			Fyke netting				Electrofishing			
				TL (cm)				TL (cm)		
Common name	Scientific name	Total	Catch	Mean	Min	Max	Catch	Mean	Min	Max
alewife	*Alosa pseudoharengus*	1	1	6.4	--	--	--	--	--	--
bowfin	*Amia calva*	8	4	52.1	39.7	62.6	4	56.2	42.3	63.5
goldfish	*Carassius auratus*	1	--	--	--	--	1	37.9	--	--
quillback	*Carpiodes cyprinus*	1	--	--	--	--	1	53.6	--	--
white sucker	*Catostomus commersonii*	20	1	43.2	--	--	19	41.1	28.2	53.2
common carp	*Cyprinus carpio*	4	--	--	--	--	4	60.5	56.6	66.4
spotfin shiner	*Cyprinella spiloptera*	312	312	6.2	3.5	10.3	--	--	--	--
gizzard shad	*Dorosoma cepedianum*	454	407	9.9	7.1	19.6	47	12.8	10.1	19.6
northern pike	*Esox lucius*	3	1	66.6	--	--	2	81.3	74.4	88.2
banded killifish	*Fundulus diaphanus*	20	13	7.8	6.3	9.6	7	7.8	6.8	8.9
channel catfish	*Ictalurus punctatus*	3	3	26.9	8.1	63.5	--	--	--	--
brook silverside	*Labidesthes sicculus*	380	335	7.0	4.5	10.0	45	8.0	6.7	10.5
pumpkinseed	*Lepomis gibbosus*	82	25	9.4	5.5	19.2	57	9.0	5.5	17.8
bluegill	*Lepomis macrochirus*	187	137	6.2	2.5	19.0	50	11.0	3.1	19.8
common shiner	*Luxilus cornutus*	2	--	--	--	--	2	11.1	10.6	11.6
largemouth bass	*Micropterus salmoides*	52	14	11.0	6.3	24.1	38	20.5	7.5	42.4
white perch	*Morone americana*	151	35	10.2	5.2	11.9	116	11.1	7.8	18.2
round goby	*Neogobius melanostomus*	182	175	7.1	3.2	14.0	7	8.7	7.0	11.3
emerald shiner	*Notropis atherinoides*	42	27	8.8	4.0	11.2	15	9.6	8.3	11.1
golden shiner	*Notemigonus crysoleucas*	50	35	9.4	7.5	14.6	15	11.4	8.2	17.7
spottail shiner	*Notropis hudsonius*	11	7	9.0	7.8	12.3	4	9.1	8.7	9.5
mimic shiner	*Notropis volucellus*	2	2	4.1	3.5	4.7	--	--	--	--
Chinook salmon	*Oncorhynchus tshawytscha*	1	--	--	--	--	1	78.6	--	--
yellow perch	*Perca flavescens*	153	18	16.2	8.9	22.9	135	14.1	9.1	20.5
bluntnose minnow	*Pimephales notatus*	59	58	6.3	4.6	9.4	1	7.1	--	--
black crappie	*Pomoxis nigromaculatus*	4	3	20.0	16.2	25.7	1	19.5	--	--
flathead catfish	*Pylodictis olivaris*	1	1	100.0	--	--	--	--	--	--
walleye	*Sander vitreus*	2	--	--	--	--	2	23.7	23.3	24.0
	Total	2188	1614				574			

