PROJECT CLARITY
2021 Annual Monitoring 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 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 hypereutrophic 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). However, annual mean TP concentrations of less than 100 µg/L have been observed the past four years and this year's mean concentration, as reported below, was 64 µg/L. Nonetheless, even 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 Outdoor Discovery Center Macatawa Greenway (hereafter, ODC), the Macatawa Area Coordinating Council, and Niswander Environmental, initiated a long-term monitoring program in the Lake Macatawa watershed in 2013. This effort provides critical information on the performance of restoration projects that are part of Project Clarity, as well as the ecological status of Lake Macatawa. The goal of the monitoring effort is to measure pre- and post-restoration conditions in the watershed, including Lake Macatawa. This report documents AWRI's monitoring activities in 2021, in combination with data reported previously from 2013-2020. 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, the performance of iron slag filters as a possible BMP for reducing phosphorus concentrations in tile drain effluent, and the Lake Macatawa 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 provide some encouraging signs. Mean water clarity continues to improve and mean total phosphorus concentrations continue to decline. However, we also observed an increase in soluble reactive phosphorus (SRP) concentrations, which is concerning because this is the form of phosphorus that is readily used by algae. Chlorophyll concentrations, an indicator of algal abundance, remain well above the target of a healthy lake, likely due to the improved water clarity (more light for photosynthesis) and the increased SRP. 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, and an examination of possible in-lake restoration activities to accelerate the recovery of lake health.

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 2021 (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 (DO, temperature, pH, specific conductivity, TDS, ORP, turbidity, chlorophyll a [chl a], and phycocyanin [cyanobacterial pigment]) were taken using a YSI 6600 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 2019 – fall 2021) 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 toxin produced by cyanobacteria (blue-green algae). We used the ELISA QuantiPlate kit for Microcystins High Sensitivity, which is not as sensitive an assay as using High-Performance Liquid Chromatography (HPLC) but serves as a useful screening tool if microcystin is present in the lake. This kit has a greater detection limit than the QuantiTubes that were used in 2017 but still ranks below the HPLC for sensitivity. Advisories for microcystin consumption have been developed by the World Health Organization (WHO) and US EPA. For drinking water, the WHO advisory is triggered when microcystin concentrations >1 µg/L and the EPA advisory is >1.6 µg/L; for 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 2021 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

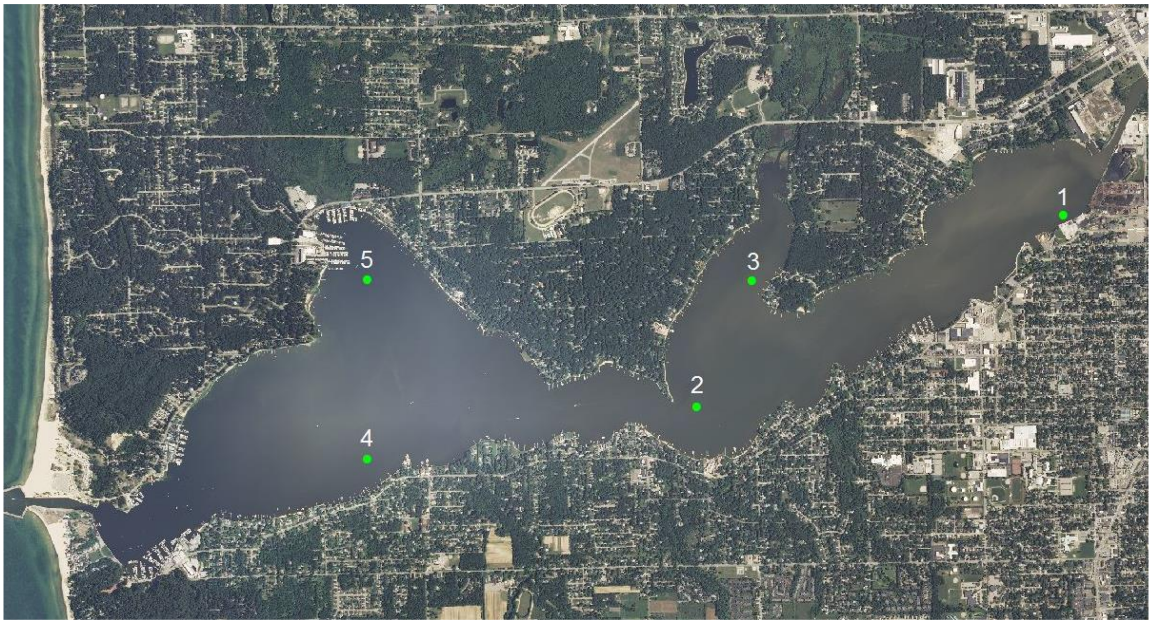


Figure 1. Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring.

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. 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. 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 near the Middle Macatawa restored wetland and 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), and Weather Underground. Linear regressions on P and precipitation amount were conducted in Microsoft Excel.

3. Results and Discussion

3.1 Sampling Year 2021

Lake Macatawa was well-mixed in spring and fall 2021, as both water temperature and DO were similar between sampling depths (Table 2). Summer DO at the near bottom sampling depths at both Site 1 (nearest to the Macatawa River mouth: 0.53 mg/L) and site 4 (nearest to the Lake Michigan channel: 0.41 mg/L) were among the lowest measured by AWRI in Lake Macatawa (Fig. 2). Multiyear LOWESS (locally weighted scatterplot smoothing) analysis of summer DO in bottom depth samples shows that 2021 continued 2020's trend of declining from 2018-19's relatively higher DO's; this fit improves when considering only sites 1, 2, and 4 (3-site $R^2 = 0.41$, Fig. 2A) in the main flow of Lake Macatawa, as opposed to including all 5 sites (5-site $R^2 = 0.17$, Fig. 2B). More variable conditions in the embayments (sites 3 and 5) likely account for the poorer fit when all 5 sites are considered.

Surface and bottom water SRP ranged 2.5-24 µg/L across sites and seasons, with the notable bottom depth exception of 240 µg/L at Site 1 (closest to the Macatawa River) during fall; removing this likely outlier considerably reduces fall mean bottom SRP to below detection (< 5 µg/L; Table 3, Figs. 2A, B). Low SRP concentrations are not necessarily an indication of good water quality, as this bioavailable form of P may be very low because the algae have used it all. Thus, TP is considered a better index of water quality.

Surface and bottom TP often exceeded the 50 µg/L TMDL and followed the same pattern as SRP, ranging 31-92 µg/L, with a maximum value of 398 µg/L at site 1 bottom during fall (Table 3, Figs. 2C, D). This high value is likely due to the very high rainfall the watershed experience on October 24-25 (>1.8 in), which resulted in soil erosion and subsequent transport of high-P sediment loads into Lake Macatawa at the site closest to the inflow. This reading gives additional weight to the importance of controlling sediment erosion in the watershed. With the expectation of more intense rainfall in the future in this region (Byun et al. 2019), the need for erosion control becomes even more critical.

Mean SRP and TP concentrations at the bottom depths exceeded their surface depth concentrations in each season at each site; however, in some cases, these differences were modest (Table 3). TP and SRP concentrations at Site 1 remain the highest among all lake sites and among both sampling depths (Fig. 3A-D), indicating that three lake trends remain intact: 1) watershed runoff remains the major source of P to Lake Macatawa; 2) the lake itself is responsible for at least some P retention (presumably due to sedimentation of both biotic and biotic material) as water flows to Lake Michigan; and 3) inflow from Lake Michigan helps dilute the P concentrations in Lake Macatawa, especially at the westernmost sampling sites, similar to observations in Muskegon Lake (Liu et al. 2018).

Chl *a* surface concentration ranged 12-52 µg/L and seasonal means exceeded EGLE's hypereutrophic boundary of 22 µg/L (Table 3; Fig. 3E). Bottom chl *a* concentration ranged 5-49 µg/L; summer was the only season when all sites were below the 22 µg/L threshold (Table 3; Fig. 3F). We emphasize that the 22 µg/L target is still quite liberal and would produce noticeable algal blooms in the water column. For comparison, the Chl *a* restoration target for Muskegon Lake is only 10 µg/L (Steinman et al. 2008).

NO_3^- varied seasonally and was generally highest during the summer, except for a fall bottom depth spike that corresponded with TP and SRP spikes at the same time and location (Table 3; Figs. 4A, B). NH_3 and TKN showed patterns across sites and seasons, with sites closer to the watershed being higher than sites closer to Lake Michigan, and concentrations at all sites decreasing throughout the sampling year (Table 3; Figs. 4E, F).

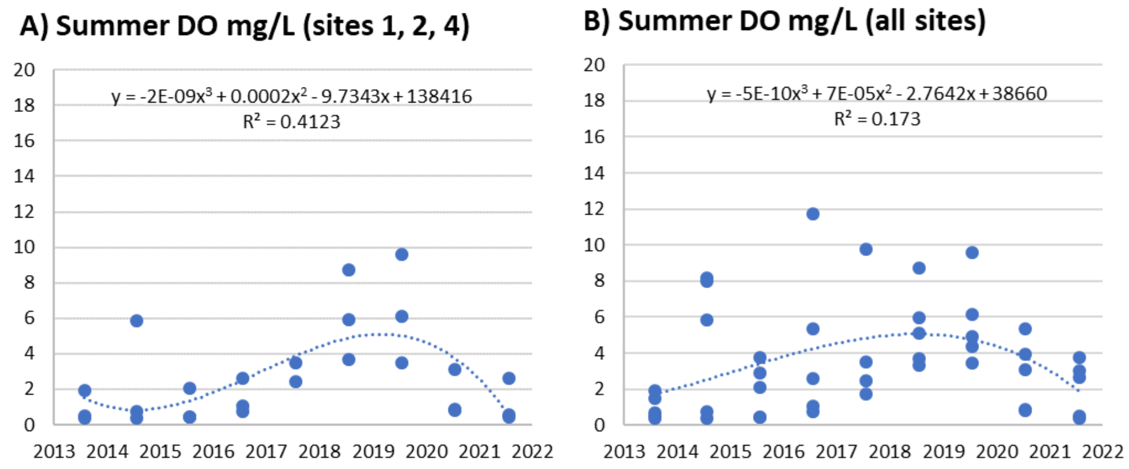
Microcystin concentrations were tested at all seasons, sites, and depths and were one or more degrees of magnitude below World Health Organization and Environmental Protection Agency guidelines for recreational waters (respectively 20 µg/L and 2 µg/L). Microcystin concentrations remained ≤0.1 µg/L throughout 2021 sampling and the highest concentrations were found during spring on the eastern and middle parts of the lake at site 1 top (0.10 µg/L), 3 top (0.08 µg/L) and 2 bottom (0.07 µg/L). However, these concentrations remain well below regulatory guidelines.

Table 2. Lake-wide means (1 SD) of select general water quality parameters recorded during 2021 monitoring year. Within 2021, "n" is the number of lake sites composing the seasonal mean at each depth. Data are shaded for readability. Dates of sampling events: 5/27/2021; 7/28/2021; 10/27/2021. Water quality was not measured at the middle depth in Spring 2021.

Season	Depth	n	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Spring	Surface	5	20.21 (1.00)	8.46 (0.81)	656 (82)	0.395 (0.049)	12.3 (3.0)
	Middle	5	ND (NA)	ND (NA)	ND (NA)	ND (NA)	ND (NA)
	Bottom	5	19.35 (1.02)	6.72 (1.70)	630 (76)	0.379 (0.045)	16.7 (5.9)
Summer	Surface	5	26.37 (0.64)	8.31 (0.77)	503 (51)	0.327 (0.034)	ND (NA)
	Middle	5	26.06 (0.26)	6.60 (2.13)	509 (44)	0.331 (0.029)	ND (NA)
	Bottom	5	23.61 (2.49)	2.08 (1.53)	474 (63)	0.308 (0.041)	ND (NA)
Fall	Surface	5	12.54 (0.44)	8.51 (0.35)	523 (72)	0.340 (0.047)	11.5 (3.6)
	Middle	5	12.30 (0.83)	8.40 (0.26)	517 (66)	0.336 (0.043)	17.9 (16.2)
	Bottom	5	12.07 (1.09)	8.47 (0.33)	518 (66)	0.337 (0.043)	20.7 (20.0)

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 Kendal nitrogen [TKN]), laboratory extracted chlorophyll *a* (chl *a*), and Secchi disk depths measured during 2021 monitoring year. Within 2021, "n" is the number of lake sites composing the seasonal mean at each depth. Data are shaded for readability. See Table 2 for dates of sampling events. Note different units for the analytes.

Season	Depth	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	5	9 (9)	53 (16)	1.07 (0.14)	0.58 (0.44)	2.06 (0.73)	24 (4)	1.0 (0.1)
	Bottom	5	11 (8)	66 (18)	0.85 (0.16)	0.59 (0.41)	1.93 (0.62)	21 (8)	
Summer	Surface	5	3 (0)	54 (21)	1.93 (0.11)	0.30 (0.27)	1.73 (0.48)	26 (15)	1.3 (0.2)
	Bottom	5	13 (17)	61 (20)	1.51 (0.57)	0.70 (0.64)	2.00 (0.65)	9 (3)	
Fall	Surface	5	5 (7)	66 (18)	0.97 (0.48)	0.24 (0.18)	1.28 (0.40)	37 (9)	0.9 (0.4)
	Bottom	5	50 (106)	127 (152)	1.79 (1.93)	0.22 (0.23)	1.34 (0.57)	32 (14)	


A) Summer DO mg/L (sites 1, 2, 4)

B) Summer DO mg/L (all sites)

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

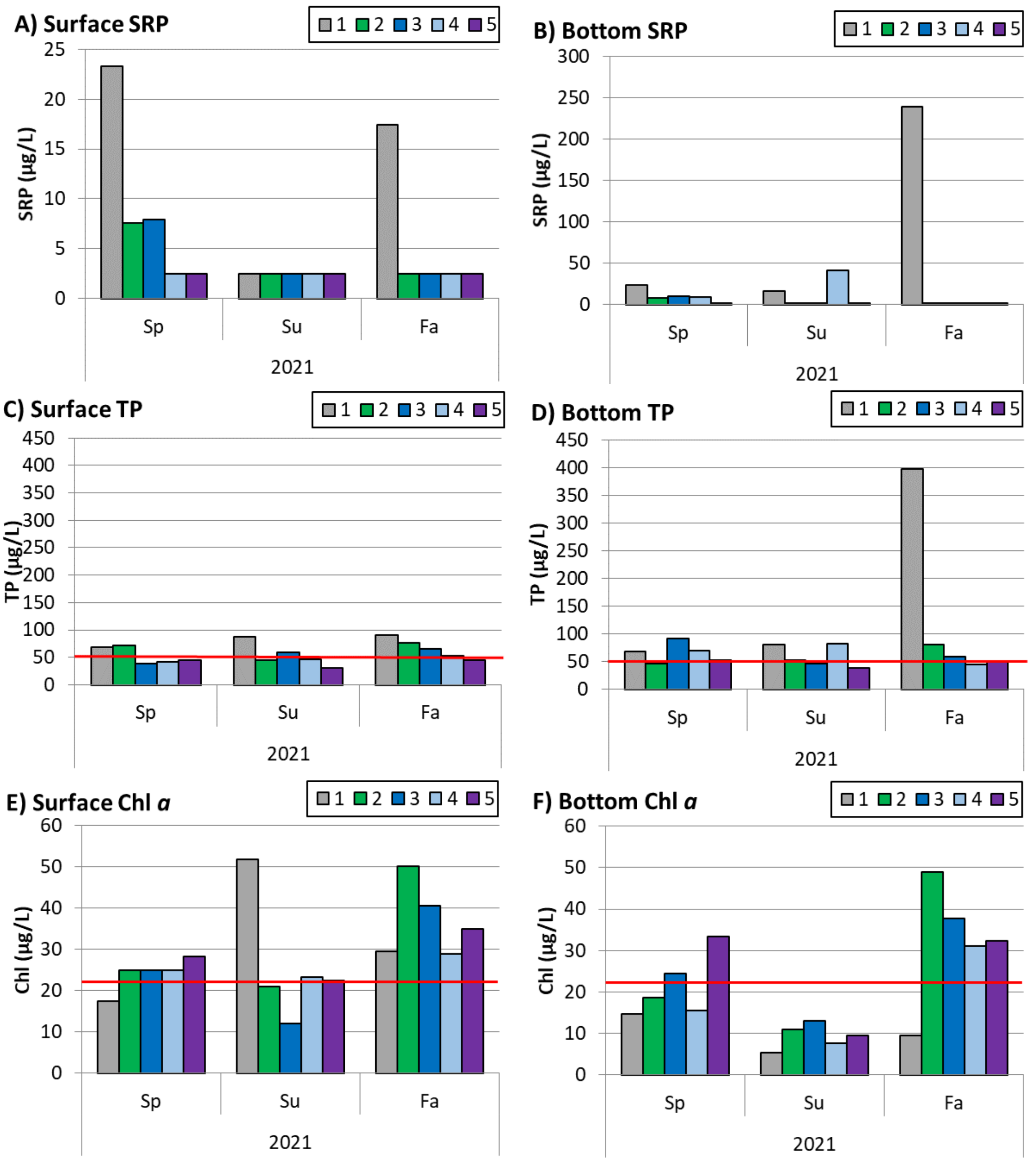


Figure 3. Soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); and chlorophyll *a* ([chl *a*]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2021. The red horizontal lines on TP figures (C, D) indicate the interim total maximum daily load (TMDL) goal of 50 µg/L (Walterhouse 1999). The red horizontal lines on chl *a* figures (E, F) indicate 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.

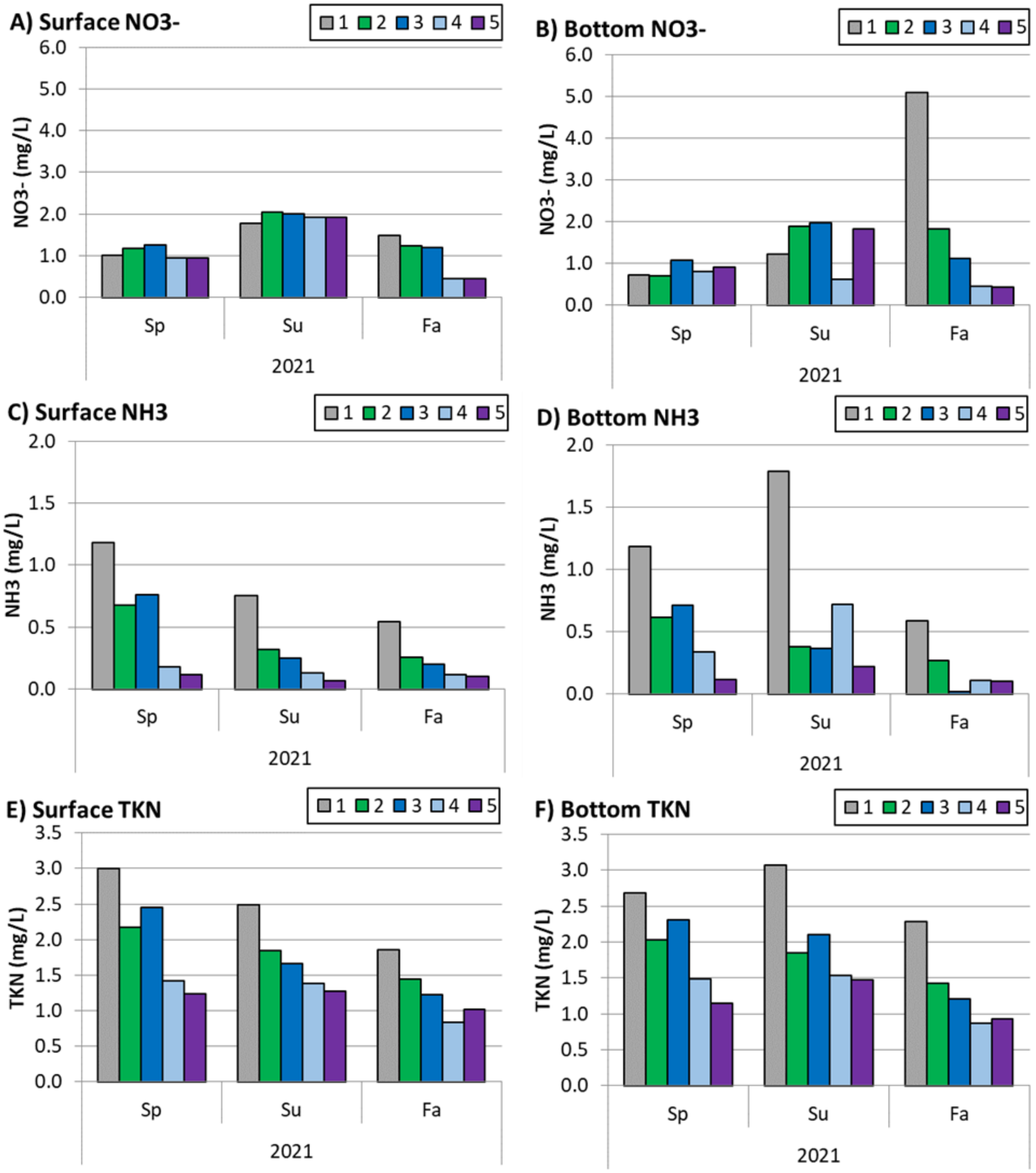


Figure 4. Nitrate ([NO$_3^-$]: A, B); ammonia ([NH$_3$]: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2021. Note scales change on y-axes.

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; and 3) the importance of internal nutrient loading in the lake (Steinman and Spears 2020). Given that watershed-based management changes are both recent and at a relatively small scale in the Macatawa watershed, it is not expected that Lake Macatawa water quality will respond quickly. Nonetheless, this monitoring effort helps establish baselines and allows the evaluation of trends.

As was observed in 2020, both surface and bottom SRP concentrations in Lake Macatawa in 2021 remain significantly higher during post-restoration compared to pre-restoration, which is driven largely by the spring data (Table 4; Fig. 7). This year's analyses exclude data collected from 2016 to 2018, which includes the years immediately following major restoration construction activities (Fig. 5A, B), which may have resulted in greater release of SRP. Research in the western basin of Lake Erie has shown that implementation of modified tillage practices to reduce sediment erosion has resulted in increased loading of soluble phosphorus (Jarvie et al. 2017), so a similar phenomenon may be occurring in the Macatawa watershed. Although the sample size for this analysis is small (n=5 per seasonal sampling event and n=40 total per restoration period), suggesting results should be viewed with caution, this trend should be reviewed and considered by the agricultural community; increasing concentrations of SRP is a concern, given that this is the most bioavailable form of P and readily used by algae.

Post-restoration summer and fall TP concentrations continue to follow a trend consistently seen since 2018 of being lower than during pre-restoration (Table 4, Fig. 5C, D). Unlike SRP, post-restoration TP concentrations had a significantly lower range of values than pre-restoration samples and this was seen at both sampling depths (both $P<0.001$; Fig. 7C, D); this continues to suggest that sediment transport may be declining, as much of the TP is associated with sediment. A decline in sediment would result in increased water clarity and a concomitant increase in Secchi depth (i.e., greater water clarity), as was observed in 2021 ($P<0.001$; Figs. 5G, 7G).

We started measuring nitrogen concentrations in Lake Macatawa in 2017, after experiments revealed that algal growth in the lake was co-limited by phosphorus and nitrogen (Steinman et al. 2016). As a consequence, we do not have pre- vs. post-restoration comparison data for N. However, since we began measuring different forms of N in 2017, both forms of inorganic N (nitrate and ammonia), as well as TKN, have exhibited a strong spatial distribution, with highest concentrations at site 1 and lowest concentrations at site 5 (Fig. 6), reflecting the strong inputs from the watershed. Summer 2021 marked the first time that we measured substantial nitrate concentrations, irrespective of site (Fig. 6A, B); previously low summer values were attributed to rapid uptake by during this period of high-productivity. However, mean chl *a* concentrations during summer 2021 were relatively low compared to previous years. Hence, the higher nitrate concentrations may have been due to a combination of reduced uptake because of less phytoplankton (Fig. 5E, F) or more runoff from the watershed.

Chl *a* concentrations may be slowly decreasing over time as no statistical differences were detected between pre- and post-restoration concentrations in both surface and bottom sample means (Table 4; Figs. 5E, 7E). However, our sampling effort is limited and we may be missing episodic blooms.

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 2021). 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	6	15 (20)	99 (61)	1.36 (0.48)	0.29 (0.29)	1.74 (0.35)	57 (30)	0.7 (0.3)
	Bottom	Pre	2	3 (1)	98 (30)	ND	ND	ND	24 (3)	
		Post	6	15 (20)	101 (62)	1.29 (0.49)	0.42 (0.18)	1.60 (0.54)	38 (17)	
Summer	Surface	Pre	3	6 (3)	110 (66)	ND	ND	ND	67 (39)	0.4 (0.1)
		Post	6	5 (3)	70 (21)	0.58 (0.76)	0.24 (0.09)	1.41 (0.20)	61 (29)	0.8 (0.3)
	Bottom	Pre	3	17 (18)	107 (49)	ND	ND	ND	32 (13)	
		Post	6	11 (4)	81 (23)	0.52 (0.56)	0.49 (0.14)	1.42 (0.35)	30 (12)	
Fall	Surface	Pre	3	10 (12)	134 (23)	ND	ND	ND	63 (43)	0.4 (0.1)
		Post	6	8 (5)	76 (8)	0.94 (0.73)	0.37 (0.24)	1.33 (0.27)	53 (25)	0.6 (0.1)
	Bottom	Pre	3	11 (13)	158 (19)	ND	ND	ND	61 (35)	
		Post	6	16 (17)	91 (18)	1.18 (0.89)	0.37 (0.22)	1.34 (0.28)	44 (12)	

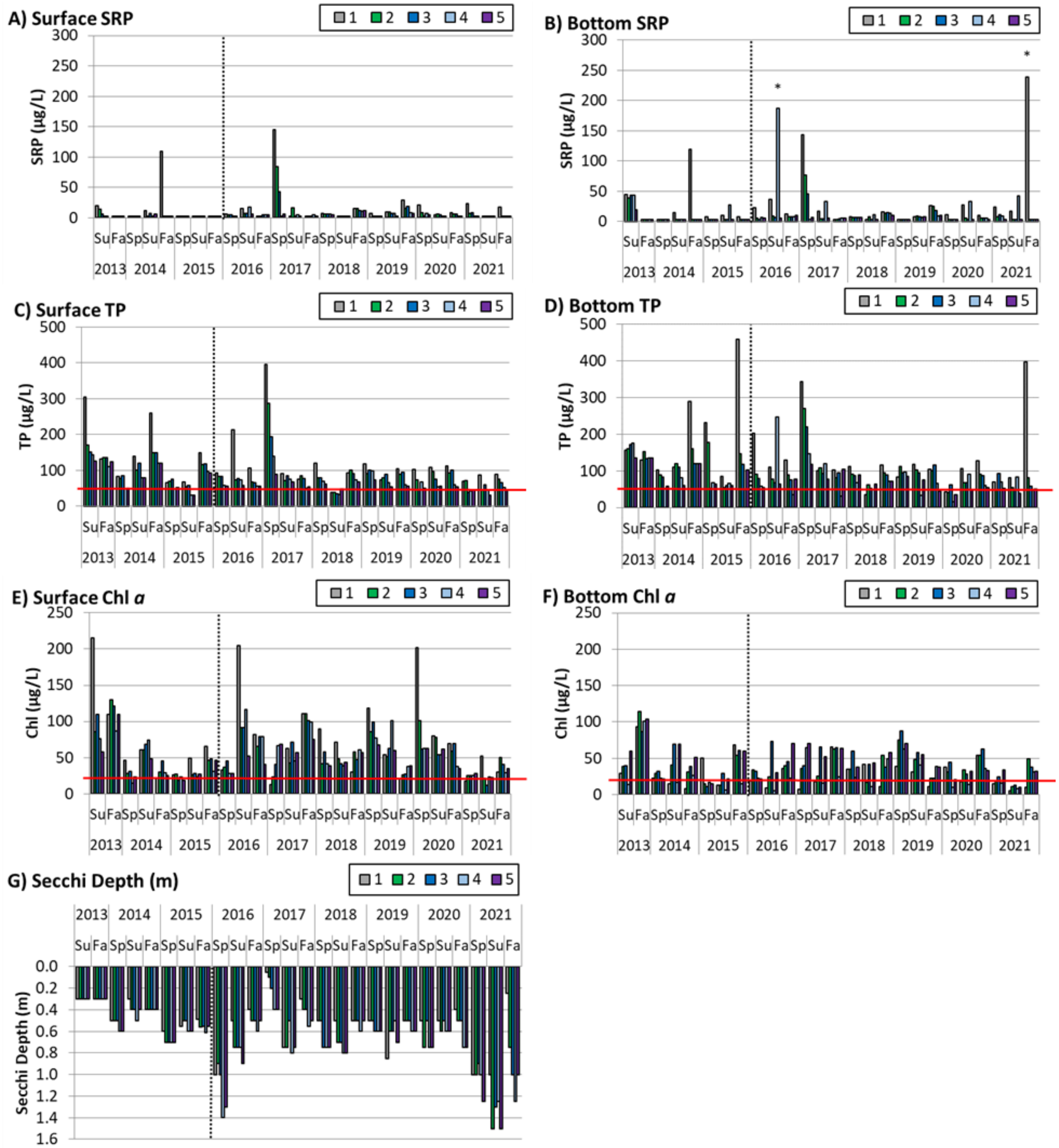


Figure 5. Soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); chlorophyll *a* ([chl *a*]: E, F); and Secchi disk depth: G) levels measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2021. The red horizontal lines on TP figures (C, D) indicate the interim total daily maximum load (TMDL) goal of 50 µg/L (Walterhouse 1999). Red horizontal lines on chl *a* figures (E, F) indicate 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.

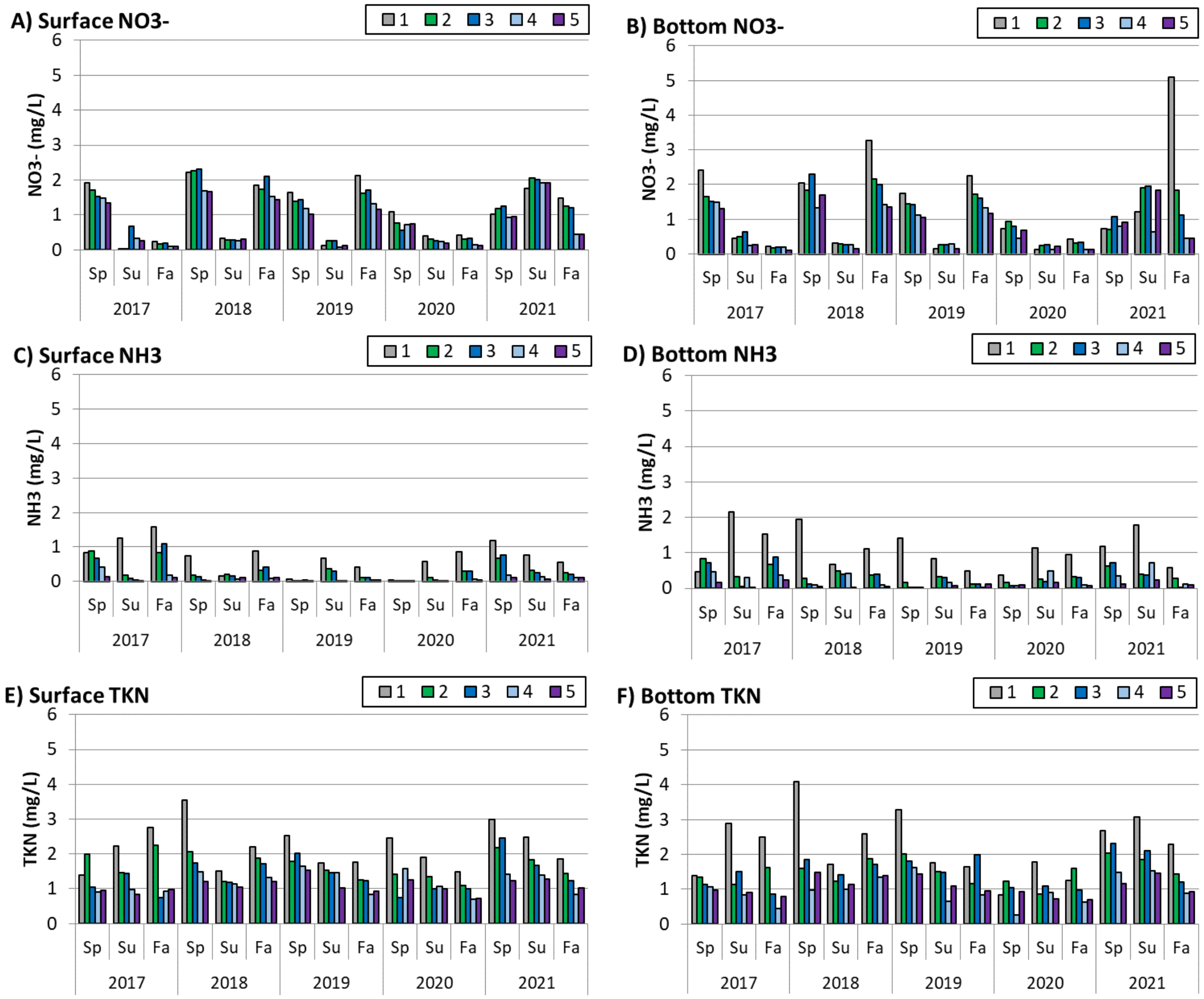


Figure 6. Nitrate ([NO$_3^-$]: A, B); ammonia ([NH$_3$]: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2017 through 2021. Note scales change on y-axes.