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 20 September 2022. 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	Scientific name	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max
alewife	*Alosa pseudoharengus*	**0**	--	--	--	**0**	--	--	--	**1**	6.4	--	--	**0**	--	--	--
bowfin	*Amia calva*	**0**	--	--	--	**4**	52.1	39.7	62.6	**0**	--	--	--	**0**	--	--	--
white sucker	*Catostomus commersonii*	**0**	--	--	--	**0**	--	--	--	**1**	43.2	--	--	**0**	--	--	--
spotfin shiner	*Cyprinella spiloptera*	**90**	6.3	4.0	9.8	**110**	6.6	4.7	9.9	**8**	7.3	5.1	9.9	**104**	5.7	3.5	10.3
gizzard shad	*Dorosoma cepedianum*	**302**	9.6	7.1	15.9	**104**	10.9	7.9	19.6	**1**	8.9	--	--	**0**	--	--	--
northern pike	*Esox lucius*	**1**	66.6	--	--	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--
banded killifish	*Fundulus diaphanus*	**0**	--	--	--	**0**	--	--	--	**11**	8.0	6.3	9.6	**2**	7.1	6.3	7.8
channel catfish	*Ictalurus punctatus*	**0**	--	--	--	**3**	26.9	8.1	63.5	**0**	--	--	--	**0**	--	--	--
brook silverside	*Labidesthes sicculus*	**46**	6.8	4.5	8.3	**65**	7.2	5.2	9.3	**98**	7.4	5.2	10.0	**126**	6.7	4.5	8.5
pumpkinseed	*Lepomis gibbosus*	**13**	9.1	5.5	16.7	**7**	9.0	5.7	16.5	**4**	11.9	6.6	19.2	**1**	6.7	--	--
bluegill	*Lepomis macrochirus*	**56**	6.2	2.5	19.0	**36**	5.6	2.6	14.5	**6**	12.1	4.6	18.9	**39**	6.0	3.1	18.5
largemouth bass	*Micropterus salmoides*	**5**	14.1	7.2	24.1	**3**	9.5	6.3	13.1	**1**	9.9	--	--	**5**	9.1	7.8	10.9
white perch	*Morone americana*	**14**	10.5	7.2	11.9	**6**	9.7	7.1	11.5	**10**	10.0	5.2	11.6	**5**	10.5	9.8	11.1
round goby	*Neogobius melanostomus*	**54**	7.6	3.5	11.2	**33**	7.2	3.2	10.8	**21**	7.3	3.8	10.2	**67**	6.6	3.5	14.0
emerald shiner	*Notropis atherinoides*	**7**	5.3	4.0	7.6	**0**	--	--	--	**20**	10.0	8.5	11.2	**0**	--	--	--
golden shiner	*Notemigonus crysoleucas*	**3**	9.2	8.7	9.6	**11**	9.1	8.0	10.4	**15**	9.7	7.5	14.6	**6**	9.2	8.5	10.1
spottail shiner	*Notropis hudsonius*	**3**	9.6	7.8	12.3	**1**	9.2	--	--	**0**	--	--	--	**3**	8.4	8.2	8.6
mimic shiner	*Notropis volucellus*	**2**	4.1	3.5	4.7	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--
yellow perch	*Perca flavescens*	**3**	13.5	10.7	18.2	**3**	20.7	19.5	22.9	**5**	17.1	10.4	20.2	**7**	14.8	8.9	19.5
bluntnose minnow	*Pimephales notatus*	**8**	6.8	4.6	7.7	**47**	6.0	4.7	8.3	**0**	--	--	--	**3**	8.3	7.5	9.4
black crappie	*Pomoxis nigromaculatus*	**2**	21.0	16.2	25.7	**1**	18.0	--	--	**0**	--	--	--	**0**	--	--	--
flathead catfish	*Pylodictis olivaris*	**1**	100.0	--	--	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--
	Total	610				434				202				368			

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 22 September 2022. 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	Scientific name	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max	Catch	Mean	Min	Max
bowfin	*Amia calva*	**0**	--	--	--	**0**	--	--	--	**1**	62.6	--	--	**3**	54.0	42.3	63.5
goldfish	*Carassius auratus*	**0**	--	--	--	**0**	--	--	--	**1**	37.9	--	--	**0**	--	--	--
quillback	*Carpiodes cyprinus*	**0**	--	--	--	**1**	53.6	--	--	**0**	--	--	--	**0**	--	--	--
white sucker	*Catostomus commersonii*	**0**	--	--	--	**1**	28.2	--	--	**9**	39.2	31.0	44.5	**9**	44.5	37.2	53.2
common carp	*Cyprinus carpio*	**3**	61.8	59.4	66.4	**1**	56.6	--	--	**0**	--	--	--	**0**	--	--	--
gizzard shad	*Dorosoma cepedianum*	**8**	13.9	10.1	17.7	**35**	12.5	10.6	19.6	**4**	13.1	11.0	15.6	**0**	--	--	--
northern pike	*Esox lucius*	**0**	--	--	--	**0**	--	--	--	**1**	88.2	--	--	**1**	74.4	--	--
banded killifish	*Fundulus diaphanus*	**0**	--	--	--	**0**	--	--	--	**2**	7.5	7.1	7.8	**5**	8.0	6.8	8.9
brook silverside	*Labidesthes sicculus*	**9**	8.0	7.1	8.5	**8**	7.8	6.7	8.5	**21**	8.1	6.9	9.0	**7**	8.2	7.1	10.5
pumpkinseed	*Lepomis gibbosus*	**11**	11.5	6.8	15.5	**45**	8.2	5.5	16.3	**1**	17.8	--	--	**0**	--	--	--
bluegill	*Lepomis macrochirus*	**23**	12.0	4.7	19.8	**17**	9.8	5.2	18.6	**5**	6.8	3.1	13.7	**5**	14.9	5.2	19.7
common shiner	*Luxilus cornutus*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**2**	11.1	10.6	11.6
largemouth bass	*Micropterus salmoides*	**12**	31.2	13.9	39.9	**11**	22.1	12.3	42.4	**7**	10.5	8.2	13.8	**8**	10.8	7.5	15.1
white perch	*Morone americana*	**33**	11.7	10.1	18.2	**50**	10.8	10.0	12.1	**20**	10.8	8.6	17.4	**13**	10.9	7.8	15.9
round goby	*Neogobius melanostomus*	**0**	--	--	--	**0**	--	--	--	**6**	9.0	7.7	11.3	**1**	7.0	--	--
emerald shiner	*Notropis atherinoides*	**0**	--	--	--	**3**	9.5	8.7	10.2	**12**	9.6	8.3	11.1	**0**	--	--	--
golden shiner	*Notemigonus crysoleucas*	**3**	14.0	9.1	9.0	**4**	11.7	8.4	17.7	**4**	9.0	8.2	9.5	**4**	11.6	9.2	14.7
spottail shiner	*Notropis hudsonius*	**1**	9.0	--	--	**1**	8.7	--	--	**0**	--	--	--	**2**	9.3	9.0	9.5
chinook salmon	*Oncorhynchus tshawytscha*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**1**	78.6	--	--
yellow perch	*Perca flavescens*	**7**	14.7	10.5	20.4	**21**	13.8	9.8	18.8	**35**	14.5	9.4	19.0	**72**	14.0	9.1	20.5
bluntnose minnow	*Pimephales notatus*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**1**	7.1	--	--
black crappie	*Pomoxis nigromaculatus*	**0**	--	--	--	**0**	--	--	--	**1**	19.5	--	--	**0**	--	--	--
walleye	*Sander vitreus*	**2**	23.7	23.3	24.0	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--
	Total	112				198				130				134			