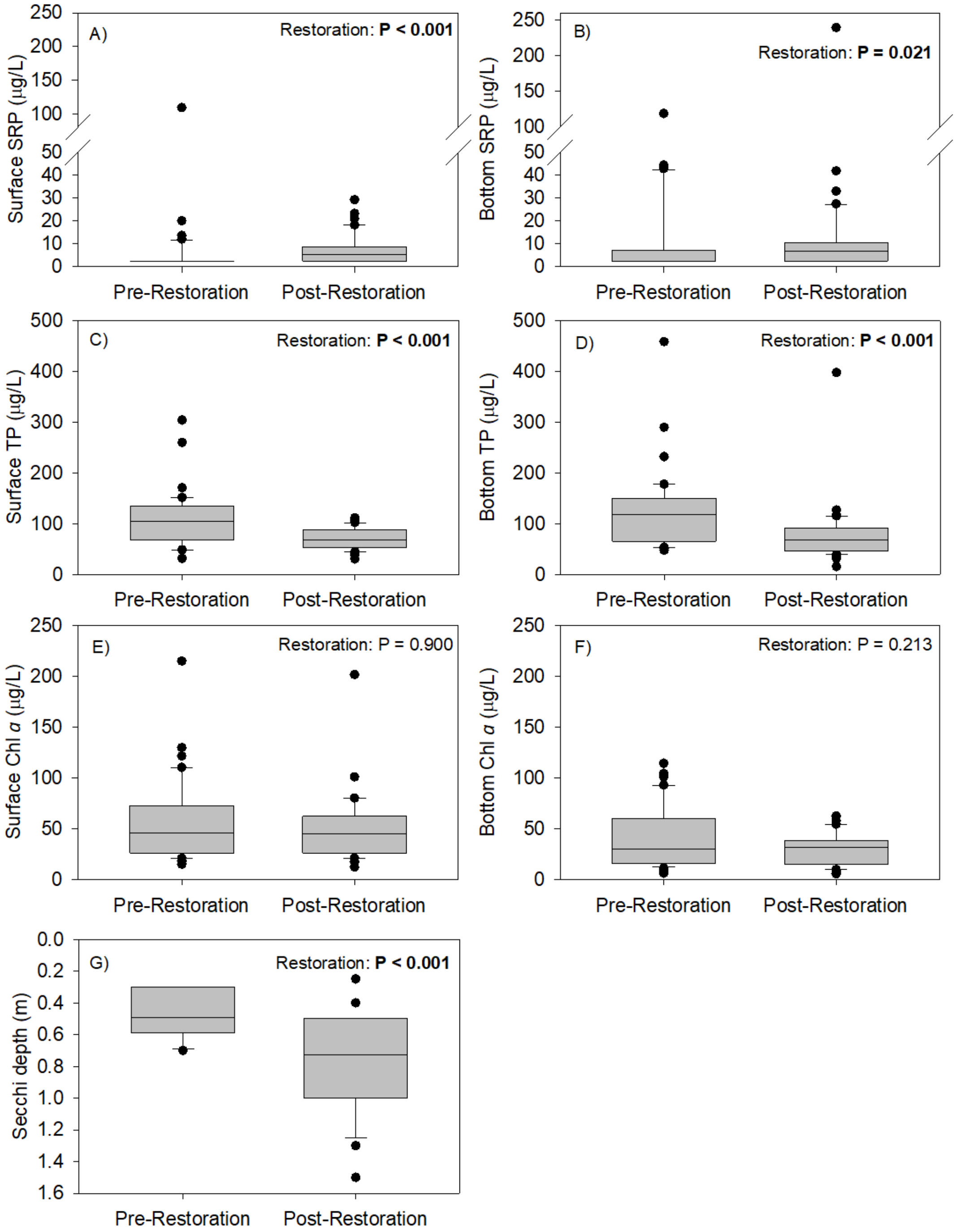


Figure 7. Box plots of soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); chlorophyll *a* ([chl *a*]: E, F; and Secchi disk depth: G) levels measured at the 5 monitoring stations in Lake Macatawa during all pre-restoration sampling dates (summer 2013 – fall 2015) and an equal and seasonally corresponding number of post-restoration sampling dates (summer 2019 – fall 2021). 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 Dashboard

It is well known that precipitation will influence lake condition because runoff carries nutrients and sediment, which ultimately reach the downstream receiving water bodies (Baker et al. 2019). Hence, when examining lake condition in a particular year, it makes sense to compare the lake health to the precipitation regime in that year. 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 ($R^2<0.01$, 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 2013-2021 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 2021 data: the SRP fit is best with 2-month data while the TP fit is best with 1-day precipitation data (Fig. 9). However, R^2 values (0.33 for both) are still weak. Using the more recent antecedent precipitation data, instead of the full antecedent calendar year may be a better indicator of the precipitation-P relationship for Lake Macatawa.

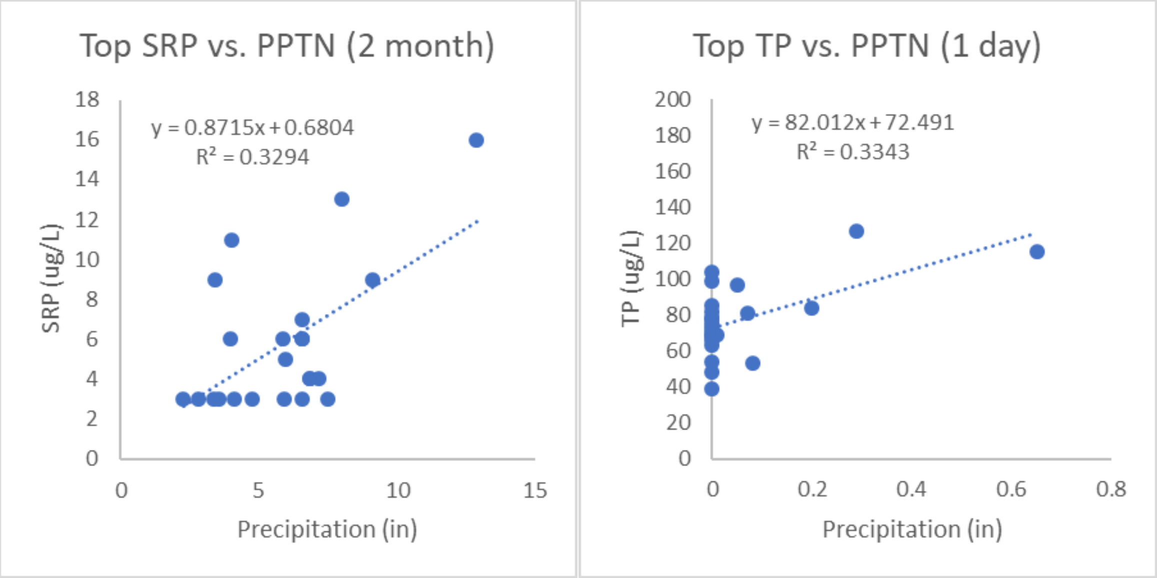


Figure 9. Linear regressions plotting annual precipitation vs. mean soluble reactive phosphorus (SRP) and total phosphorus (TP) concentrations in Lake Macatawa. Surface SRP and TP data are lake-wide means of seasonal 2013-2021 AWRI sampling events. Precipitation data sources were provided by the National Climatic Data Center/National Centers for Environmental Information (2013-2021; NOAA).

4. Summary

The 2021 water quality in Lake Macatawa showed improvement in some areas but also some indicators of where vigilance or action is recommended. Although TP concentrations remain above the 50 µg/L TMDL target, post-restoration concentrations continue to improve. As noted in last year's report, dissolved phosphorus (SRP) values have increased significantly over time; while it is unclear if this is related to soil tillage practices in the watershed or changes in algal use of dissolved P (i.e., less algae → less uptake), we do recommend the agricultural community evaluate their tillage practices and continue the implementation of BMPs wherever and whenever possible.

The optimism expressed by last year's reduced nitrate levels in spring and fall may have been misplaced based on the increases observed in 2021. Nitrate, similar to SRP, is in the dissolved form and readily taken up by algae. Hence, it is unclear if the increased concentrations reflect less phytoplankton, increased loading rates, or perhaps a combination of the two. Regardless, nitrate concentrations increased back to the 2018-2019 levels in 2021. With the completion of the computational SWAT model for the Macatawa watershed (Iavorivska et al. 2020), this tool can help assess how different agricultural scenarios will impact downstream water quality. We recommend ODC consider its utilization in the future.

Overall, water quality trends are generally positive, although as noted previously, the current phosphorus and chlorophyll concentrations are well above what should be observed in a "healthy" lake. There will continue to be year-to-year variation in these indicators, and it will take time to see overall trends. We caution once again that it can take decades for actions in the watershed to result in improvements in a lake.

The appendices address additional studies AWRI is conducting in the lake and watershed. Fish monitoring (Appendix A), funded through Project Clarity, is in its 8th year, and the current data indicated that the littoral fish assemblage showed both positive and negative indicators of the lake's ecological health. Yellow perch, bluegill, and pumpkinseed were common species captured in our surveys, and they are indicators of good water quality. However, gizzard shad and spotfin shiner were commonly found and are often associated with poor water quality. Although the near absence of rock bass in the Lake Macatawa catch is another sign of poor water quality, 2021 was the first year this species was captured in the lake since fish monitoring began in 2014.

The iron slag filter project (Appendix B), funded through MDARD, has been effective at reducing P concentrations, but their optimal effectiveness is in regions with very high SRP concentrations in the tile drain effluent. There appears to be no concern over their leaching of toxic substances but given the cost of implementation and maintenance, their impact in reducing P will be localized at high-P "hot spots".

The Lake Macatawa Dashboard (Appendix C) 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.

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. We recommend 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.
- The impact of a changing climate should be incorporated into future management plans. One way to do that is through the use of predictive models. AWRI has developed a SWAT model for the Lake Macatawa watershed that can be used for this purpose.
- 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. Hence, we recommend that consideration be given to plant surveys and phytoplankton identification in the future.
- From the start of PC, it was understood that controlling pollutants from the watershed was absolutely critical. It made neither economic nor ecological sense to implement lake restoration measures as long as the pollution kept flowing into Lake Macatawa. Lake conditions, while still more impaired than desired, are starting to improve. It may be time to start considering a lake management plan, including actions, timelines, and budgets.

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7. Appendices

Appendix A. Long-Term Fish Monitoring of Lake Macatawa

Appendix B. Iron Slag Filter Report

Appendix C. Lake Macatawa Dashboard

Appendix A. Long-Term Fish Monitoring of Lake Macatawa

Long-Term Fish Monitoring of Lake Macatawa: Results from Year 8 (2021)

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Introduction

This study was initiated to provide critical information on littoral fish populations 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 to 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 (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 assess how the lake is responding to watershed restoration activities.

Our primary objective in the eighth year (2021) of sampling Lake Macatawa 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 represent 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 (all other sampling was completed). As water levels in Lake Michigan receded in 2021, we were able to sample fish at all sites.

Fish sampling.—At each study site, we sampled fish via fyke netting and boat electrofishing. Using both sampling gears helps to 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 13 October 2021 during daylight hours (i.e., between 0900 and 1400) and fished for ~24.4 h (range = 23.4-25.3 h). Fyke nets had been previously set 4-16 September (2014-2020), but we were forced to delay sampling to October in 2021 because of poor weather conditions. 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 description of the design of the fyke nets is reported in Breen and Ruetz (2006). We conducted nighttime boat electrofishing at each site on 9 September 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. 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, total dissolved solids, turbidity, pH, oxidation-reduction potential [ORP], 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 electrofishing transect during nighttime fish sampling when water clarity was sufficient.

Results and Discussion

We characterized water quality variables at each site during fish sampling in 2021 (Tables 2 and 3). The mean water depth at fyke nets was 84 cm (Table 2). Mean water temperature during fyke netting (19.9 °C; Table 2) was cooler than boat electrofishing (22.3 °C; Table 3) likely because boat fyke netting was conducted about 1 month later than electrofishing due to weather delays. At fyke nets, mean percent cover of macrophytes was low at most sites, with values <7% at sites #1, #2, and #3, but 57% at site #4. Water clarity made visually estimating macrophyte cover difficult during nighttime boat electrofishing in 2021; we were able to estimate percent macrophyte cover only at sites #2 (35%) and #3 (70%). There may be a trend of increasing percent macrophyte cover over time (Figure 2B). We hypothesized that low densities of macrophytes in Lake Macatawa during 2014 and 2015 were caused by insufficient light penetrating the water column to allow submersed plants to grow; turbidity measurements were generally higher in 2014 and 2015 than subsequent years (Figure 3). Turbidity can result from inflowing sediment and abundant phytoplankton growth, both of which can reduce light penetration in the water column and inhibit plant growth.

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 was likely related to turbidity (i.e., lower turbidity is associated with more macrophytes), with overall mean turbidity (11.5 NTU, n = 12) in 2021 less than the long-term mean (16.7 NTU, n = 96; Figure 3B). 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).

Compared to six Lake Michigan drowned river mouths, water quality in Lake Macatawa (measured during autumn fish sampling) has been most similar to Kalamazoo Lake, especially with respect to high turbidity and specific conductivity (Janetski and Ruetz 2015). Turbidity and specific conductivity were higher in Lake Macatawa than in Muskegon Lake, the drowned river mouth lake for which we have the longest time series of water quality observations (Bhagat and Ruetz 2011; see also https://www.gvsu.edu/wri/director/muskegon-lake-water-quality-dashboard-78.htm). Although there has been a pattern of turbidity and specific conductivity decreasing over time, specific conductivity in 2021 was greater than in 2020 during the limited sampling (Figure 3; see main report for more complete data on water quality). High levels of turbidity and specific conductivity often are associated with relatively high anthropogenic disturbance in Great Lakes coastal wetlands (Uzarski et al. 2005). Thus, the water quality we measured in Lake Macatawa appears on the degraded side of the spectrum among Lake Michigan drowned river mouths (see Uzarski et al. 2005, Janetski and Ruetz 2015), but there may be an overall trend towards improvement (Figure 3). Within the lake itself, there was typically a gradient in specific conductivity and turbidity in most years, with higher levels at the east end (i.e., near river mouth) and lower levels closer to Lake Michigan (Tables 2 and 3; Figure 3). This is to be expected given that most of the sediment entering the lake comes from the Macatawa River, which runs off largely agricultural land and through urbanized Holland, while backflow from oligotrophic Lake Michigan during westerly winds can bring cleaner, colder water into Lake Macatawa, similar to what has been observed in Muskegon Lake (Liu et al. 2018).

We captured 1,618 fish comprising 30 species in Lake Macatawa during 2021 sampling surveys (Table 4). The total catch was similar to previous years, but the number of fish species captured was at the upper bound of what we have previously encountered (Figure 4). The most abundant fishes in the combined catch (i.e., fyke netting and boat electrofishing) were brook silverside (29%), bluegill (16%), spotfin shiner (15%), and round goby (12%), which composed 71% of the total catch (Figure 5A). Five of the 30 species captured during 2021 were non-native to the Great Lakes basin (Bailey et al. 2004)—alewife, goldfish, common carp, white perch, and round goby—which composed 15% of the total catch, with most of the non-native fishes being round goby (Table 4). For comparison, we captured 2,102 fishing comprising 25 species in Muskegon Lake during autumn 2021 (with similar sampling effort in terms of sites and gear to the sampling reported here for Lake Macatawa). Three of the 25 species in Muskegon Lake were non-native to the Great Lakes basin—common carp, white perch, and round goby—which composed 18% of the catch (98% of non-native fish species captured in Muskegon Lake in autumn 2021 were round goby).

In fyke netting, brook silverside (33%), bluegill (20%), spotfin shiner (19%), and round goby (15%) were the most abundant fishes in the catch, composing 87% of all fish captured (Figure 5B). The most abundant species at each site were spotfin shiner, brook silverside, and bluegill at site #1, bluegill and spotfin shiner at site #2, brook silverside at site #3, and round goby and brook silverside at site #4 (Table 5). The number of fish captured also varied among sites, with the most fish captured at site #4 and the least at site #3 (Table 5; Figure 6A). Compared with the previous fyke netting surveys, the most abundant species in the catch varied among years (Figure 7), as did the patterns in total catch among sites (Figure 6A). The main difference in the relative abundance (i.e., percentage of a fish species in the total catch for a given year) in 2021 was that we captured more brook silverside, round goby, and spotfin shiner, whereas we captured less gizzard shad compared with most previous years (Figure 7). As we continue monitoring Lake Macatawa, we will be better able to assess spatiotemporal patterns and whether these observed patterns are associated with other environmental variables.

In boat electrofishing, the most abundant fishes captured were gizzard shad (19%), yellow perch (18%), brook silverside (16%), largemouth bass (14%), and white perch (8%), which composed 76% of the total catch (Figure 5C). The most abundant species in the catch were largemouth bass at site #1, white perch and gizzard shad at site #2, gizzard shad and yellow perch at site #3, and yellow perch, brook silverside, and largemouth bass at site #4 (Table 6). Total catch also varied among sites in 2021, with the highest catch at site #4 and lowest catch at site #1 (Figure 6B). Compared with previous boat electrofishing surveys, the most abundant species in the catch varied among years, although the pattern was more similar among recent years (i.e., 2016-2021; Figure 8). The main difference in 2021 was that gizzard shad were less common in the catch than in recent (i.e., 2019-2020) years (Figure 8). Overall, there appears to be less variability in species composition based on boat electrofishing surveys compared with fyke netting surveys (see Figure 8 vs. Figure 7).

In conclusion, the observations reported here are the eighth year of an effort to characterize the littoral fish assemblage of Lake Macatawa. This monitoring effort is providing a baseline to assess how the fish assemblage responds to restoration activities in the Lake Macatawa watershed. After 8 years of fish monitoring, there are both positive and negative indicators of the ecological health in Lake Macatawa. 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 likely indicates poor water quality (Janetski and Ruetz 2015; Cooper et al. 2018), although 2021 was the first year we captured this species in Lake Macatawa since we began fish monitoring in 2014. 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 underlying mechanisms driving spatiotemporal patterns.

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Table 1. Locations (latitude and longitude) for each 2021 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	42.79599	-86.12121	42.79580	-86.12039	42.79567	-86.12289
2	42.79012	-86.14380	42.79056	-86.14439	42.78819	-86.14447
3	42.78623	-86.17454	42.78679	-86.17539	42.78583	-86.17398
4	42.77954	-86.19719	42.77917	-86.19748	42.78056	-86.19578

Note : For the electrofishing transect at site #2, we skipped some of the area in the middle of the transect to go around a marina.