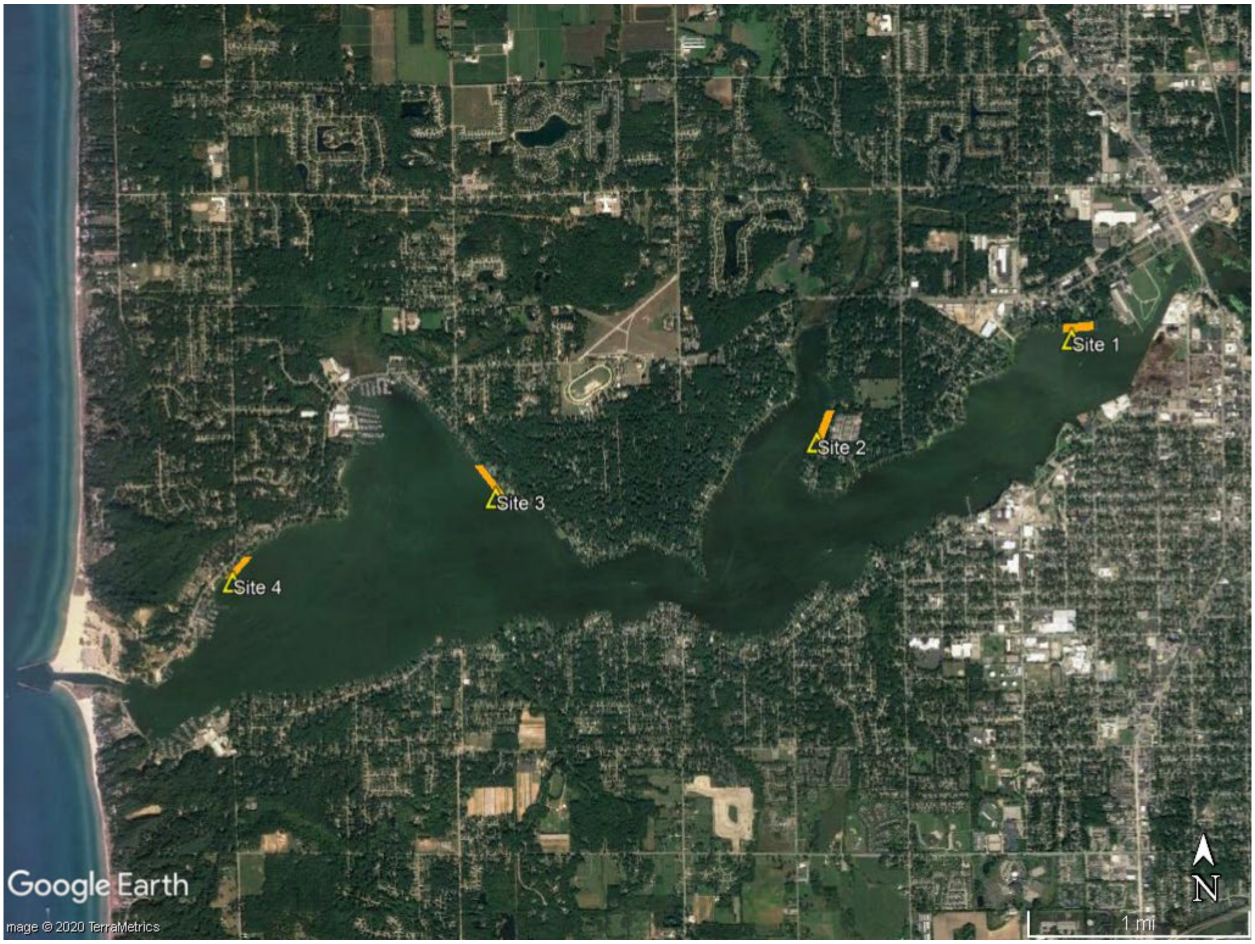

Figure 1. Map of Lake Macatawa (Ottawa County, Michigan) showing fish sampling sites (triangles). The orange transects depict approximately where boat electrofishing was conducted at each site. Site #1 is closest to the Macatawa River and site #4 is closest to Lake Michigan. Note that riparian vegetation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