Table 2. Mean ± 1 standard error (*n* = 3) of water quality variables at fish sampling sites in Lake Macatawa. Measurements were made during fyke netting on 13 October 2021 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	Oxidation Reduction Potential	Chlorophyll *a* (µg/L)
1	78 ± 5	19.62 ± 0.02	8.01 ± 0.14	87.6 ± 1.6	560 ± 1	0.36 ± 0.00	14.5 ± 0.9	7.54 ± 0.06	24.5 ± 8.0	43.7 ± 1.6
2	83 ± 4	19.68 ± 0.12	8.62 ± 0.06	94.4 ± 0.4	529 ± 0	0.34 ± 0.00	13.3 ± 2.8	7.81 ± 0.02	41.0 ± 2.9	39.9 ± 1.8
3	92 ± 2	19.72 ± 0.03	10.47 ± 0.01	114.6 ± 0.2	444 ± 0	0.29 ± 0.00	4.8 ± 0.4	8.23 ± 0.03	65.4 ± 2.8	25.3 ± 0.0
4	84 ± 1	20.65 ± 0.08	11.13 ± 0.11	124.2 ± 1.3	441 ± 0	0.29 ± 0.00	13.4 ± 4.2	8.36 ± 0.02	60.5 ± 3.8	29.5 ± 1.5

Table 3. Water quality variables at fish sampling sites in Lake Macatawa. Measurements were made during nighttime boat electrofishing on 9 September 2021 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	Oxidation Reduction Potential (mV)	Chlorophyll *a* (µg/L)
1	22.89	10.32	120.2	584	0.380	15.8	7.99	44.0	59.1
2	22.64	12.71	147.7	500	0.325	8.7	8.82	52.2	26.6
3	22.49	12.68	146.0	409	0.266	4.5	8.8	64.9	23.1
4	21.18	9.79	110.3	416	0.270	4.6	8.49	31.5	24.4

Table 4. Number and total length (TL; mean, minimum, and maximum) of fish captured by fyke netting (*n* = 12 nets) on 14 October 2021 at four sites and boat electrofishing (*n* = 4 transects) on 9 September 2021 at four sites in Lake Macatawa. Total is the total catch combined for both gears.

			Fyke netting				Electrofishing			
				TL (cm)				TL (cm)		
Common name	Scientific name	Total	Catch	Mean	Min	Max	Catch	Mean	Min	Max
alewife	*Alosa pseudoharengus*	2	--	--	--	--	2	8.1	7.8	8.3
rock bass	*Ambloplites rupestris*	3	3	6.1	6.0	6.3	--	--	--	--
yellow bullhead	*Ameiurus natalis*	1	1	26.1	26.1	26.1	--	--	--	--
brown bullhead	*Ameiurus nebulosus*	1	1	11.2	11.2	11.2	--	--	--	--
bowfin	*Amia calva*	9	3	54.1	50.0	56.3	6	50.1	43.0	58.1
freshwater drum	*Aplodinotus grunniens*	3	--	--	--	--	3	19.5	17.1	22.8
goldfish	*Carassius auratus*	2	--	--	--	--	2	23.4	12.3	34.5
white sucker	*Catostomus commersonii*	12	--	--	--	--	12	39.7	37.5	45.0
common carp	*Cyprinus carpio*	6	--	--	--	--	6	50.2	15.0	62.8
spotfin shiner	*Cyprinella spiloptera*	236	236	6.9	2.7	10.2	--	--	--	--
gizzard shad	*Dorosoma cepedianum*	95	19	10.6	8.2	11.9	76	13.0	9.6	20.2
banded killifish	*Fundulus diaphanus*	6	4	4.2	3.5	4.5	2	9.3	8.8	9.8
channel catfish	*Ictalurus punctatus*	1	1	58.7	58.7	58.7	--	--	--	--
brook silverside	*Labidesthes sicculus*	468	404	7.1	3.5	10.5	64	7.4	4.8	10.7
green sunfish	*Lepomis cyanellus*	1	1	6.1	6.1	6.1	--	--	--	--
pumpkinseed	*Lepomis gibbosus*	28	15	14.7	12.0	18.0	13	12.5	6.0	16.7
bluegill	*Lepomis macrochirus*	262	242	5.5	3.0	18.8	20	10.5	3.5	19.6
common shiner	*Luxilus cornutus*	1	1	11.9	11.9	11.9	--	--	--	--
largemouth bass	*Micropterus salmoides*	69	14	11.1	3.7	39.0	55	13.8	7.1	37.3
white perch	*Morone americana*	38	5	16.9	11.0	20.5	33	12.6	8.1	19.2
silver redhorse	*Moxostoma anisurum*	1	1	39.2	39.2	39.2	--	--	--	--
shorhead redhorse	*Moxostoma macrolepidotum*	3	3	46.8	43.5	49.5	--	--	--	--
round goby	*Neogobius melanostomus*	188	182	6.3	3.3	15.1	6	8.9	7.1	9.7
emerald shiner	*Notropis atherinoides*	17	16	7.6	3.6	11.5	1	8.9	8.9	8.9
golden shiner	*Notemigonus crysoleucas*	40	24	9.4	6.5	10.7	16	12.0	8.0	16.6
spottail shiner	*Notropis hudsonius*	21	18	9.4	4.3	12.0	3	11.0	10.7	11.3
yellow perch	*Perca flavescens*	87	18	16.1	10.6	30.0	69	11.3	8.4	19.8
bluntnose minnow	*Pimephales notatus*	13	11	6.7	3.2	9.0	2	6.8	6.2	7.4
black crappie	*Pomoxis nigromaculatus*	2	2	22.0	19.9	24.1	--	--	--	--
walleye	*Sander vitreus*	2	--	--	--	--	2	50.2	50.1	50.2
	Total	1618	1225				393			

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 14 October 2021. 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
rock bass	*Ambloplites rupestris*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**3**	6.1	6.0	6.3
yellow bullhead	*Ameiurus natalis*	**0**	--	--	--	**1**	26.1	--	--	**0**	--	--	--	**0**	--	--	--
brown bullhead	*Ameiurus nebulosus*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**1**	11.2	--	--
bowfin	*Amia calva*	**0**	--	--	--	**2**	56.1	55.9	56.3	**0**	--	--	--	**1**	50.0	--	--
spotfin shiner	*Cyprinella spiloptera*	**164**	6.9	2.7	10.2	**58**	7.1	4.4	10.0	**0**	--	--	--	**14**	6.9	3.6	8.9
gizzard shad	*Dorosoma cepedianum*	**16**	10.5	8.2	11.4	**2**	11.1	10.5	11.6	**0**	--	--	--	**1**	11.9	--	--
banded killifish	*Fundulus diaphanus*	**3**	4.1	3.5	4.5	**0**	--	--	--	**0**	--	--	--	**1**	4.5	--	--
channel catfish	*Ictalurus punctatus*	**1**	58.7	--	--	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--
brook silverside	*Labidesthes sicculus*	**63**	7.0	4.5	10.5	**36**	6.9	5.1	8.4	**163**	7.1	4.5	9.2	**142**	7.2	3.5	9.1
green sunfish	*Lepomis cyanellus*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**1**	6.1	--	--
pumpkinseed	*Lepomis gibbosus*	**0**	--	--	--	**14**	14.9	12.0	18.0	**0**	--	--	--	**1**	12.4	--	--
bluegill	*Lepomis macrochirus*	**60**	6.1	3.6	18.8	**103**	5.3	3.0	17.0	**8**	4.7	4.2	5.6	**71**	5.3	4.1	11.1
common shiner	*Luxilus cornutus*	**1**	11.9	--	--	**0**	--	--	--	**0**	--			**0**	--	--	--
largemouth bass	*Micropterus salmoides*	**1**	10.9	--	--	**1**	39.0	--	--	**4**	8.6	7.9	9.5	**8**	8.8	3.7	13.0
white perch	*Morone americana*	**1**	11.0	--	--	**2**	19.0	17.5	20.5	**0**	--	--	--	**2**	17.8	17.4	18.2
silver redhorse	*Moxostoma anisurum*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**1**	39.2	--	--
shorhead redhorse	*Moxostoma macrolepidotum*	**2**	46.5	43.5	49.5	**0**	--	--	--	**0**	--	--	--	**1**	47.4	--	--
round goby	*Neogobius melanostomus*	**2**	7.9	5.8	10.0	**15**	7.9	4.8	13.6	**11**	9.7	7.7	15.1	**154**	5.8	3.3	12.6
emerald shiner	*Notropis atherinoides*	**1**	11.5	--	--	**0**	--	--	--	**9**	9.3	8.1	10.9	**6**	4.4	3.6	5.1
golden shiner	*Notemigonus crysoleucas*	**10**	9.5	8.8	9.8	**14**	9.3	6.5	10.7	**0**	--	--	--	**0**	--	--	--
spottail shiner	*Notropis hudsonius*	**15**	10.1	4.3	12.0	**3**	6.2	5.3	7.0	**0**	--	--	--	**0**	--	--	--
yellow perch	*Perca flavescens*	**1**	11.4	--	--	**4**	15.8	11.1	24.1	**0**	--	--	--	**13**	16.5	10.6	30.0
bluntnose minnow	*Pimephales notatus*	**1**	8.5	--	--	**5**	7.6	5.9	9.0	**0**	--	--	--	**5**	5.4	3.2	8.3
black crappie	*Pomoxis nigromaculatus*	**1**	19.9	--	--	**1**	24.1	--	--	**0**	--	--	--	**0**	--	--	--
	Total	343				261				195				426			

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 9 September 2021. 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*	**2**	8.1	7.8	8.3	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--
bowfin	*Amia calva*	**0**	--	--	--	**0**	--	--	--	**3**	47.2	43.0	50.7	**3**	52.9	49.8	58.1
freshwater drum	*Aplodinotus grunniens*	**2**	20.7	18.5	22.8	**1**	17.1	--	--	**0**	--	--	--	**0**	--	--	--
goldfish	*Carassius auratus*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**2**	23.4	12.3	34.5
white sucker	*Catostomus commersonii*	**1**	41.5	--	--	**1**	38.1	--	--	**9**	39.7	37.5	45.0	**1**	39.5	--	--
common carp	*Cyprinus carpio*	**4**	58.6	55.3	62.8	**0**	--	--	--	**1**	51.6	--	--	**1**	15.0	--	--
gizzard shad	*Dorosoma cepedianum*	**3**	10.3	9.6	10.9	**17**	14.5	9.9	20.2	**47**	12.9	10.2	14.8	**9**	11.6	9.7	12.9
banded killifish	*Fundulus diaphanus*	**0**	--	--	--	**0**	--	--	--	**1**	8.8	--	--	**1**	9.8	--	--
brook silverside	*Labidesthes sicculus*	**1**	8.0	--	--	**13**	7.9	6.4	10.2	**16**	7.3	5.8	8.3	**34**	7.2	4.8	10.7
pumpkinseed	*Lepomis gibbosus*	**2**	13.4	12.3	14.5	**8**	12.1	6.0	16.0	**1**	6.8	--	--	**2**	16.0	15.3	16.7
bluegill	*Lepomis macrochirus*	**3**	17.3	15.3	19.6	**11**	10.3	3.5	15.7	**0**	--	--	--	**6**	7.6	5.0	16.9
largemouth bass	*Micropterus salmoides*	**9**	21.3	10.8	37.3	**13**	16.8	9.2	28.1	**8**	12.7	8.4	26.6	**25**	9.8	7.1	20.2
white perch	*Morone americana*	**6**	18.0	16.8	19.2	**20**	10.8	8.6	16.5	**2**	8.7	8.1	9.2	**5**	15.0	8.6	17.5
round goby	*Neogobius melanostomus*	**0**	--	--	--	**0**	--	--	--	**1**	8.9	--	--	**5**	8.9	7.1	9.7
emerald shiner	*Notropis atherinoides*	**0**	--	--	--	**0**	--	--	--	**1**	8.9	--	--	**0**	--	--	--
golden shiner	*Notemigonus crysoleucas*	**1**	16.2	--	--	**8**	11.7	8.0	16.6	**3**	13.0	9.9	16.5	**4**	10.5	8.9	14.3
spottail shiner	*Notropis hudsonius*	**0**	--	--	--	**2**	11.0	10.7	11.3	**1**	11.0	--	--	**0**	--	--	--
yellow perch	*Perca flavescens*	**1**	19.5	--	--	**12**	13.1	9.6	19.2	**20**	9.7	8.9	10.5	**36**	11.3	8.4	19.8
bluntnose minnow	*Pimephales notatus*	**0**	--	--	--	**0**	--	--	--	**0**	--	--	--	**2**	6.8	6.2	7.4
walleye	*Sander vitreus*	**0**	--	--	--	**0**	--	--	--	**2**	50.2	50.1	50.2	**0**	--	--	--
	Total	35				106				116				136			

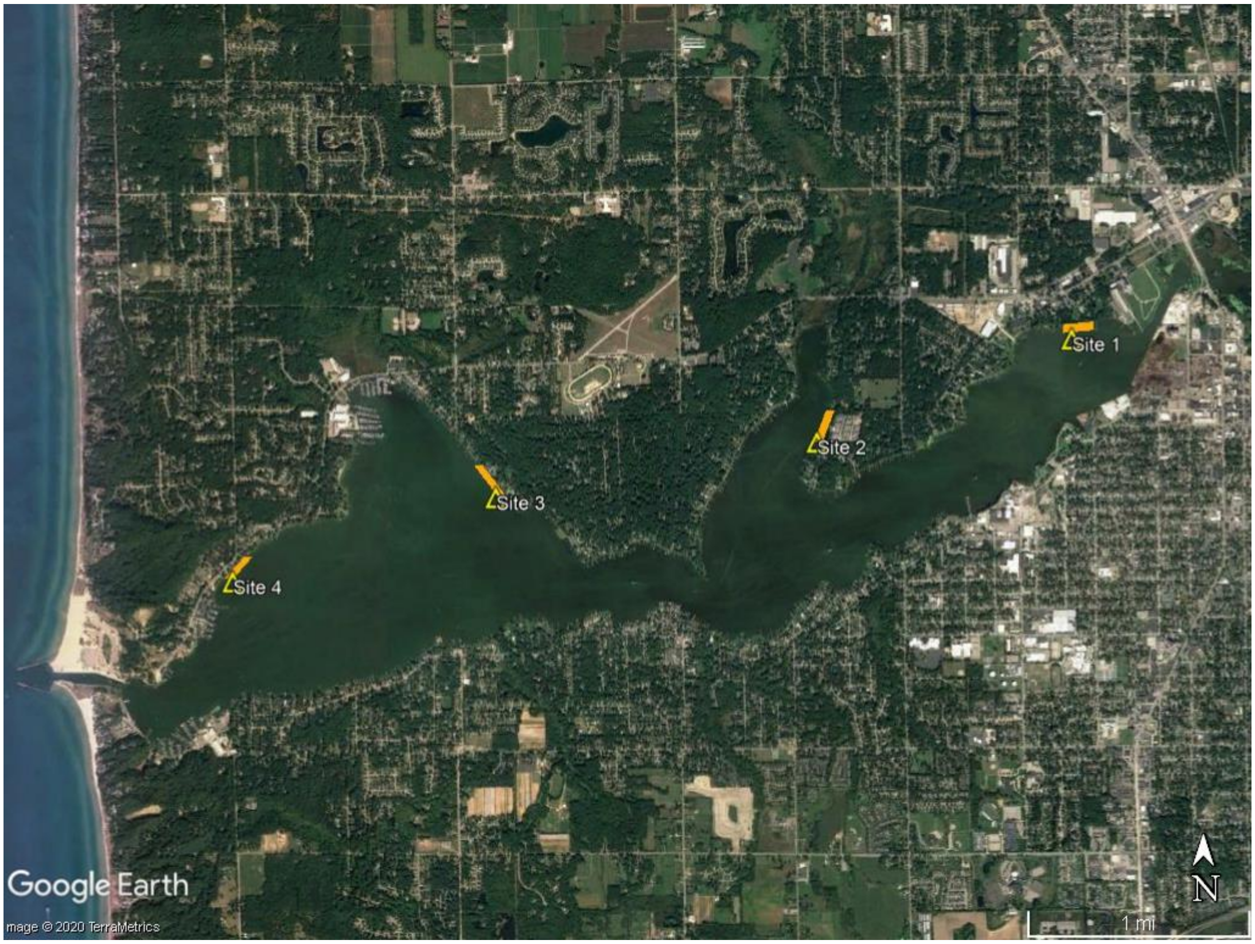

Figure 1. Map of Lake Macatawa (Ottawa County, Michigan) showing fish sampling sites (triangles). The orange transects depict approximately where boat electrofishing was conducted at each site. Site #1 is closest to the Macatawa River and site #4 is closest to Lake Michigan. Note that riparian vegetation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