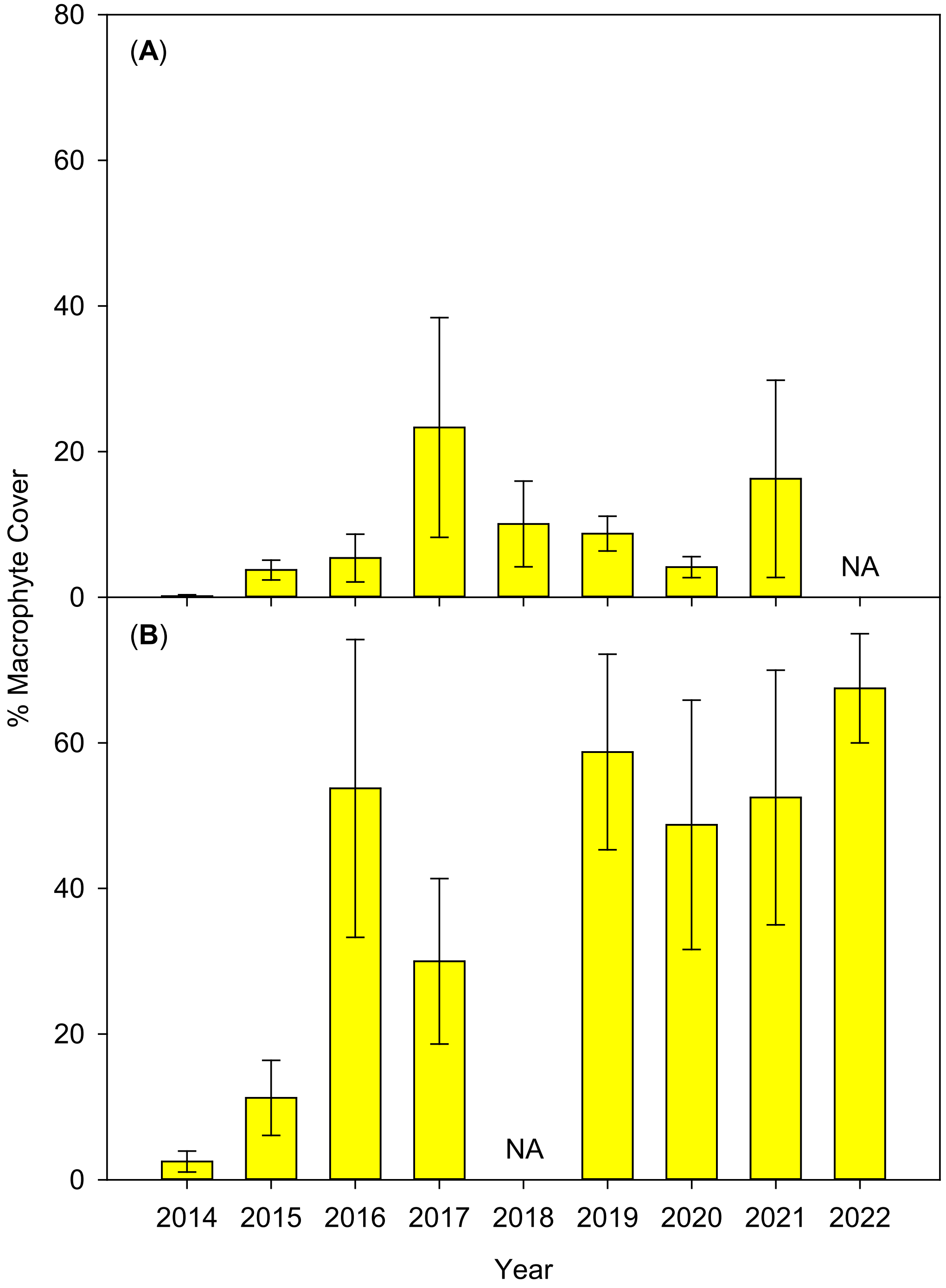

Figure 2. Mean (±1 standard error) percent macrophyte cover visually estimated at (**A**) fyke net locations and (**B**) boat electrofishing transects in Lake Macatawa (*n* = 4 sites per year; however, the *n* = 2 sites for 2021 and 2022 boat electrofishing because of poor visibility). Note that the 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).

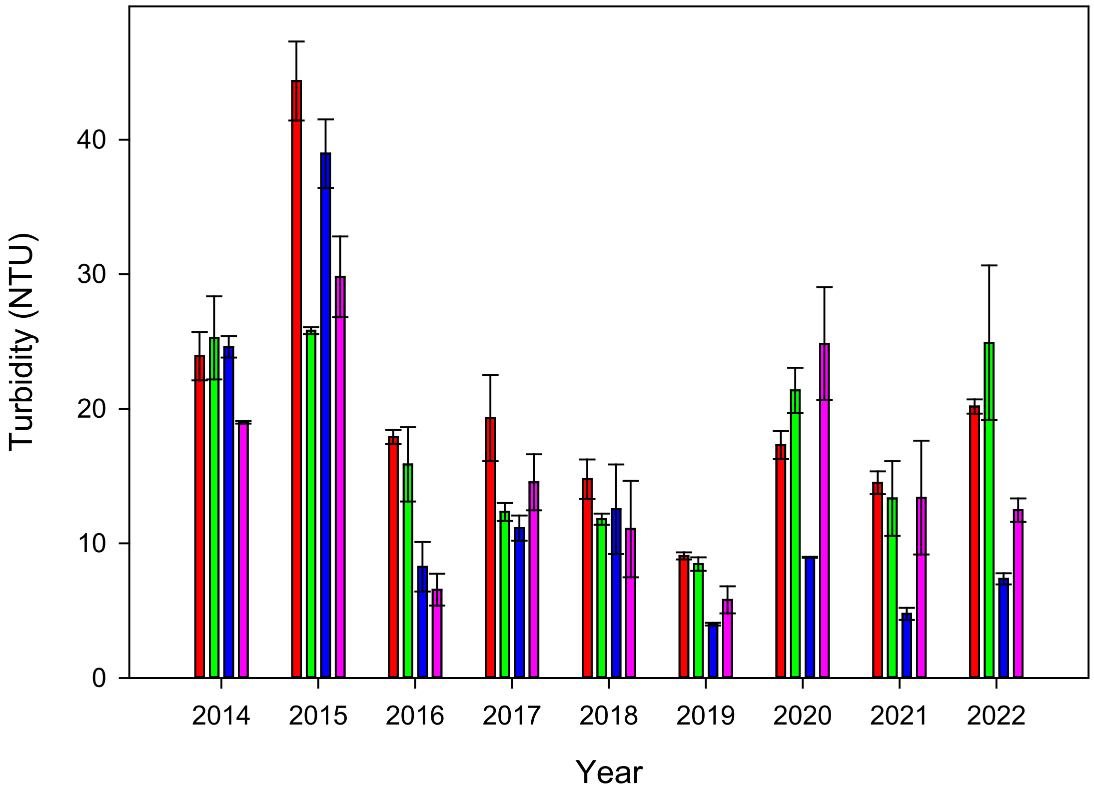

Figure 3. Mean turbidity measured during fyke netting in Lake Macatawa. Error bars represent ±1 standard error (*n* = 3 nets per site), although they may be too small to be visible for some means.