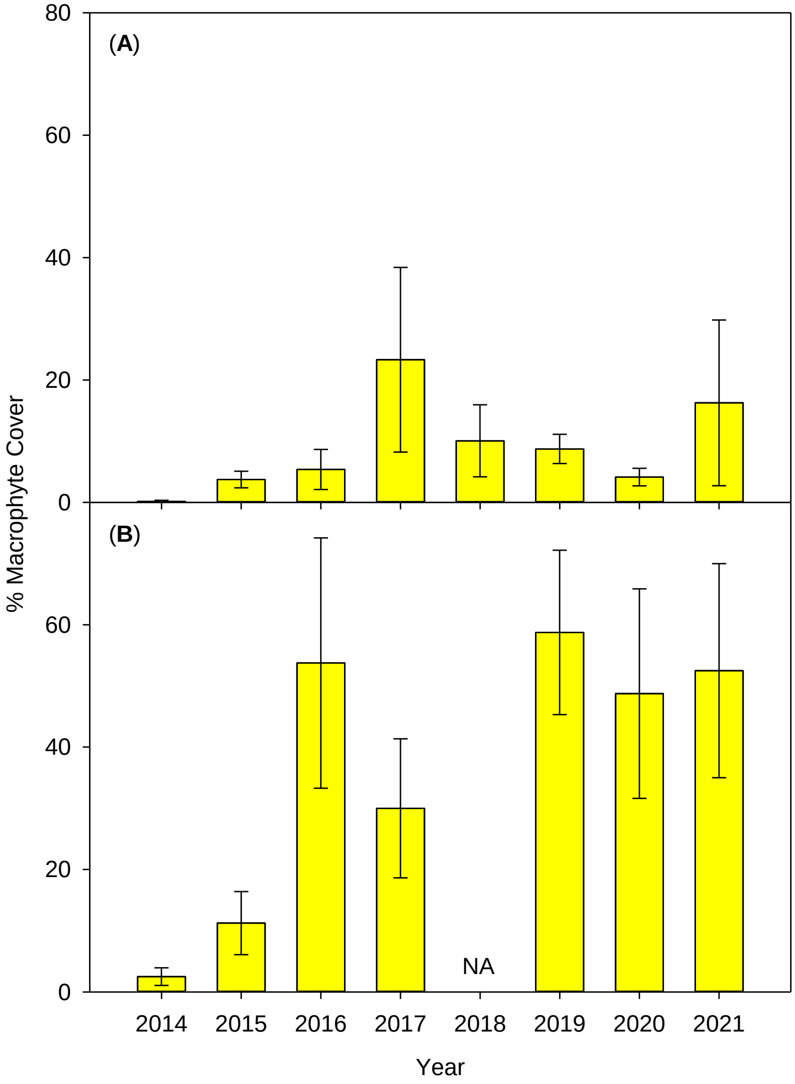

Figure 2. Mean (±1 standard error) percent macrophyte cover visually estimated at (**A**) fyke net locations and (**B**) boat electrofishing transects in Lake Macatawa (*n* = 4 sites per year; however, the *n* = 2 sites for 2021 boat electrofishing because of poor visibility). Note that the area where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

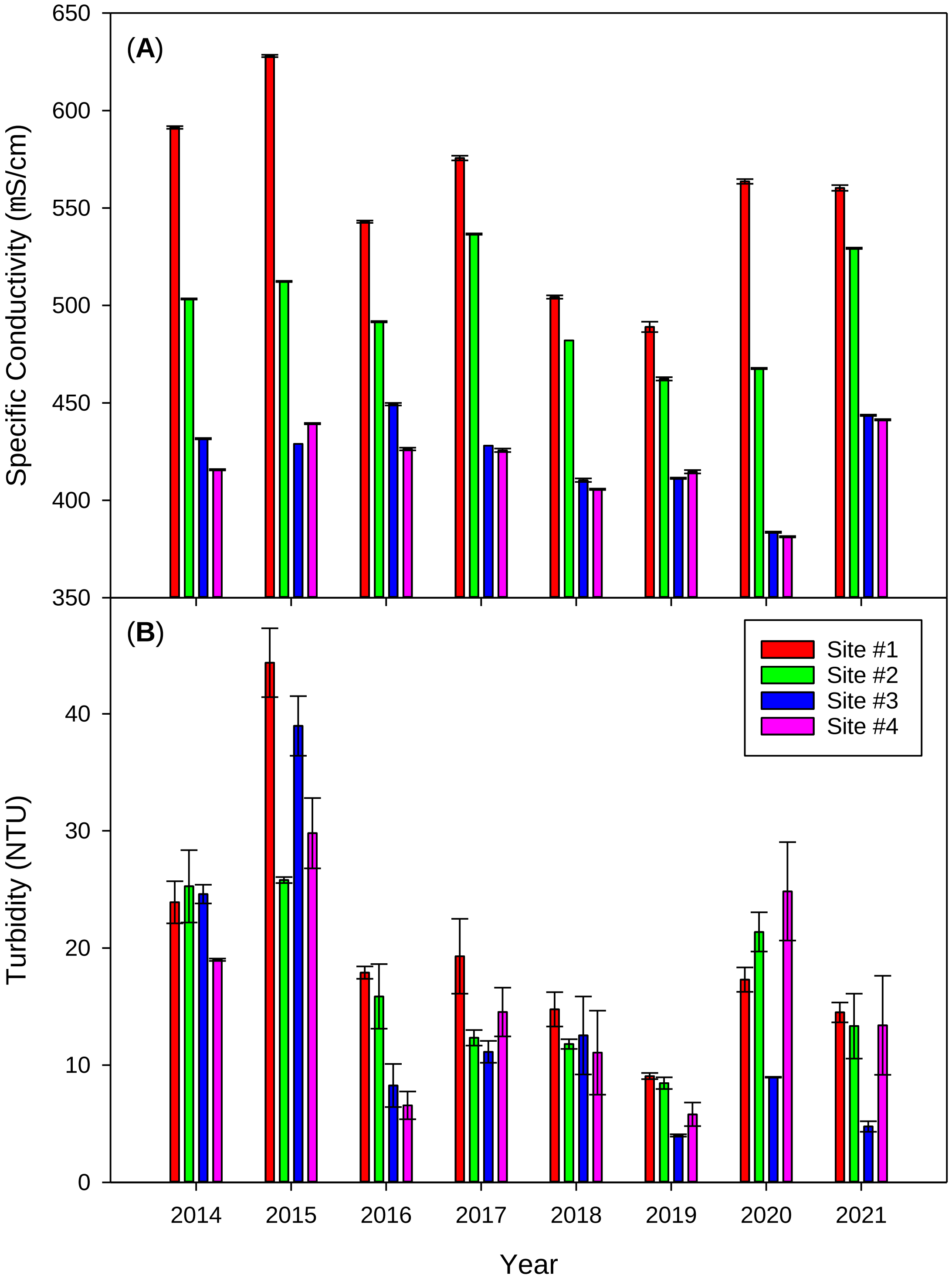

Figure 3. Mean (**A**) specific conductivity and (**B**) turbidity measured during fyke netting in Lake Macatawa. Error bars represent ±1 standard error (*n* = 3 nets per site), although they may be too small to be visible for some means.

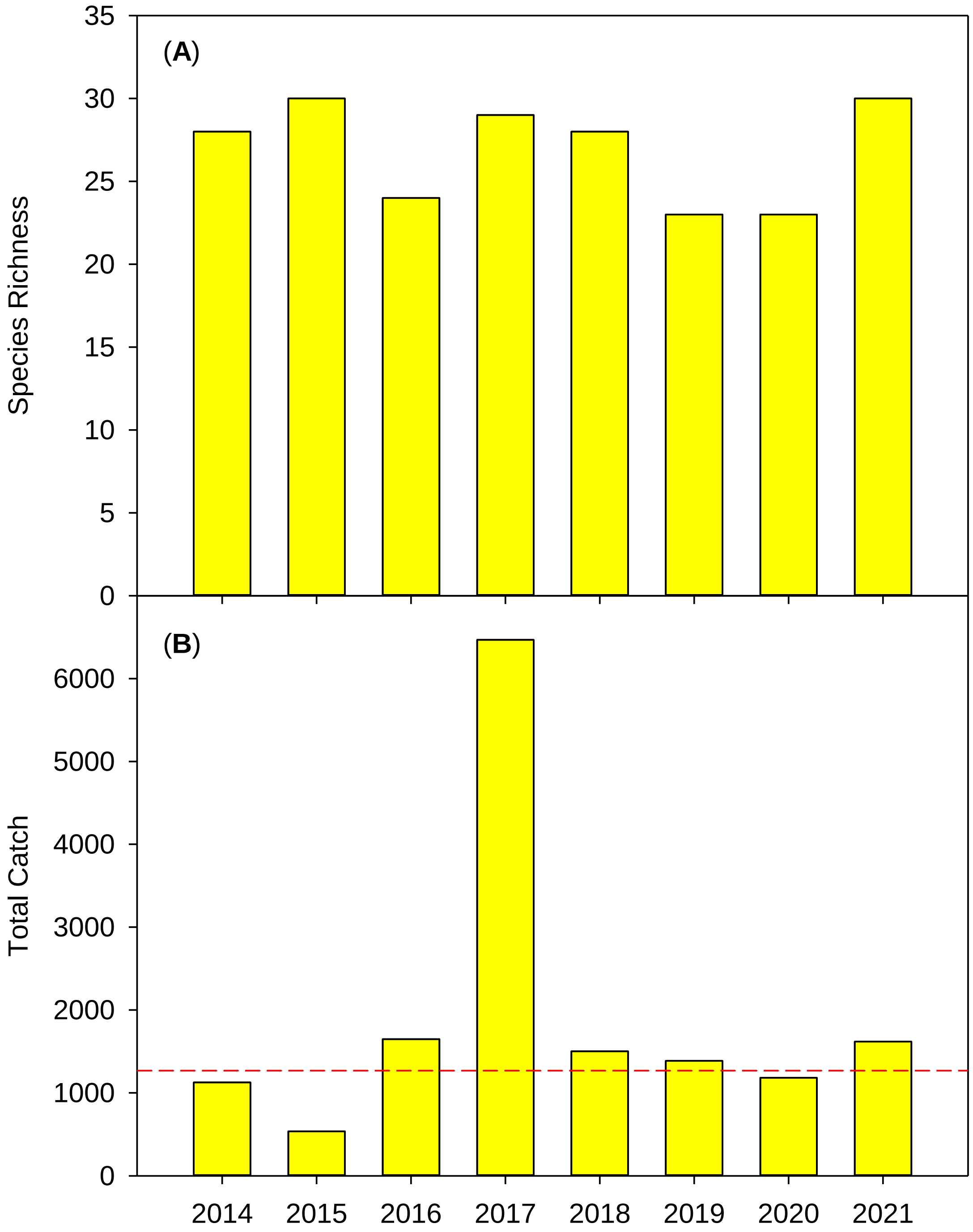

Figure 4. (**A**) Number of fish species captured and (**B**) total number of fish captured using both fyke netting and boat electrofishing each year in Lake Macatawa (dashed red line is average over all years excluding 2017). *Note*: the high catch in 2017 was due to 5,288 brook silversides captured from a single fyke net at site #4, and fyke netting in 2020 only was completed at three sites rather than the typical four sites.

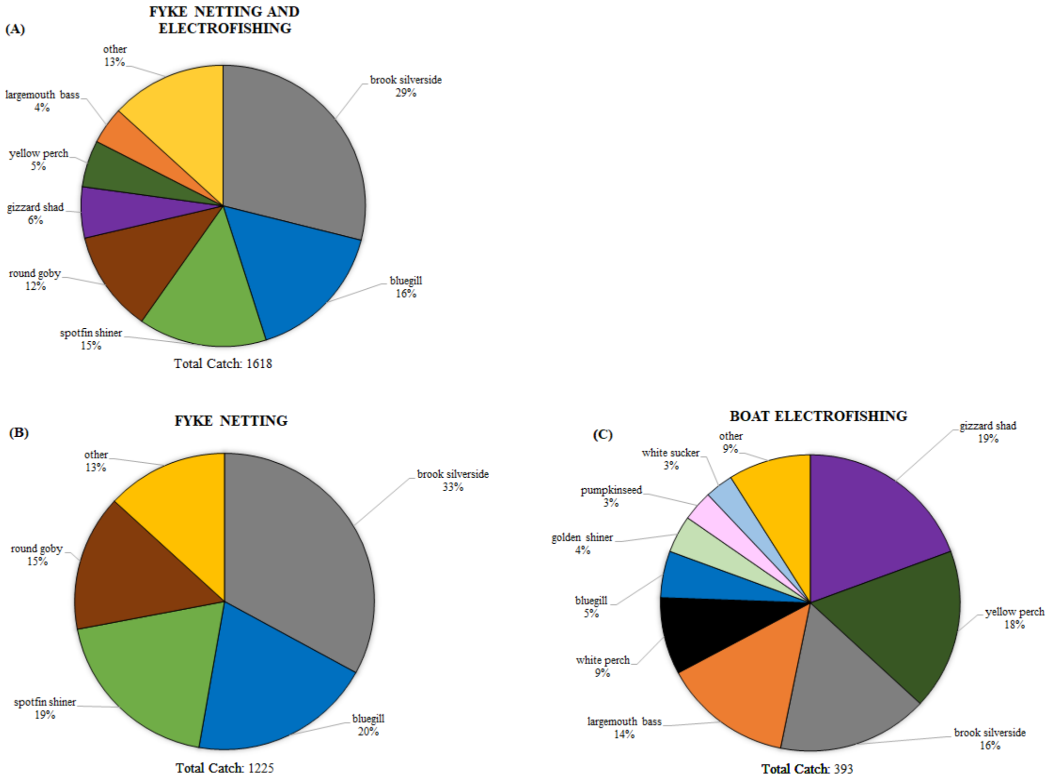

Figure 5. Fish species captured in littoral habitats of Lake Macatawa by (**A**) fyke netting and boat electrofishing (i.e., combined catch), (**B**) fyke netting (*n* = 12 nets), and (**C**) boat electrofishing (*n* = 4 transects) during September-October 2021. Catch data, including the species pooled in the “other” category, are reported in Table 4.

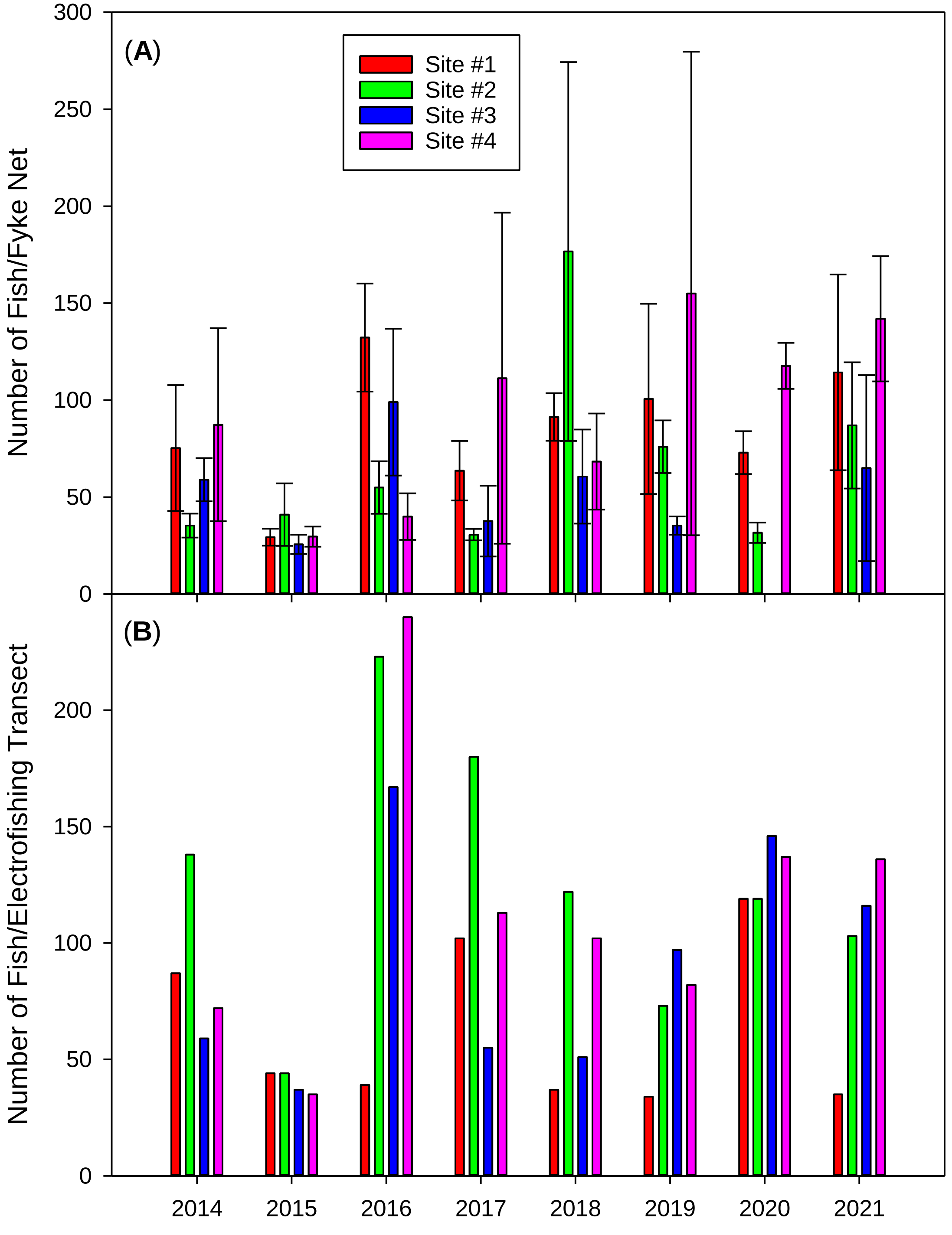

Figure 6. (**A**) Mean number (±1 standard error) of fish captured in fyke nets (n = 3 nets per site) and (**B**) number of fish captured during a boat electrofishing transect (n = 1 transect per site) in Lake Macatawa. *Note*: 5,288 brook silversides captured in a single fyke net at site #4 in 2017 were excluded when calculating means (and SE) for fyke netting. Fyke nets were not set at site #3 in 2020.