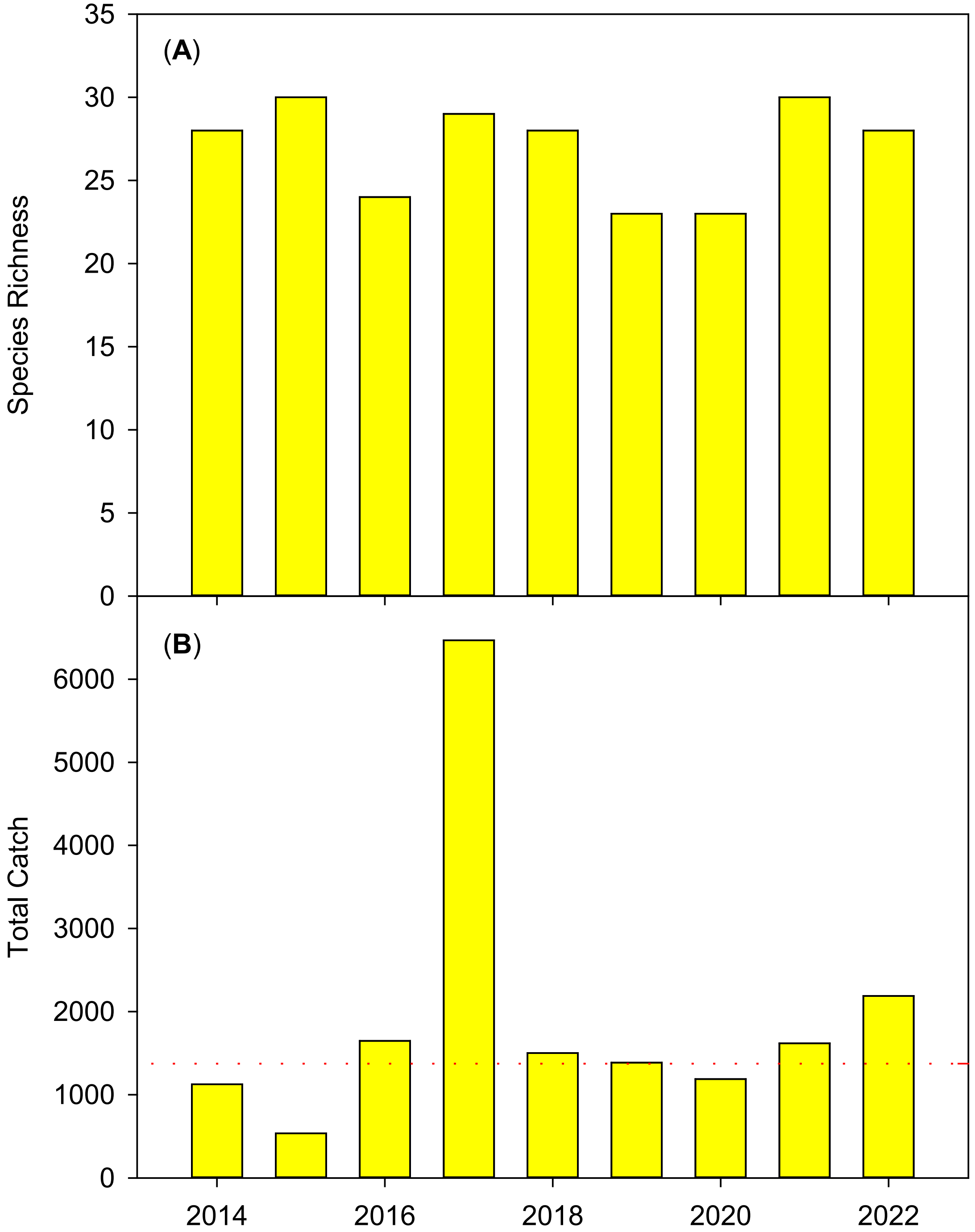

Figure 4. (**A**) Number of fish species captured and (**B**) total number of fish captured using both fyke netting and boat electrofishing each year in Lake Macatawa (dashed red line is long-term mean; *n* = 9 years). *Note*: the long-term mean total catch excludes 5,288 brook silversides captured in 2017 from a single fyke net at site #4 (i.e., a total catch of 1,180 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.

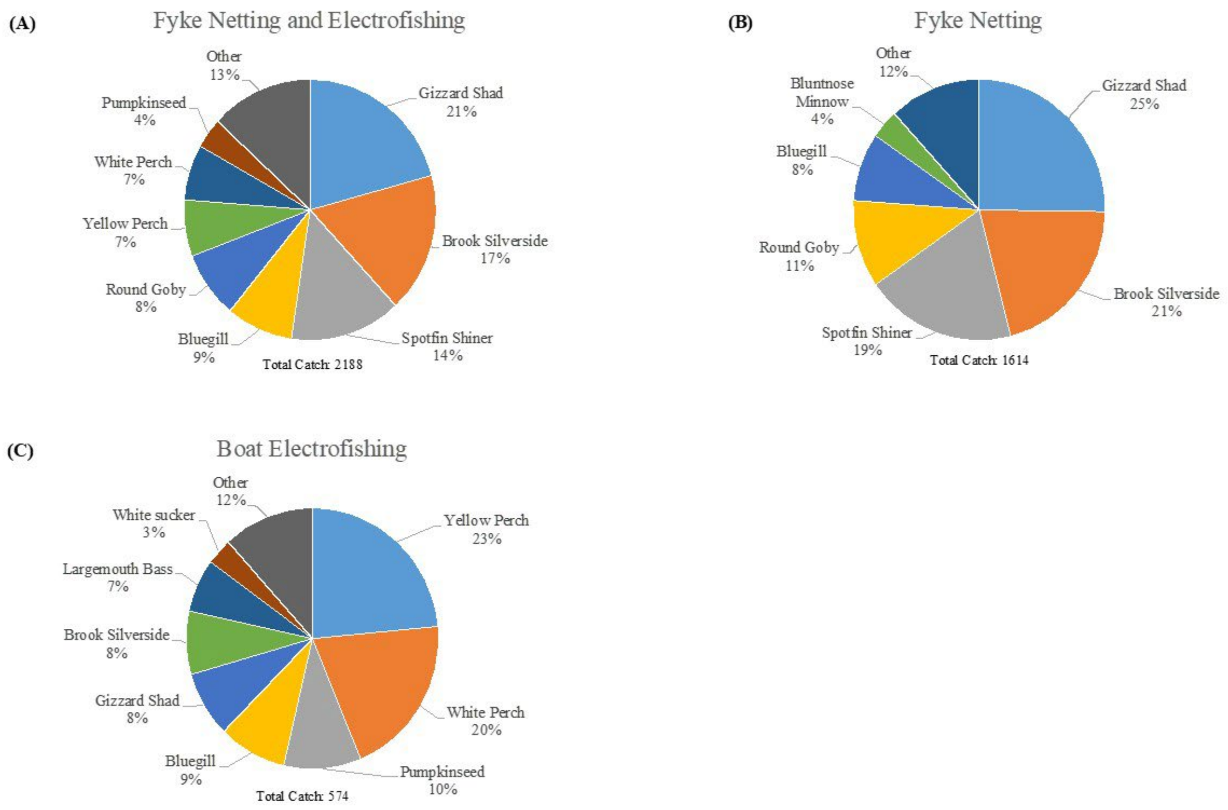

Figure 5. Fish species captured in littoral habitats of Lake Macatawa by (**A**) fyke netting and boat electrofishing (i.e., combined catch), (**B**) fyke netting (*n* = 12 nets), and (**C**) boat electrofishing (*n* = 4 transects) during September 2022. Catch data, including the species pooled in the "other" category, are reported in Table 4.

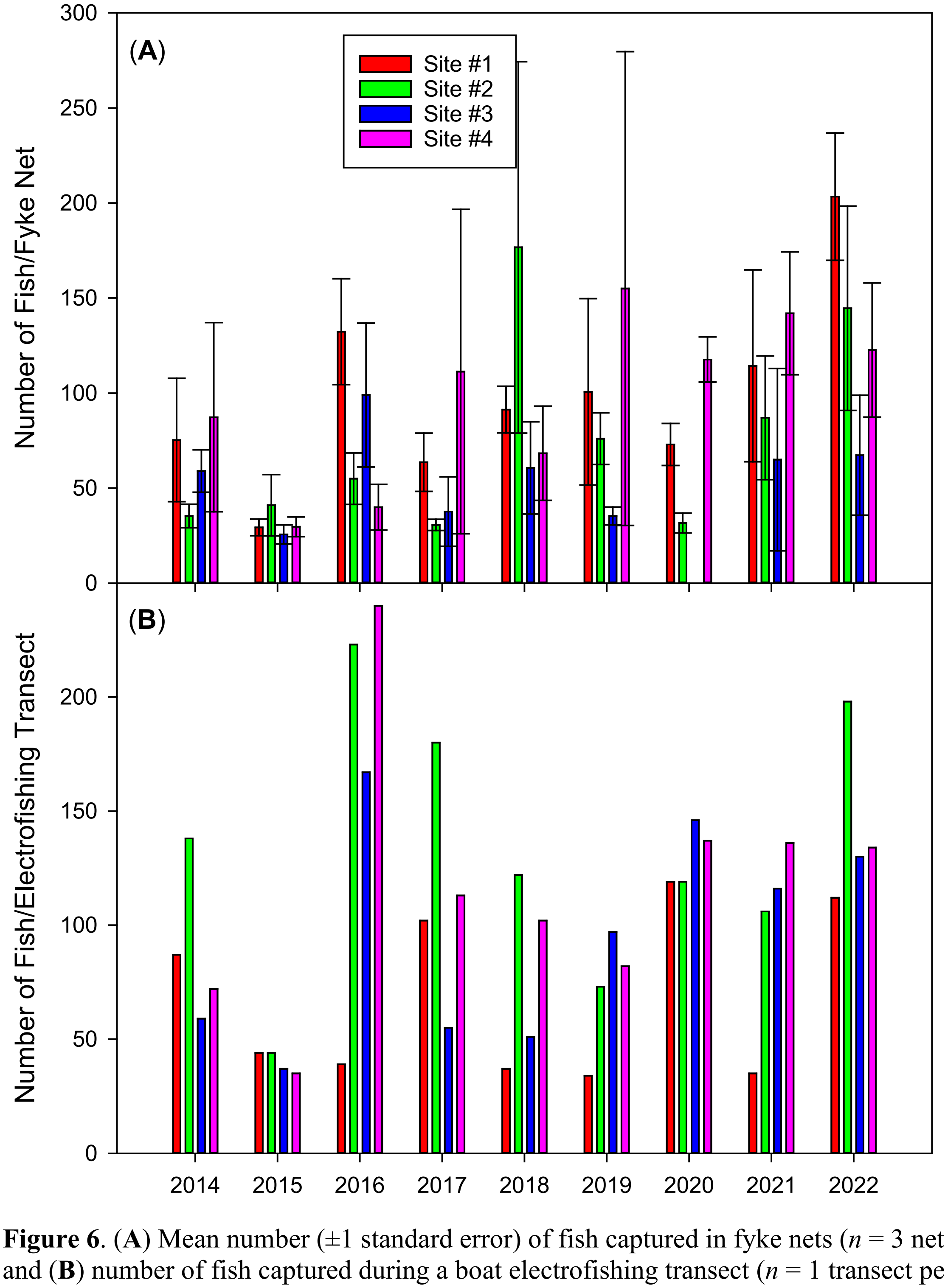

Figure 6. (**A**) Mean number (±1 standard error) of fish captured in fyke nets (*n* = 3 nets per site) and (**B**) number of fish captured during a boat electrofishing transect (*n* = 1 transect per site) in Lake Macatawa. *Note*: 5,288 brook silversides captured in a single fyke net at site #4 in 2017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