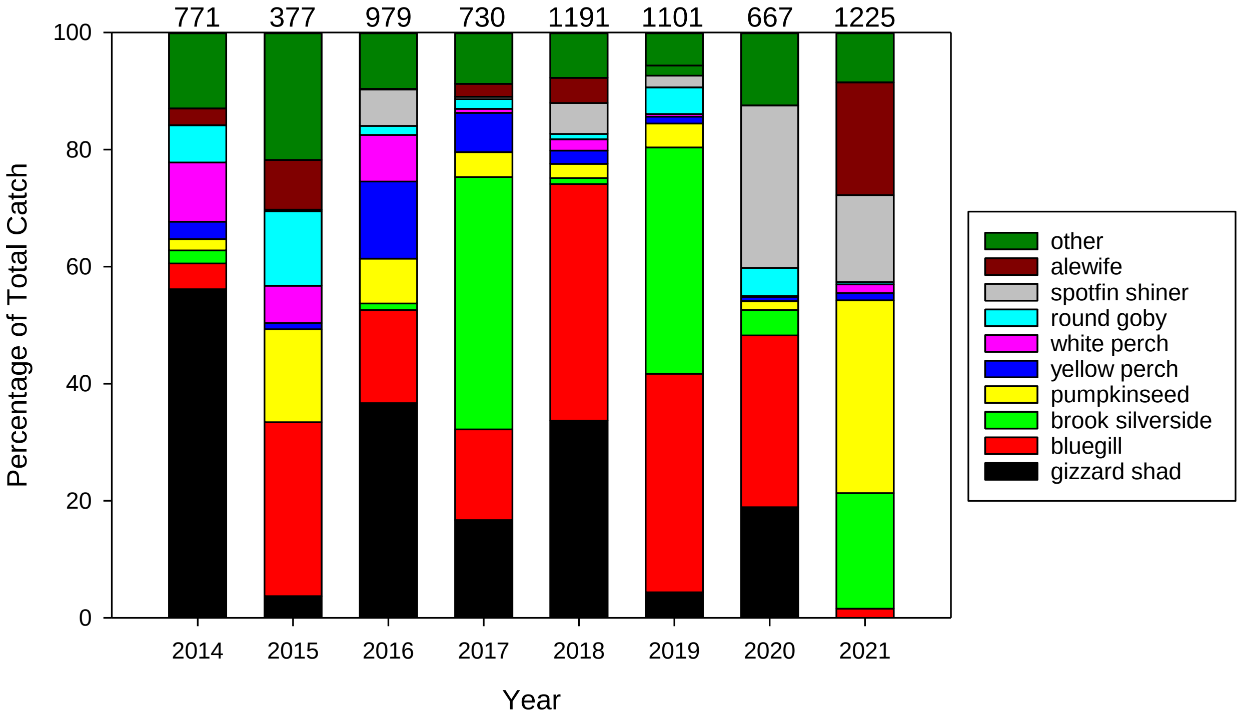

Figure 7. Fish species composition (pooled across sites) in fyke netting surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar. *Note*: 5,288 brook silversides captured in a single fyke net at site #4 in 2017 were excluded from the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

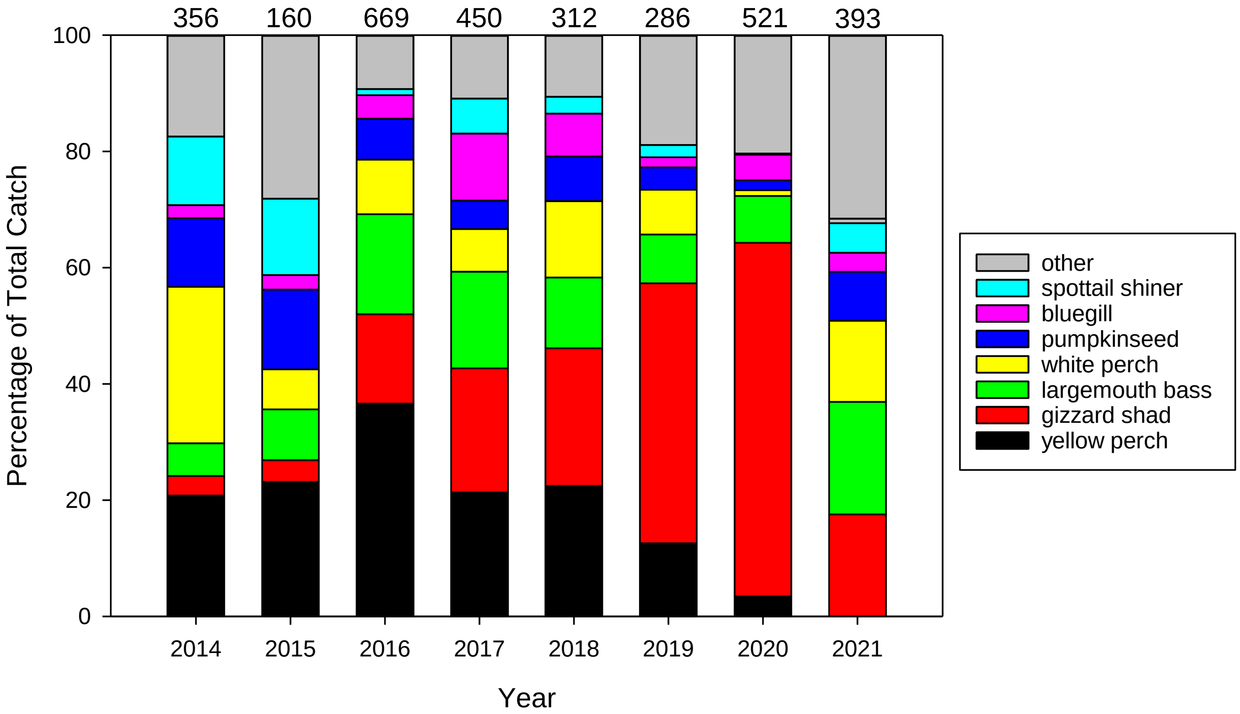

Figure 8. Fish species composition (pooled across sites) in nighttime boat electrofishing surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar.

Appendix B. Slag Filter BMP Report

Slag Filter BMP Preliminary Performance in the Macatawa Watershed, Monitoring Year 2

Prepared for:

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1. Overview

Excess phosphorus is resulting in the eutrophication of water bodies throughout the world (Paerl et al., 2016), often resulting in harmful algal blooms in both freshwater and marine systems (Boesch, 2019; Wurtsbaugh et al., 2019). Agricultural runoff is one of the main sources of excess nutrient loading to aquatic systems (Carpenter et al., 1998; Mrdjen et al., 2018); controlling this runoff, through either structural or non-structural Best Management Practices (BMPs), is the conventional means to reduce eutrophication. Implementing and enforcing regulatory measures is far less common, although litigation to enforce numeric nutrient standards is known to occur (Fumero and Rizzardi, 2000).

Lake Macatawa and its watershed suffer from excess phosphorus (P) (Walterhouse, 1999). The TMDL (total maximum daily load) for the lake calls for a P reduction of 55,000 lb/yr from the estimated load of 138,500 lb/yr), with the majority of that load reduction coming from nonpoint sources (Walterhouse, 1999). If fully implemented, the model results indicate that the water column total phosphorus (TP) concentration will be reduced to 50 µg/L, thereby meeting the TMDL goal.

It is well established that land use, and especially hydrologic connectivity in the watershed, plays a major role in nutrient loading to lakes (Soranno et al., 2015). Previous research has demonstrated that agriculture is a major source of nonpoint P in the Macatawa watershed (Steinman et al., 2018; Iavorivska et al., 2021). Although overland flow is generally considered the major transport mechanism for P, there are situations when significant P transport occurs through agricultural tile drainage (King et al., 2015; Michaud et al., 2019), which provides direct input to surface drains via outfalls. It is currently uncertain how much P enters Lake Macatawa from surface runoff vs. subsurface runoff, but very high concentrations of both TP and bioavailable P were measured in tile drain effluent from agricultural fields in the watershed (Clement and Steinman, 2017). Similar findings have been reported for agricultural areas in other parts of the Midwest, including central Ohio (Mrdjen et al., 2018) and the western basin of Lake Erie (Calhoun et al., 2002; Smith et al., 2015), which in both cases led to harmful algal blooms (Michalak et al., 2013; Wynne and Stumpf, 2015; Mrdjen et al., 2018).

Various BMPs have been implemented in the Macatawa watershed to reduce P loading, including among others, grassed waterways, cover crop plantings, gypsum application, two-stage ditches, and wetland restoration, although their effectiveness has been questioned (Steinman et al., 2018; Kindervater and Steinman, 2019). Iron slag, a waste product from the steel industry, can chemically bind P and has been implemented previously in agricultural settings (Hua et al., 2016; Roychand et al., 2020). Interest was expressed as to whether iron slag filters may be an effective management practice in the Macatawa watershed. To that end, various public and private entities involved in Project Clarity (https://outdoordiscovery.org/project-clarity/) committed to install a series of iron slag filters at the end of agricultural tile lines in the watershed. Our goal has been to evaluate the efficiency of these systems in removing P, while also monitoring for the presence of potentially toxic chemicals leaching from the iron slag, which may be released into surface waterways. Although these filters have been installed in Ohio, to our knowledge, this is their first usage in Michigan.

2. Materials and Methods

2.1 Study Area

The Macatawa watershed (464 km^2) is located in Ottawa and Allegan Counties (MI) and drains into Lake Macatawa (Figure 1). Land use is dominated by agriculture (46%) and developed (33%), which has 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. Lake surface area is 7.2 km^2. This drowned river mouth lake is relatively shallow, with an average depth of 3.6 m and a maximum depth of 12 m in the western basin. The Macatawa River, the main tributary to the lake, flows into the lake's shallow eastern basin. A navigation channel at the western end of the lake connects Lake Macatawa with Lake Michigan.

This 2021 report builds upon previous pre- and post-installation monitoring in 2019-2020. Water quality monitoring continued at three existing iron slag filter sites (Behind Mill 1 and Oak Grove 2 constructed in April 2019; Fillmore Flex constructed in September 2019) and new sampling began at one freshly installed iron slag filter (Joe's House, constructed in April 2021). Due to the COVID-19 pandemic, sampling was halted for several months in spring 2020 due to the state of Michigan's "stay-at-home" executive order. Sampling resumed once the order was lifted. Additional sites in the watershed were sampled for consideration for slag filter installation; however, we present data in this report only for the completed slag filters.

Filters are designed to work passively, receiving water after it infiltrates through soils into subsurface tiled drains (Figure 2). Water moves up and through the iron slag in large concrete tank(s), where the iron slag binds with and removes the P from the water before the water passively releases to adjacent surface waterways (Figures 2, 3). A layer of calcium carbonate particulate was applied within the treatment tank on top of the iron slag to help balance tile drain water pH. A control box allows for the slag filter to be bypassed if too much water is moving through the tile drains (indicated by standing water on the farm field), and serves as the inflow access point for water collection for most sites. Outflow water can be sampled either from the outflow pipe or via access points in the top of the tank with a hose and hand pump (see below).

2.2 Field and Laboratory Processes

Prior to installation, grab samples were taken monthly at the outflow pipe, which at that time was a direct open connection from the tile drain pipes to adjacent surface waters. Pre-installation sampling dates are provided in Table 1. Post-installation samples were collected bimonthly; sampling approaches varied among sites due to differences in filter design and implementation (Figure 4). Post-installation sampling occurred at the inflow using a hand pump and hose to siphon water accessed through an inflow pipe at Behind Mill 1 (Figure 4A) and through a control box at Oak Grove 2, Fillmore Flex, and Joe's House (Figures 1, 4B). Outflow was sampled at the original outflow pipe (Figure 4E; which remained after installation) for all sites; however, when the outflow pipe was inaccessible due to being underwater (the surface drains are very flashy and water levels can rise quickly after a rain event [Steinman et al., 2018], submerging the outflow pipes), samples were taken via one of the access points on top of the tank using a hand pump and hose without disturbing the calcium carbonate top layer (Figures 4C, D).

General water quality was monitored with a YSI 6600 data sonde (temperature, dissolved oxygen [DO], pH, specific conductivity [SpCond], total dissolved solids [TDS], redox potential [ORP], and turbidity). Grab samples were collected for analysis of TP and soluble reactive P (SRP). All samples were placed in a cooler on ice and brought back to the lab, usually within 4 hours, where they were stored and processed appropriately. Water for SRP analyses was syringe-filtered through 0.45-µm membrane filters into scintillation vials and refrigerated until analysis. TP and SRP were analyzed on a SEAL AQ2 discrete automated analyzer (U.S. EPA, 1993). Any values below detection were calculated as ½ the detection limit.

2.3 Metals and PAHs

Chemical analysis sampling for metals (mercury, arsenic, barium, cadmium, chromium, cobalt, copper, lead, molybdenum, nickel, selenium, silver and zinc), low-level mercury, Polycyclic Aromatic Hydrocarbons ([PAHs] 2-Methylonaphthalene, Acenaphthene, Acenaphthylene, Anthracene, Benzo (a) anthracene, Benzo (a) pyrene, Benzo (b) fluoranthene, Benzo (g,h,i) perylene, Benzo (k) fluoranthene, Chrysene, Dibenz (a,h) anthracene, Fluoranthene, Fluorene, Indeno (1,2,3-cd) pyrene, Naphthalene, Phenanthrene, and Pyrene) and available cyanide was conducted 1-week post-installation and then every 6-months post-installation, for up to 2.5 years post-installation as of this reporting year. Analyses were conducted at TRACE Analytical Laboratories, Inc. (Muskegon, MI) using Standard Methods (US EPA, 1993). Any values below analytical detection methods were calculated as ½ their detection limits. Reporting detection limits for chromium improved (i.e., became better at detecting smaller concentrations) between pre-construction and 1-week post-construction sampling at Behind Mill 1 and Oak Grove 2 sites, changing the limit from <0.050 mg/L to <0.0050 mg/L.

2.4 *Data Analysis*

The water residence time in the reservoir depends on the rate at which the water enters the slag filter, determined by rain, irrigation, and the control box. This means that water during baseflow conditions can spend much longer in the reservoir than water during stormflow conditions, especially in dry summer months. Therefore, for statistical purposes, the inflow and outflow values were paired for each sampling event rather than using grand means. SRP, TP, and turbidity samples were analyzed using either paired t-tests or Wilcoxon signed rank tests, depending on normality. Normality assumptions were tested using Shapiro-Wilk tests. Significance was set at $\alpha = 0.05$. Data analysis was conducted using SigmaPlot (v14.0). Percent reductions were calculated for the paired mean inflow and mean outflow measurements post-installation for SRP and TP by calculating the difference between each nutrient's respective mean inflow and mean outflow concentrations, dividing that number by the mean inflow concentration, and multiplying it by 100. Negative percent reduction values indicated an increase in P concentration.

3. Results

3.1 Water Quality Sampling

Sampling events in 2021 occurred with similar frequency and seasonality at Behind Mill 1, Oak Grove 2, and Fillmore Flex. Across all sites, mean water temperatures increased ~0.5-2 °C from inflow to outflow (Table 1). Mean DO correspondingly decreased at each site between flow sampling locations and the lowest mean DO of 4.7 (±1.9) mg/L was measured at Joe's House (Table 1). Mean inflow pH was generally circumneutral at all sites and mean outflow was higher than inflow (i.e., more basic; Table 1). Behind Mill 1 outflow pH (mean 9.82±0.79) was consistently higher than corresponding inflows (mean 7.26±0.61) throughout the year (Table 1) and reached a maximum of 11.3 in June 2021. Mean SpCond ranged 613-1083 µS/cm among sites and flows, with Fillmore Flex being the lowest and Oak Grove 2 being the highest, although variability among all sites overlapped (Table 1). Mean ORP was steady between flows at each site (Table 1). Mean turbidity decreased at each site's outflow and never exceeded <29 NTU regardless of whether it was inflow or outflow (Table 1).

Iron slag filters continued to result in reduced P concentrations in 2021. At the older three sites (Behind Mill 1, Oak Grove 2, Fillmore Flex), mean TP inflow ranged 332-750 µg/L and outflows were reduced by 97.5%, 35.8%, and 35.3% respectively; all reductions were statistically significant ($P<0.05$; Table 2). Differences in mean SRP were more variable between sites with Behind Mill1 showing a strong ($P<0.001$) 98.7% reduction, while Oak Grove 2 and Fillmore Flex had similar SRP concentrations in the inflows and outflows (Table 2). Mean turbidity followed the same trends as TP and showed large reductions in the outflow (60%-84%; $P<0.05$; Table 2).

The newly installed iron slag filter at Joe's House experienced very low flow volumes throughout the year and there were only two instances through the year when we had usable paired inflow-outflow data. Given the limited number of observations, statistical results should be interpreted cautiously. That stated, mean TP at Joe's House mean inflow (868 µg/L) was much higher than the mean outflow (150 µg/L), showing 82.7% reduction in TP and the paired t-test indicated this difference was statistically significant ($P=0.029$; Table 2). Both mean SRP and turbidity declined in the outflow at this site, but the differences were not statistically significant due to limited statistical power and high variance (Table 2).

3.2 Metals and PAHs

New 2021 sampling events for metals and PAHs were conducted at 1.5, 2, and 2.5 years post-installation at Behind Mill 1 and Oak Grove 2; at 1, 1.5, and 2 years post-installation at Fillmore Flex; and at 6 months post-installation at Joe's House. Pre-installation and 1-week post-installation metals sampling did not occur at Joe's House. All metals, PAH compounds, and available cyanide were below U.S. Environmental Protection Agency (EPA; source: https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals) and World Health Organization (WHO; source: https://www.wqa.org/learn-about-water/common-contaminants) standards for drinking water. Recreational water standards are unavailable.

Mercury was below 14 ng/L at all sites, maintaining the trend from previous reporting years of concentrations being two orders of magnitude below EPA (2,000 ng/L) and WHO (6,000 ng/L) drinking water standards (Figure 5A). Behind Mill 1 concentrations consistently decreased from its 6-month post-installation peak and ended the monitoring year with concentrations lower than pre-installation. Oak Grove 2 and Fillmore Flex remained steady across both sampling years, although Fillmore Flex was generally higher and showed more variation in mercury concentrations. Joe's House 6-month measurement was the lowest value among all the sites for that given post-installation time period.

Arsenic was below detection at all sites in 2021 (Figure 5B). Barium at Behind Mill 1 in 2021 was consistently below detection, while other sites were more variable and had ranges similar to those seen during 2020 sampling (Figure 5C). Chromium was consistently below detection at all sites except for Fillmore Flex at 1-year post-installation, yet it remained one order of magnitude below drinking water guidelines (Figure 5D). Copper was measured at all sites and in slightly increased concentrations compared to last year with 2-years and 2.5-years post-installation measurements higher than pre-installation (Figure 5E). Zinc was found at all sites in 2021. Behind Mill 1, which had been consistently below detection in 2020, was the highest of all sites with 0.77 mg/L at 2-years post-installation (Figure 5F).

Cadmium, cobalt , lead, molybdenum, nickel, selenium, silver, Naphthalene, 2-Methylnaphthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benzo (a) anthracene, Chrysene, Benzo (b) fluoranthene, Benzo (k) fluoranthene, Benzo (a) pyrene, Indeno (1,2,3-cd) pyrene, Dibenz (a,h) anthracene, Benzo (g,h,i) perylene, Nitrobenzene-d5, 2-Fluorobiphenyl, and Terphenyl-d14, were all below detection limits for all sites and sampling dates (data not shown).

4. Summary

The iron slag filters assessed as part of this study have shown that after one year of performance, they are effective at removing P from tile drain effluent. We observed considerable variation in the percent reduction among the 3 sites, indicating the importance of site selection and environmental context in their P reduction effectiveness, which is consistent with findings from other studies (Penn et al., 2017; Hauda et al., 2020). Although both the percent and absolute reductions in P were substantial, they were still well above the 50 µg/L TMDL goal. Encouragingly, there was no indication that the iron slag is releasing toxic metals, PAH compounds, or cyanide at levels that would cause concerns for drinking water standards.

To maximize performance effectiveness, we recommend that the installation of iron slag filters should be targeted to areas where tile drain effluent SRP levels exceed 250 µg/L. Continued monitoring will determine how long they remain effective at reducing P. While they are not a panacea, when installed in combination with other BMPs, iron slag filters can play an important localized role in reducing P in watersheds that are underlain with tile drains.

Table 1. Mean (1 standard deviation [SD]) values of selected water quality parameters for tile drain in/outflow iron slag pre- and post-installation monitoring. Data are shaded to improve readability. Dates of sampling range is provided below each Pre/Post. Data are shaded to improve readability. n= number of successful sampling events per site, N/A = not applicable, ND = no data, parameter abbreviations in main text.

Site	Pre/Post	Outflow/ Inflow	n	Temp. (°C)	DO (mg/L)	pH	SpCond (µS/cm)	TDS (g/L)	ORP (mV)	Turbidity (NTU)
Behind Mill 1	Pre (9/20/2018 to 4/16/2019)	N/A	8	8.6 (5.5)	10.9 (2.0)	7.9 (0.5)	872 (130)	0.567 (0.085)	253.2 (103.0)	7.9 (16.8)
	Post (11/5/2020 to 10/20/2021)	Inflow	16	14.2 (6.1)	6.2 (2.7)	7.3 (0.6)	799 (319)	0.519 (0.208)	338.3 (127.9)	29.0 (44.8)
		Outflow	18	14.8 (5.6)	6.1 (2.4)	9.8 (0.8)	706 (127)	0.459 (0.083)	264.9 (149.4)	6.8 (14.9)
Oak Grove 2	Pre (9/20/2018 to 3/19/2019)	N/A	7	9.1 (7.2)	11.3 (2.6)	8.2 (0.3)	676 (132)	0.439 (0.086)	284.3 (72.6)	0.0 (5.4)
	Post (11/5/2020 to 10/20/2021)	Inflow	15	13.4 (5.9)	8.7 (2.9)	7.6 (0.8)	1074 (422)	0.698 (0.274)	310.3 (142.4)	19.0 (18.9)
		Outflow	18	15.2 (6.7)	7.6 (3.2)	8.1 (0.6)	1083 (531)	0.704 (0.345)	279.7 (140.5)	2.6 (3.6)
Fillmore Flex	Pre (3/26/2019 to 8/28/2019)	N/A	9	13.9 (5.7)	7.9 (1.6)	7.7 (1.8)	894 (1187)	0.581 (0.772)	221 (113.5)	20.0 (45.3)
	Post (11/5/2020 to 10/20/2021)	Inflow	13	14.4 (6.2)	8.0 (2.5)	7.1 (0.6)	765 (478)	0.497 (0.311)	286.9 (139.1)	12.1 (10.2)
		Outflow	17	16.2 (6.4)	7.2 (2.4)	8.1 (1.0)	613 (139)	0.398 (0.09)	273.1 (140.4)	3.3 (3.7)
Joe's House	Pre (1/16/2020 to 3/10/2020)	N/A	ND	ND	ND	ND	ND	ND	ND	ND
	Post (5/12/2021 to 10/20/2021)	Inflow	2	17.4 (5.2)	7.8 (3.5)	6.7 (0.6)	760 (274)	0.494 (0.178)	181.2 (333.4)	12.9 (8.5)
		Outflow	10	19.4 (2.9)	4.7 (1.9)	7.7 (0.7)	965 (834)	0.627 (0.542)	183.3 (151.1)	2.3 (1.3)

Table 2. Mean water quality parameters (1 standard deviation [SD]) for paired inflow and outflow at each site for TP, SRP and Turbidity. Data are shaded to improve readability. n= number of successful sampling events per site. α = 0.05. N/A = not applicable. Note that negative reduction % values indicate an increasing change from inflow to outflow.

Site	Analysis	n	Mean Inflow		Mean Outflow	Reduction (%)	Stats
Behind Mill 1	Pre-installation	8	TP = 167 (161) SRP = 135 (131)			N/A	N/A
	TP (µg/L)	17	750 (485)	>	19 (21)	97.5	**P < 0.001**
	SRP (µg/L)	17	478 (341)	>	6 (10)	98.7	**P < 0.001**
	Turbidity (NTU)	16	29 (45)	>	8 (16)	72.4	**P = 0.018**
Oak Grove 2	Pre-installation	7	TP = 254 (328) SRP = 229 (328)			N/A	N/A
	TP (µg/L)	14	332 (322)	>	213 (209)	35.8	**P = 0.042**
	SRP (µg/L)	14	111 (103)	≈	114 (48)	-2.7	P = 0.464
	Turbidity (NTU)	15	19 (19)	>	3 (3)	84.2	**P < 0.001**
Fillmore Flex	Pre-installation	9	TP = 721 (699) SRP = 267 (201)			N/A	N/A
	TP (µg/L)	12	702 (368)	>	454 (218)	35.3	**P = 0.045**
	SRP (µg/L)	12	338 (136)	≈	308 (124)	8.9	P = 0.544
	Turbidity (NTU)	11	10 (5)	>	4 (4)	60.0	**P = 0.017**
Joe's House	Pre-installation	5	TP = 261 (52) SRP = 216 (43)			N/A	N/A
	TP (µg/L)	2	868 (48)	>	150 (94)	82.7	**P = 0.029**
	SRP (µg/L)	2	194 (121)	≈	56 (21)	71.1	P = 0.303
	Turbidity (NTU)	2	13 (8)	≈	1 (1)	92.3	P = 0.312

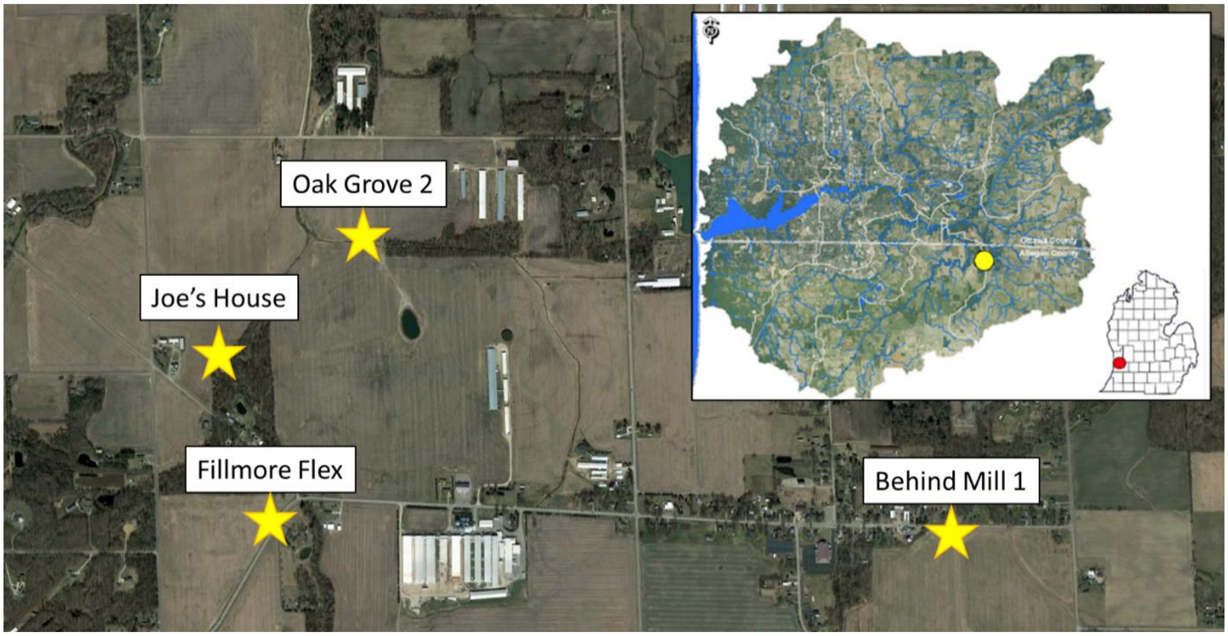

Figure 1. Completed iron slag filter sites are indicated by yellow stars, each draining approximately 30 acres. Fillmore Flex, Joe’s House, and Oak Grove 2 sites flow into the south branch of the Macatawa River, which later joins the main branch of the Macatawa River. Behind Mill 1 flows into Peter’s Creek. Insert: location of sites within the Macatawa watershed (yellow circle) and location within the lower peninsula of Michigan (red circle).

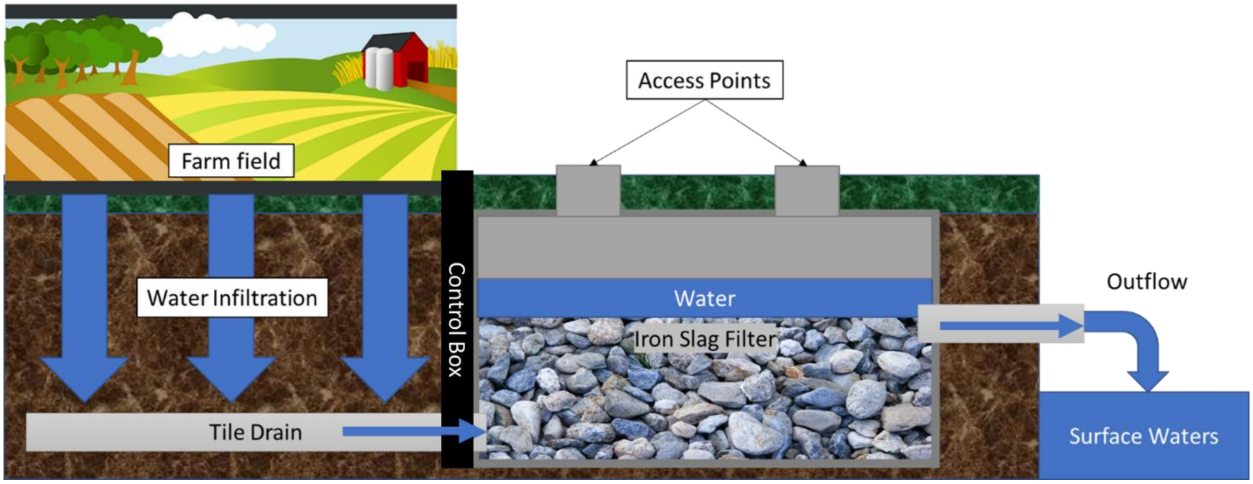

Figure 2. Stylized cross-section of iron slag filters design/function. Figure is not to scale as iron slag filter size is dependent on multiple factors (e.g. size of the tiled field, water velocity from the tile drains, soil type). See text for more detail on how the filters function. Image credit: Maggie Oudsema.

Figure 3. Inlet pipes being laid in the bottom of an iron slag filter. Drainage water enters at the bottom, moves up through the iron slag material (not yet installed) and leaves out a pipe near the top (not pictured) that leads to a nearby surface drain (not pictured). Photo credit: Macatawa Area Coordinating Council.

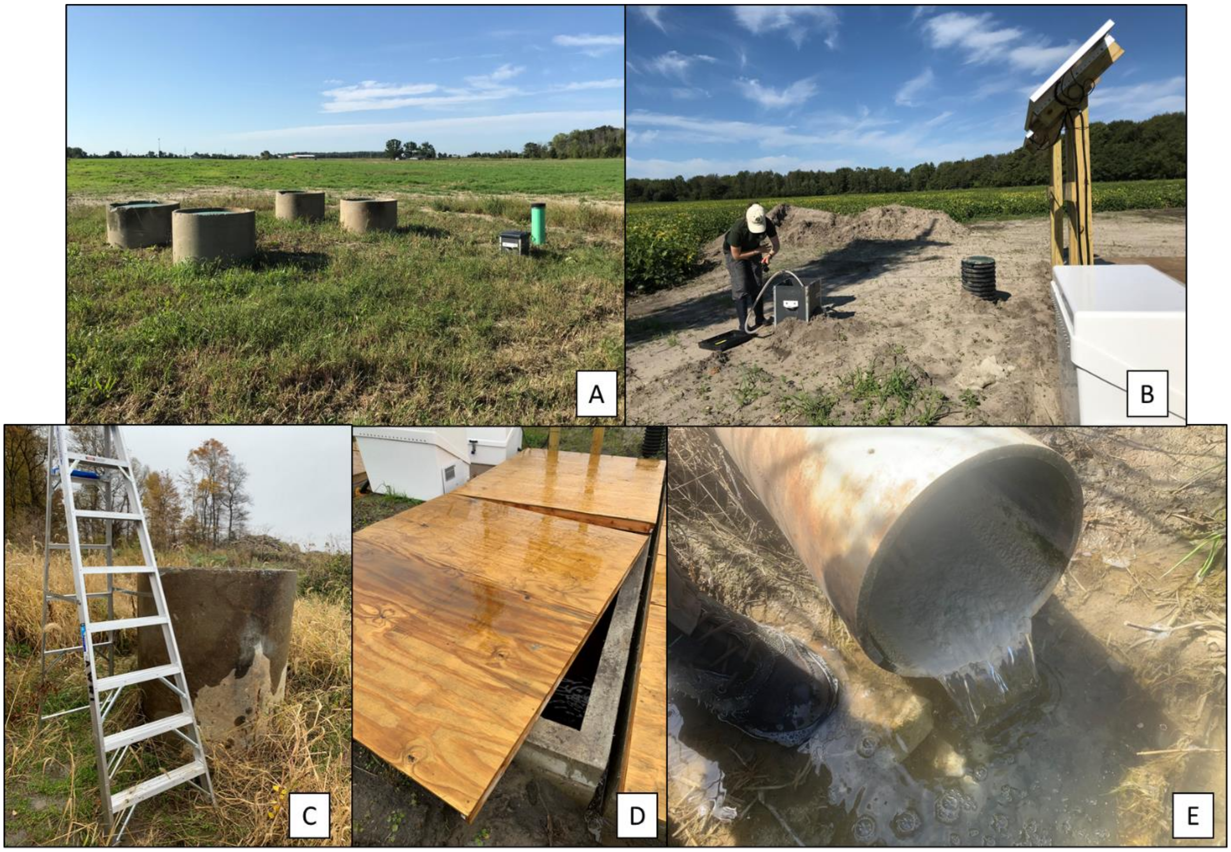

Figure 4. Photos of different sampling locations. A) Behind Mill 1 with completed iron slag filters in place. The green tube (far right) is an inflow sampling port that was installed only at this location. Access ports (for cement upright tubes) are for two slag filter basins (considered to be one slag filter site) that receive tile drain water from the adjoining field (in background) and are used to sample outflow. B) Sampling via a hand pump siphon to sample from a below-ground control box (inflow) at Fillmore Flex; Oak Grove 2 has a similar constructed inflow access (not shown). C) Slag filter outflow access point for Oak Grove 2, which required a ladder to remove the large plastic cap to sample outflow water. D) Slag filter outflow access point at Fillmore Flex, which is covered with large plywood lids. E) Outflow pipe at Behind Mill 1 directly after installation; the white particulate residue inside the tube is from the calcium carbonate layer placed on top of the iron slag inside the tanks to balance pH. Photo credit: Maggie Oudsema.

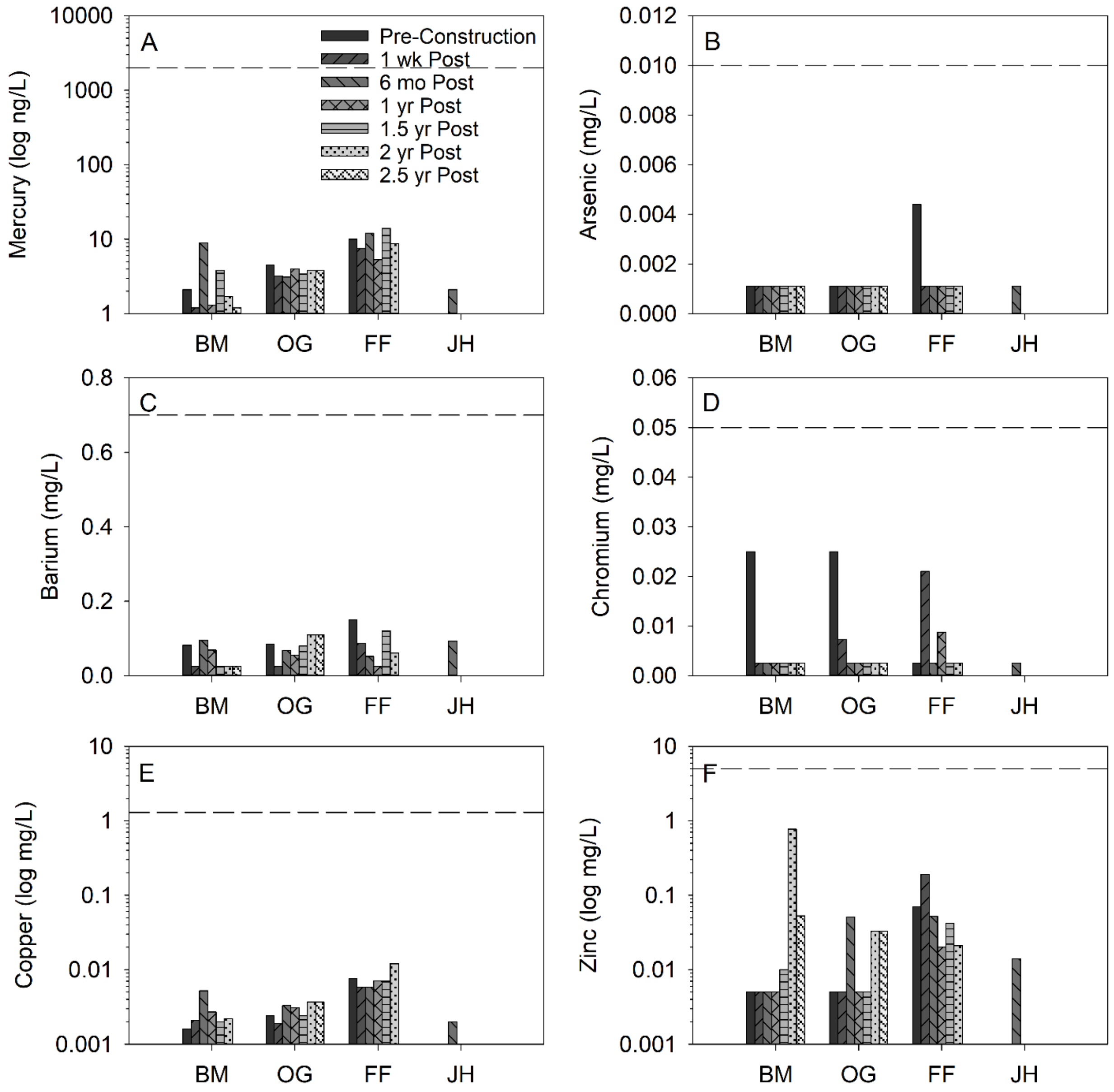

Figure 5. Metals for pre-installation, 1-week, every 6-months following post-installation at Behind Mill 1 (BM), Oak Grove 2 (OG), and Fillmore Flex (FF), and Joe's House (JH). The black dashed line represents the drinking water standard from either the EPA or WHO, which ever was the smaller of the two standards for the given analyte. The legend in panel A applies to panels B-F. Note that y-axes for panels A, E, and F have logarithmic scales.

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Appendix C. Lake Macatawa Dashboard

Lake Macatawa Water Quality Dashboard

2021

Prepared: February 2022

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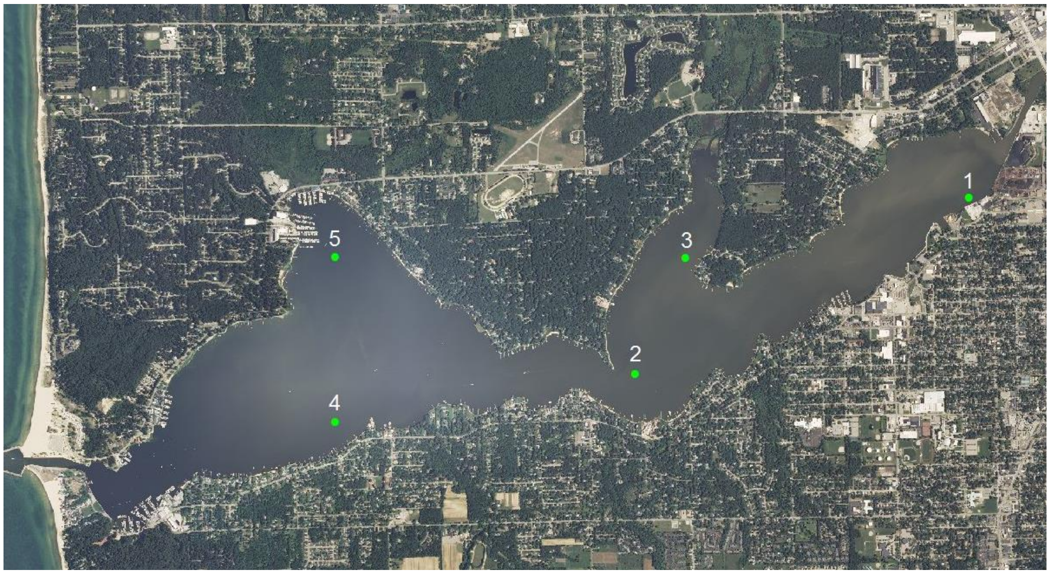
Introduction

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.

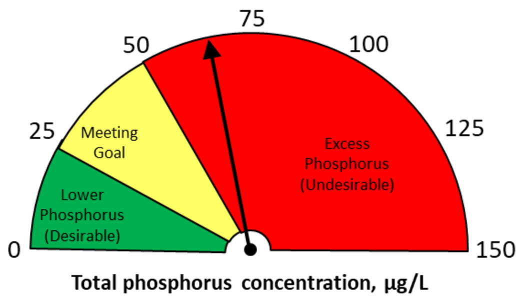
Historical data are included in the dashboard to facilitate comparison of current findings with past status of the selected water quality indicators. Sources for historical data include U.S. EPA (1972; STORET), Michigan Department of Environment, Great Lakes, and Energy (formerly MDEQ; 1982-2012; S. 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).



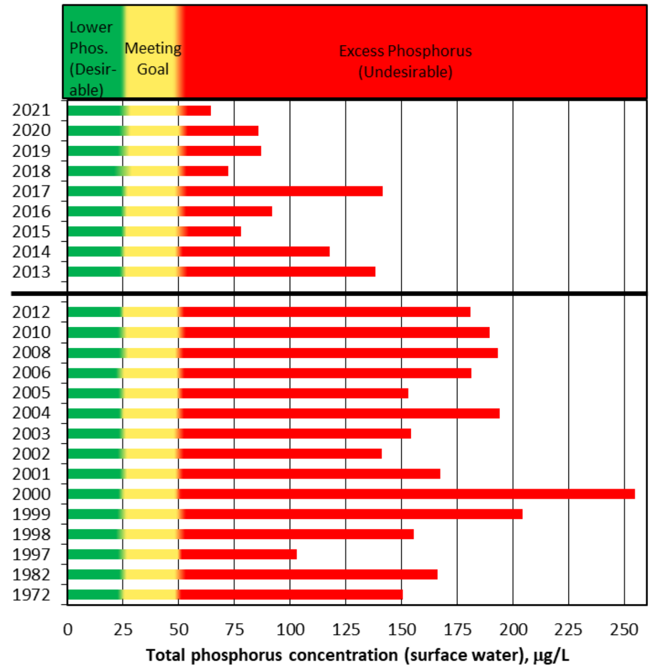
Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring. Dashboard indicators were calculated based on data from Sites 1, 2, and 4.

Total Phosphorus (surface)

2021 Mean Concentration: 64 µg/L
Target Concentration: 50 µg/L



Current status (2021)



Historical Status (1972*; 1982-2012†; 2013-2021‡)

*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).

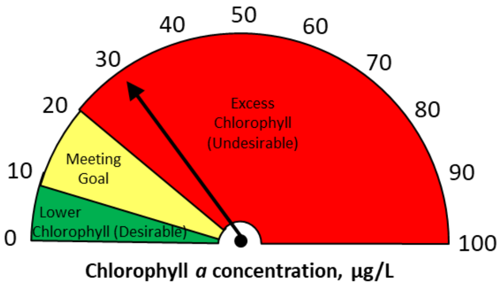
Lake Macatawa has a history of extremely high TP concentrations (i.e., > 100 µg/L), placing it in the past in the "hypereutrophic" trophic state. As a result of this nutrient enrichment, the State of Michigan established an interim target TP concentration of 50 µg/L in Lake Macatawa. Thus, the TP dashboard 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**, meaning that the average TP concentration in 2021 exceeded the water quality goal. Although the average TP concentration in recent years remains greater than the target of 50 µg/L, 2021 continues a decreasing trend in recent years and was the lowest TP average since the start of Project Clarity.

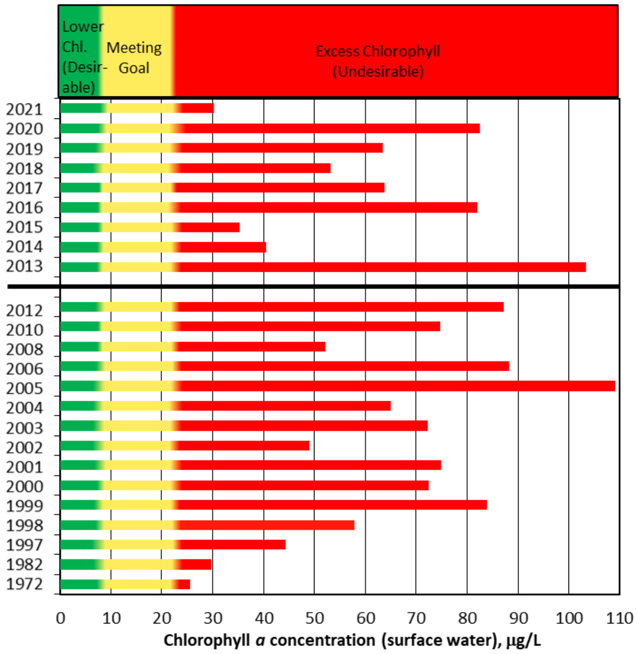
Chlorophyll *a*

2021 Mean Concentration: 30 µg/L
Target Concentration: 22 µg/L

Current status (2021)



Historical Status (1972*; 1982-2012†; 2013-2021‡)



*U.S. EPA; †EGLE; ‡AWRI

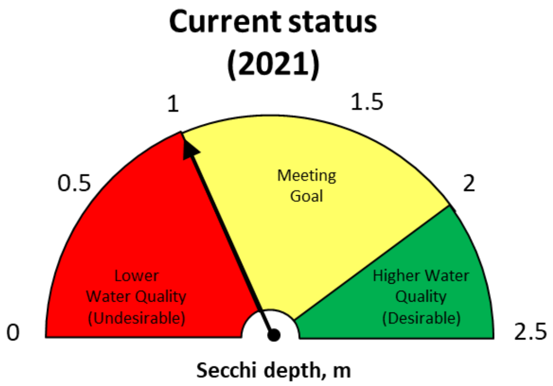
Chlorophyll *a* is the green pigment found in photosynthetic plants and algae. Measuring chlorophyll *a* is a relatively simple way to estimate the amount of algal biomass present in lake water, although it has some limitations. First, chlorophyll *a* does not provide information on whether or not the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

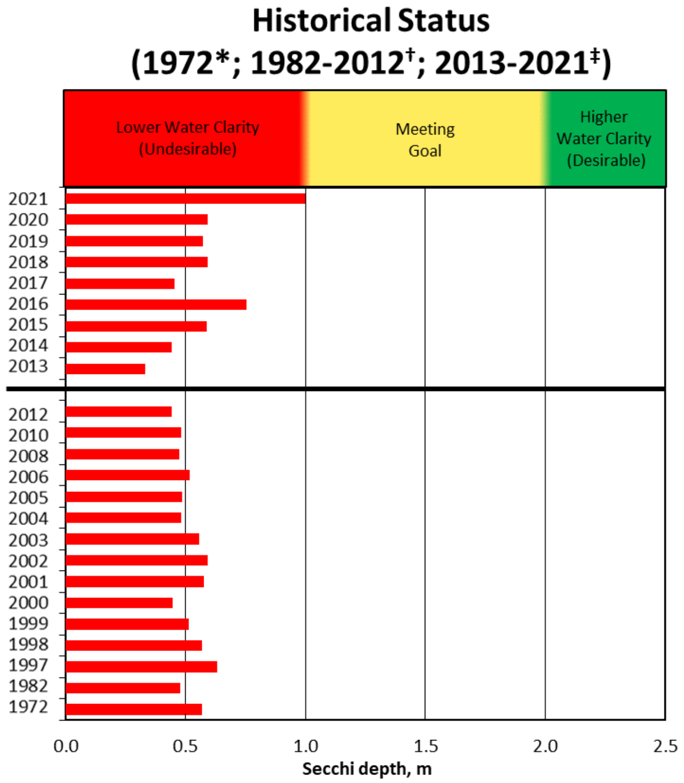
Lake Macatawa has a history of excess algal biomass and high chlorophyll *a* concentrations, typically exceeding the “hypereutrophic” threshold commonly used by EGLE (22 µg/L) in its assessments of the lake. The chlorophyll *a* dashboard shows that the concentration will meet the water quality goal once 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.

Although the current status for the chlorophyll *a* indicator is **Undesirable**, 2021 showed a major decrease in mean chlorophyll, ending a recent high concentration streak from 2016-2020.

Secchi Disk Depth (Water Clarity)

2021 Mean Depth: 1 m (~3.3 ft)
Target Depth: 1 m (~3.3 ft)





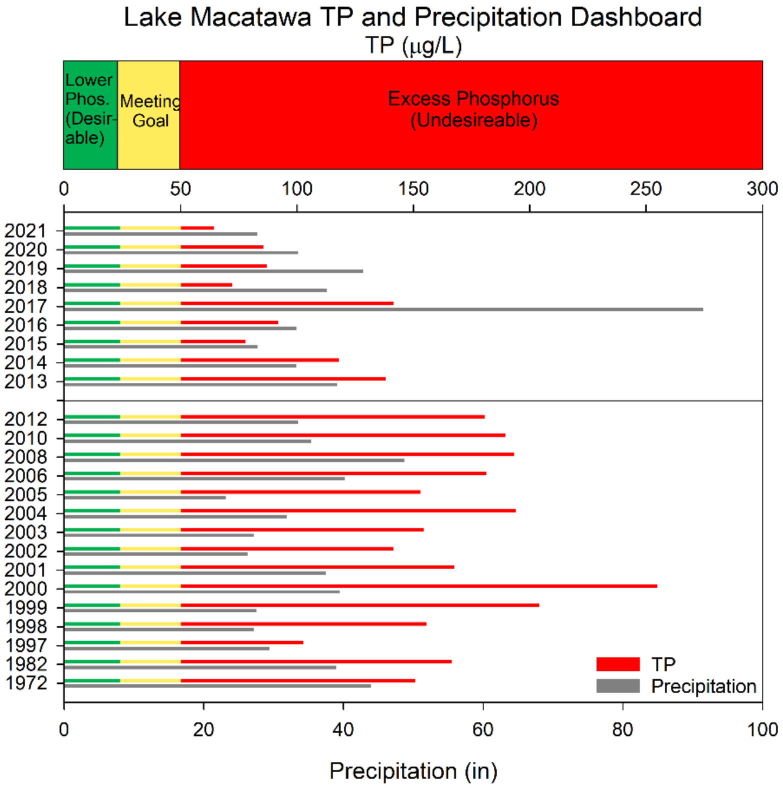
*U.S. EPA; †EGLE; ‡AWRI

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 **Meeting Goal**, meaning that the average Secchi depth in 2021 improved from recent years and currently meets the criteria of the water quality goal.

Total Phosphorus and Precipitation



Phosphorus concentrations in Lake Macatawa are influenced by many variables, but one of the most significant is precipitation because rain and snow events create runoff from farms and urban areas, when phosphorus can be transported to Lake Macatawa either in the dissolved form or as attached to sediment particles; precipitation also results in atmospheric deposition, which can contribute phosphorus directly to the lake and landscape. 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 2021, 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, the statistical relationship between the two is not significant ($R^2 = 0.008$; $p = 0.671$).

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 2013-2021, $R^2 = 0.33$; $p = 0.003$). 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.