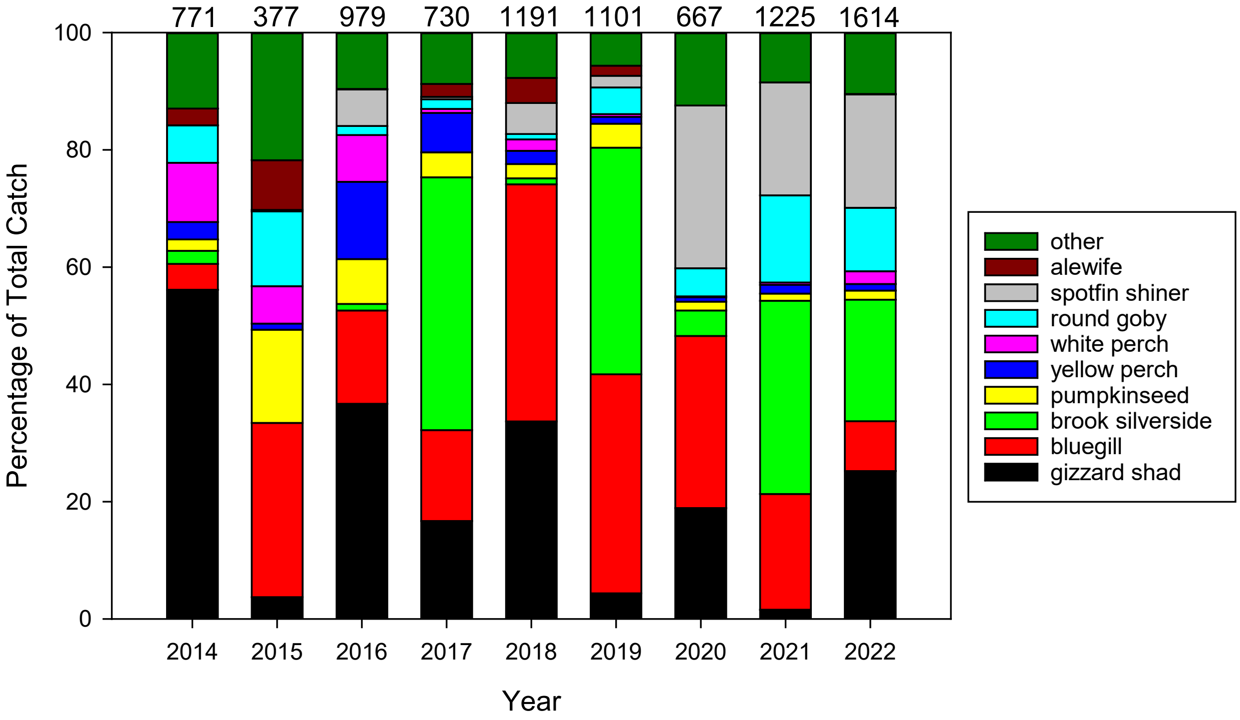

Figure 7. Fish species composition (pooled across sites) in fyke netting surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar. *Note*: 5,288 brook silversides captured in a single fyke net at site #4 in 2017 were excluded from the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

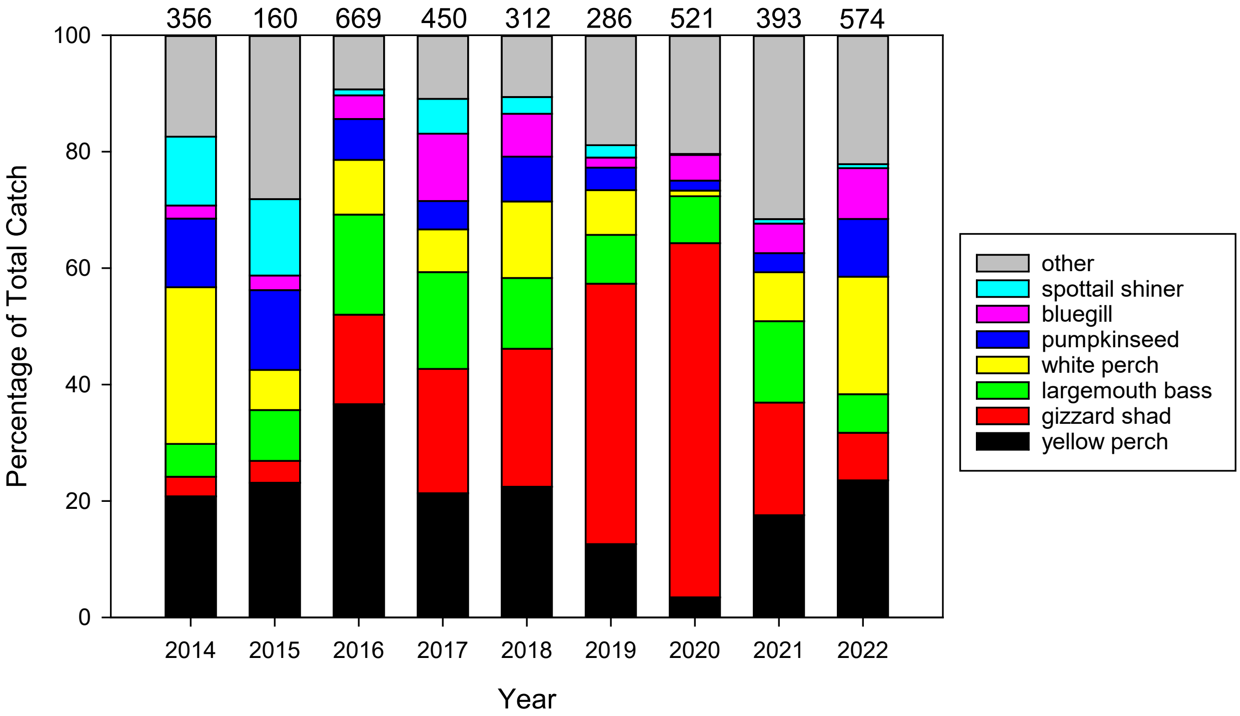

Figure 8. Fish species composition (pooled across sites) in nighttime boat electrofishing surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar.