PROJECT CLARITY
2018 Annual Monitoring Report
(Dec. 2017 – Nov. 2018)

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Michael Hassett
Maggie Oudsema
Alan Steinman, Ph.D.

Annis Water Resources Institute
Grand Valley State University
Muskegon, MI 49441

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 make it one of the most hypereutrophic 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 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 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). In recent years, monthly average TP concentrations were greater than 125 µg/L, and at times exceeded 200 µg/L (Holden 2014). Thus, meeting the TMDL target represents a major challenge in the Macatawa watershed. The TMDL estimated that a 72% reduction in phosphorus loads from the watershed would be required to meet the TP concentration target (Walterhouse 1999). Though remediation projects and BMPs 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) at Grand Valley State University, in cooperation with the Outdoor Discovery Center Macatawa Greenway (hereafter, ODC), the Macatawa Area Coordinating Council, and Niswander Environmental, has initiated a long-term monitoring program in the Lake Macatawa watershed. 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 2018, in combination with data reported previously from 2013-2017.

Although it will likely take many years before the benefits of restoration actions in the watershed are expressed in the lake, these initial results help establish the baseline conditions against which we can assess future changes, similar to what is being done in Muskegon Lake (cf. Steinman et al. 2008; Bhagat and Ruetz 2011; Ogdahl and Steinman 2015). We also include Appendix A, focused on fish monitoring in Lake Macatawa conducted by the Ruetz lab at AWRI, and Appendix B, the Lake Macatawa dashboard.

2. Methods

2.1 Overall site description

The Macatawa watershed (464 km^2 /114,000 acres) is located in Ottawa and Allegan Counties and 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. AWRI's monitoring initiative is focused on 1) two key wetland restoration areas in the Macatawa watershed (Figs. 1, 2) and 2) Lake Macatawa (Fig. 3). Details on these two efforts are provided below.

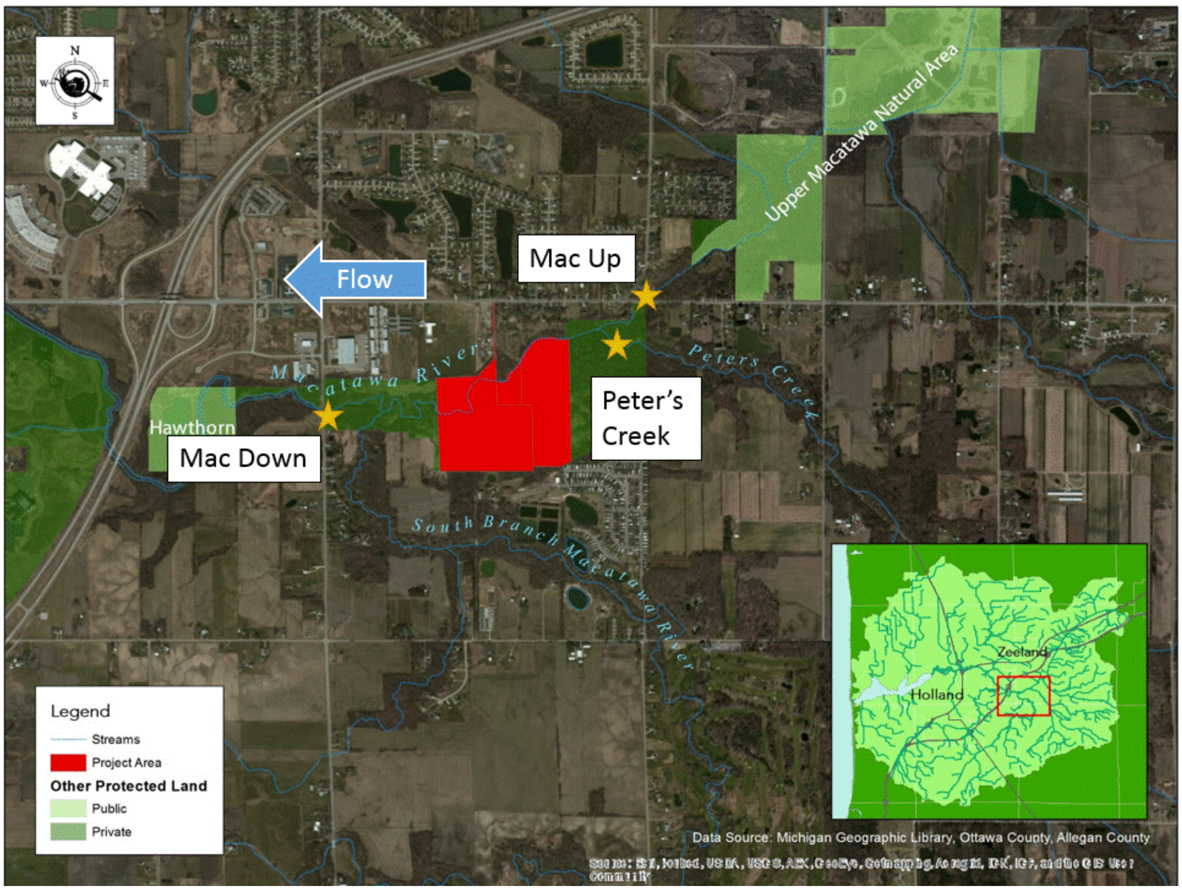

Figure 1. The Middle Macatawa wetland restoration study area, map provided by ODC. Sampling locations (n = 3), located on Peter's Creek and the Macatawa River, are indicated with gold stars. Insert shows were the property is located (red rectangle) within the Macatawa Watershed.

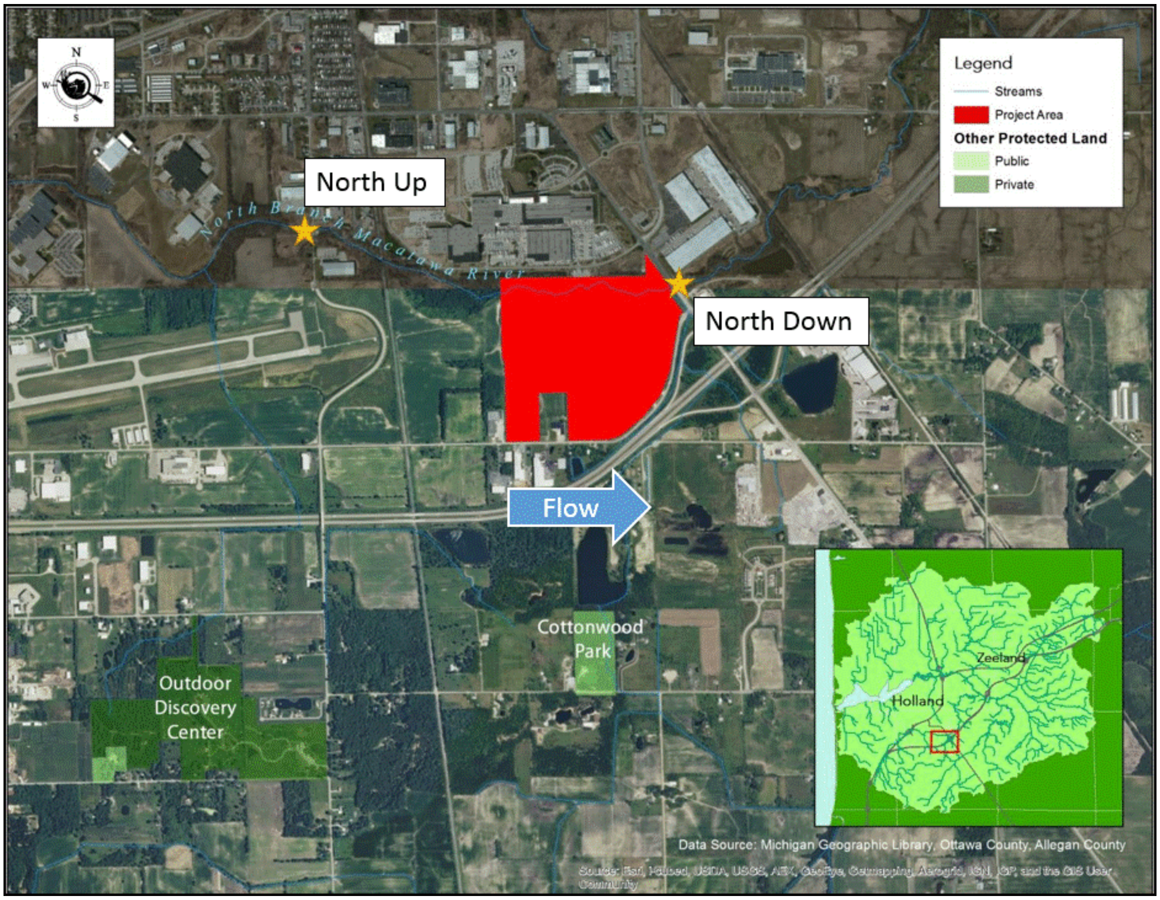

Figure 2. The Haworth wetland restoration study area, map provided by ODC. Sampling locations (n = 2), located on the North Branch of the Macatawa River, are indicated with gold stars. Insert shows were the property is located (red rectangle) within the Macatawa Watershed.

2.2 Wetland Restoration: Middle Macatawa & Haworth Properties

2.2.1 Monitoring & Data Collection

The Middle Macatawa and Haworth properties were acquired as part of Project Clarity and designated for wetland restoration. Restoration goals included slowing the flow of water in the Macatawa River and its tributaries, particularly during high flow events, thus trapping and retaining suspended sediments and nutrients. Restoration construction at Middle Macatawa and Haworth was completed in late September and early October 2015, respectively.

AWRI established monitoring sites upstream and downstream of each restoration area (Figs. 1 and 2). The Middle Macatawa study area (Fig. 1) has two upstream sites (Macatawa River [Macatawa Up] and Peter's Creek, which flow into the Macatawa River) and one downstream site (Macatawa River at the USGS gauging station [Macatawa Down]). The Haworth study area (Fig. 2) consists of monitoring locations upstream and downstream of the restoration area on the North Branch of the Macatawa River.

Water quality and hydrologic monitoring are ongoing and will continue through April 2019 (see Summary section for changes in future monitoring locations); this report includes data from December 2017 through November 2018. Sampling occurred monthly during baseflow conditions and during 2 storm events (~≥ 0.5 inches of rain proceeded by 72 hours of dry weather; Table 1). During each monitoring event, general water quality parameters (dissolved oxygen [DO], temperature, pH, specific conductivity, total dissolved solids [TDS], redox potential [ORP: oxidation-reduction potential – the degree to which a substance is capable of oxidizing or reducing another substance], and turbidity) were measured using a YSI 6600 sonde. Grab samples were collected for analysis of phosphorus (soluble reactive phosphorus [SRP], total phosphorus [TP]) and nitrogen (ammonia [NH_3], nitrate [NO_3^-], and total Kjeldahl nitrogen [TKN]) species. All water quality measurements and sample collection took place in the thalweg of the channel at permanently-established transects. Duplicate water quality samples and sonde measurements were taken every other month during baseflow conditions and all storm events. All samples were placed in a cooler on ice until received by the AWRI lab, usually within 4 hours.

Water for SRP and NO_3^- analyses was syringe-filtered through 0.45-µm membrane filters into scintillation vials; SRP was refrigerated and NO_3^- frozen until analysis. NH_3 and TKN were acidified with sulfuric acid and kept at 20°C until analysis. SRP, TP, NH_3, NO_3^-, and TKN were analyzed on a SEAL AQ2 discrete automated analyzer (U.S. EPA 1993). Any values below detection were calculated as ½ the detection limit.

Stream hydrographs were generated at each monitoring location using water level loggers and staff gauges that were installed at permanently established transects at 4 of the monitoring locations (the Macatawa Down site did not require one because we use the USGS gauge). Manual water velocity (using a Marsh McBirney Flow-mate 2000) and stage measurements were taken at each transect during each baseflow sampling event and over a range of high flow conditions to develop stage-pressure, stage-discharge, and pressure-discharge relationships. We still require additional high flow measurements at one site to complete the discharge model; weather permitting, we anticipate having enough samples to complete the model after the 2018 field season. Once calibrated, these models will be applied to the high-frequency pressure data recorded by the water level loggers to develop a stream hydrograph at each location (Chu and Steinman 2009).

Turbidity sensors (YSI 600OMS V2) were deployed at the upstream and downstream locations on the main branch of the Macatawa River in June 2018 due to a combination of late snowmelt, high flow, and coordination of sensor deployment with project partners. Due to extenuating circumstances, the turbidity sensor at Macatawa Up was relocated ~60 m downstream of the original placement to the south side of the Adams Road bridge. The sensors log turbidity measurements every 30 minutes. The turbidity sensors were removed in November 2018 to avoid possible ice damage and will be returned to their former locations before the final snowmelt in spring of 2019.

Table 1. Precipitation summary for storm events sampled by AWRI in 2018.

	2/20/2018	10/1/2018
Rainfall (in)	2.73	2.93
Duration (h)	40	38
Intensity (in/h)	0.07	0.08

2.2.2 Data Analysis

Our analysis focuses on characterizing water quality at the two restored wetlands, and identifying 1) upstream vs. downstream differences during baseflow and stormflow conditions, and 2) pre- vs. post-restoration differences in nutrients and turbidity.

Upstream vs. Downstream:

Upstream-downstream differences between site pairs (e.g., North Up vs. North Down) within 2018 at baseflow and at stormflow were statistically tested using either a two-tailed paired t-test (normally-distributed data) or Wilcoxon signed rank test (non-normally distributed data). Baseflow and storm flow conditions were evaluated separately for each site pair. A one-way analysis of variance test (ANOVA; normally distributed data) or Kruskal-Wallis test (one-way ANOVA on ranks; non-normally distributed data) was used to compare data from the three Middle Macatawa sites simultaneously. ANOVAs that detected significant differences were followed by post-hoc Tukey pairwise comparison tests. Stormflow general water quality data from the YSI 6600 was not tested in 2018 dataset due to YSI machine error during the 10/1/2018 storm event, resulting in only one remaining 2018 storm YSI 6600 data point. Precipitation and stormflow nutrient data from both the 2/20/2018 and 10/1/2018 storm events were used for reporting.

Pre- vs. Post-Restoration:

Past years of Project Clarity reporting have included statistical analysis of pre-restoration vs. post-restoration data, with minimal statistically significant differences detected overall at both wetlands. This is likely due to 1) the wetlands still being young and having suboptimal abilities to retain nutrients; and 2) high interannual variance. Due to a lack of detected effect thus far, and because we will stop sampling these sites after April 2019, tributary data in 2018 were not analyzed for pre- vs. post-restoration differences. Instead, we focused on characterizing restoration period trends as mean values.

2.3 Lake Macatawa: Long-Term Monitoring

Water quality monitoring in the lake was conducted at 5 sites during spring, summer, and fall 2018 (Table 2, Fig. 3). The sampling sites correspond with Michigan Department of Environmental Quality (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, NO_3^-, NH_3, TKN, and chl *a*. Samples also were taken for phytoplankton community composition and archived for possible future analysis.

Table 2. Location and water column depth at Lake Macatawa long-term monitoring locations.

Site	Latitude	Longitude	Depth (m)
1	42.7913	-86.1194	8.5
2	42.7788	-86.1525	5.3
3	42.7872	-86.1474	3.7
4	42.7755	-86.1822	10.2
5	42.7875	-86.1820	4.4

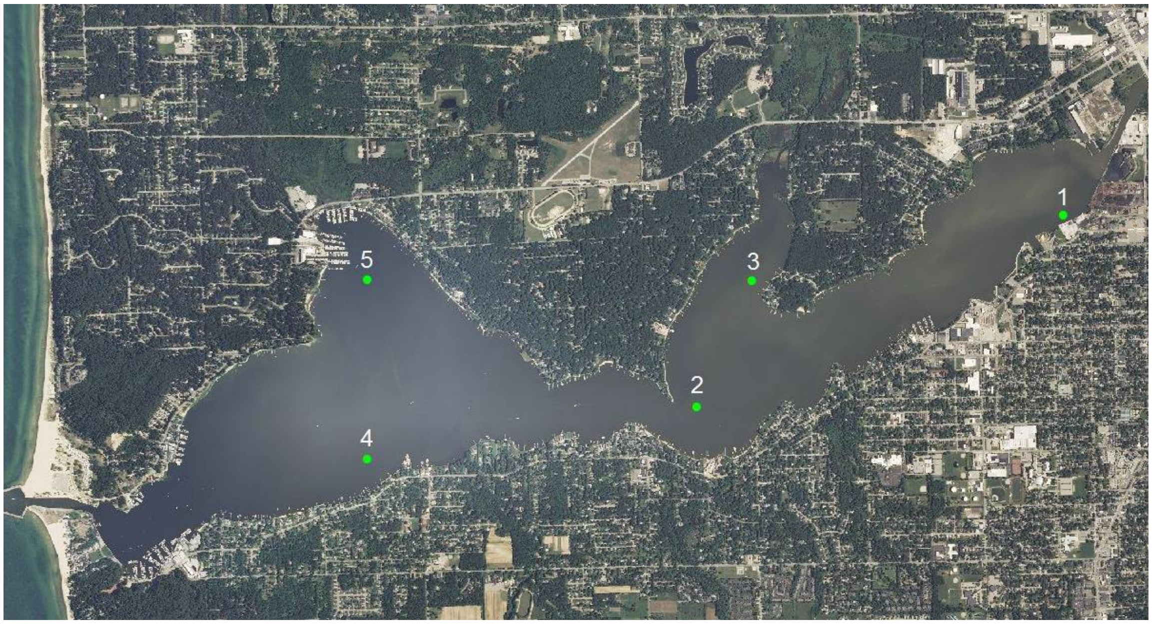

Figure 3. Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring.

Water for SRP analysis was syringe-filtered through 0.45-µm membrane filters into scintillation vials and refrigerated until analysis. SRP and TP were analyzed as previously described. Chl *a* samples were filtered through GFF filters and frozen until analysis on a Shimadzu UV-1601 spectrophotometer (APHA 1992).

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 more sensitive detection limit than the QuantiTubes that were used in 2017. Advisories for microcystin consumption have been developed by the World Health Organization (WHO) and US EPA. For drinking water, the WHO advisory is microcystin concentration >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 apply the latter two thresholds.

The Lake Macatawa fish community sampling and analysis is presented in Appendix A.

2.4 Macatawa Watershed Phosphorus – Precipitation Analysis

Phosphorus 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, as well as result in atmospheric deposition, which can contain significant amounts of phosphorus. As a consequence, it is of interest to know if changes in lake phosphorus 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 (MDEQ, and AWRI) related to precipitation depths 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 TP and precipitation amount were conducted in SigmaPlot 14.0.

2.5 Macatawa Watershed Phosphorus – Iron Slag Study

The use of large-scale iron slag filters as a means to remove phosphorus from agricultural tile drain runoff was proposed in 2018 for implementation in the Macatawa watershed. Prior to iron slag treatment tank construction, AWRI monitored general water quality with a YSI 6600 sonde and sampled for SRP and TP as described above at tile drain outlet pipes at eight proposed sites: two at Goldie West (Fig. 4), three at Oak Grove (Fig. 5), and three at Behind Mill (Figs. 6A, 6B). Water was collected during baseflow conditions only when outflow from tile drains was detected, when pipe physical integrity (i.e., no detectable cracks in outlet pipes) was intact, and when water level in drain ditches allowed for safe sampling conditions. Measurements of SRP, TP, and general water quality were collected and analyzed as described above on 9/20, 10/23, and 11/14/2018.

Figure 4. Goldie West proposed iron slag sampling sites (n=2), indicated by gold stars. Goldie West sites flow into the South Branch of the Macatawa River, which later joins the main branch of the Macatawa River between Middle Macatawa wetland upstream and downstream sampling sites near Adams Street and 96th Avenue.

Figure 5. Oak Grove proposed iron slag sampling sites (n=3), indicated by gold stars. Oak Grove sites flow into the South Branch of the Macatawa River, which later joins the main branch of the Macatawa River between Middle Macatawa wetland upstream and downstream sampling sites near Adams Street and 96th Avenue.

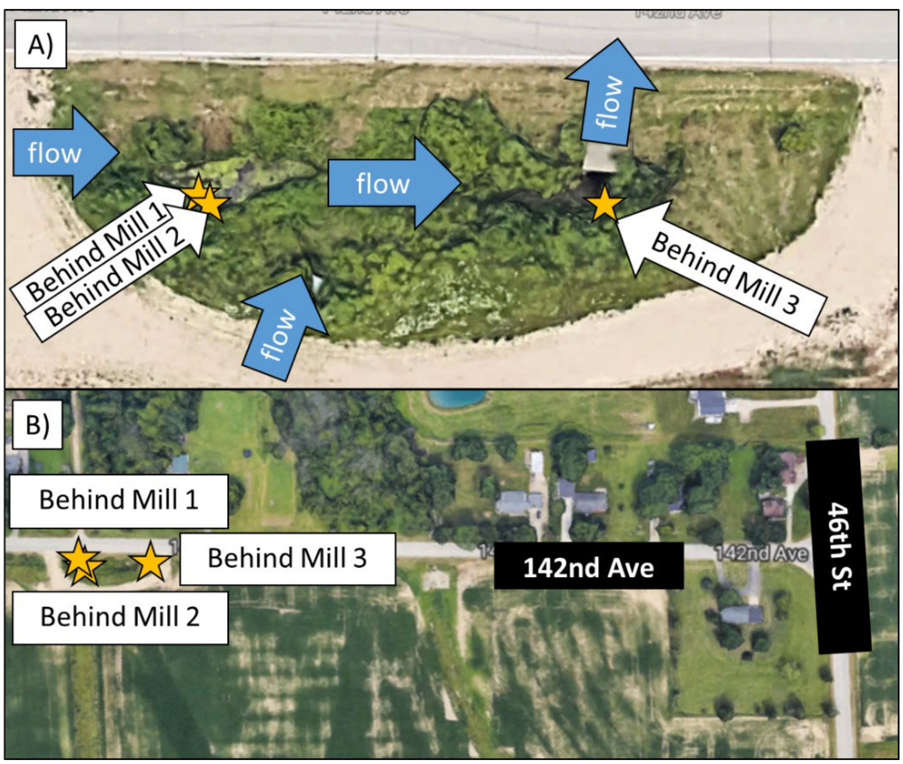

Figure 6. Behind Mill proposed iron slag sampling sites (n=3), indicated by gold stars. Behind Mill sites flow into Peter's Creek, upstream of the Middle Macatawa wetland. Panel A shows the sampling sites and flow direction, while panel B shows location of the sites relative to nearest crossroads.

3. Results and Discussion

3.1 Wetland Restoration: Middle Macatawa Property

3.1.1 Sampling Year 2018

Baseflow:

Both mean temperature (10.28-10.47°C) and DO concentrations (10.52-11.09 mg/L) were similar across the three Middle Macatawa sites in 2018 (Table 3). Mean DO concentrations remained >5 mg/L, indicative of non-impaired water quality during the 2018 sampling (Table 3). Specific conductivity, TDS, and turbidity showed more variation than other parameters among sites; conductivity exceeded 600 µS/cm at Middle Macatawa sites during every 2018 baseflow sampling event (Table 3), which generally indicates human-induced stress in aquatic ecosystems (cf. Steinman et al. 2011).

Monthly baseflow (grab; n=11) and storm event (YSI 6600 measurements; n = 1) sampling was complemented again in 2018 by the deployment of *in situ* turbidity sondes at the Middle Macatawa upstream and downstream sites. The recovered data collected by the *in situ* sondes revealed many high turbidity events from July through December 2018 that were missed by grab sampling, most likely during storm events, when turbidity was almost 50× greater than baseflow measurements (Fig. 7A). Turbidity peaks aligned with precipitation data downloaded from NOAA's NCEI. *In situ* sondes also measured specific conductivity and measured events ranging from 400-800 µS/cm (Fig. 8).

Mean SRP concentrations ranged from 22-38 µg/L among sites (Table 4). Site mean TP concentrations were 2-3x greater than respective SRP concentrations and ranged from 49-96 µg/L. Mean concentration of both P forms were greater in the Macatawa River than in Peters Creek (Table 4).

Mean NO_3^- concentrations ranged from 2.66-9.45 mg/L, surpassing the nominal 1 mg/L impairment concentration of NO_3^- in surface waters, and likely are related to agricultural fertilizer runoff (Dinnes et al. 2002). Mean NH_3 and TKN concentrations were less than that of NO_3^- (0.19-0.33 mg/L and 1.14-1.33 mg/L, respectively; Table 4), but as was observed in 2017, these concentrations remain potentially problematic, as NH_3 levels of 0.1 mg/L usually indicate polluted surface waters, whereas concentrations > 0.2 mg/L can be toxic for some aquatic animals (Cech 2003). TKN is composed of NH_3, ammonium (NH_4^+), and organic nitrogen compounds; ~15-30% of TKN was represented by NH_3. 2018 nitrogen data again suggest that much of the reduced nitrogen in the Middle Macatawa tributaries is in the form of organic nitrogen (Table 4).

Among monthly sampling events, SRP and TP concentrations in the Macatawa varied greatly throughout the year, whereas they were somewhat more consistent and lower in Peters Creek during baseflow (Figs. 9A, C; 11A, C). Nitrate concentrations were relatively steady at baseflow, although there was a clear separation in NO_3^- concentrations at all three sites; the trend was less clear for NH_3 and TKN (Figs. 10A, B, C). Consequently, Peter's Creek was found to contain significantly higher concentrations of NO_3^- than either Macatawa Up or Macatawa Down; additionally, Macatawa Down NO_3^- concentrations significantly exceeded Macatawa Up NO_3^- concentrations (Table 5, Fig. 11).

Stormflow:

Stormflow YSI 6600 general water quality data from the 10/1/2018 storm event was flagged as suspicious during data analysis, and excluded from storm to baseflow comparisons, leaving only the general water quality data from the 2/20/2018 storm. Precipitation runoff lowered the mean water temperature of tributary sites from ~10.4°C to 2.8-4.5°C and mean DO concentrations increased from ~11 mg/L to 14.24-14.5 mg/L (Table 3). These differences are likely seasonal and linked to snowmelt, as we would expect tributary sites to have colder than average temperatures in February compared to the rest of the year and accordingly, hold greater DO with the colder water. Mean specific conductivity and TDS at stormflow (2/20/2018 only) were about half of their baseflow values, but mean turbidity increased during stormflow by almost two degrees of magnitude from 5.2-8.9 NTU during baseflow to 201.9-303.1 NTU during stormflow (Table 3).

Nutrient data included both 2/20/2018 and 10/1/2018 storm events. Both SRP and TP concentrations during stormflow increased by 1-2 degrees of magnitude over baseflow, resulting in site means ranging from 275-406 µg SRP/L and 876-1090 µg TP/L (Table 4), far exceeding the proposed Lake Macatawa TMDL if 50 µg/L for TP. Mean NO_3^- and NH_3 concentrations also generally increased during stormflow, although this effect was less evident at Peter's Creek, where stormflow had a slight dilution effect on nitrate (Table 4). Mean TKN concentrations more than doubled from baseflow during stormflow at all Middle Macatawa sites, ranging from 2.5-2.94 mg/L (Table 4). When comparing stormflow data across sites, Middle Macatawa sites showed no significant differences in the measured water nutrients (Table 5, Fig. 11).

Table 3. Mean (1 SD) values of selected water quality parameters at the Middle Macatawa wetland restoration site during the 2018 post-restoration sampling year (Dec. 2017 – Nov. 2018). Note that the number of observations (n) changes between baseflow and stormflow regimes. Stormflow water quality data included only the storm event on 2/20/2018. NA = not applicable.

Flow	Site	n	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Base	Mac. Up	11	10.47 (8.75)	10.52 (2.82)	764 (127)	0.497 (0.083)	8.9 (6.2)
	Peter's Creek	11	10.42 (8.13)	11.09 (2.33)	658 (113)	0.428 (0.073)	5.2 (3.7)
	Mac. Down	11	10.28 (8.62)	11.07 (2.30)	697 (61)	0.453 (0.039)	6.2 (2.8)
Storm	Mac. Up	1	2.78 (NA)	14.50 (NA)	292 (NA)	0.190 (NA)	303.1 (NA)
	Peter's Creek	1	4.49 (NA)	14.24 (NA)	269 (NA)	0.175 (NA)	219.6 (NA)
	Mac. Down	1	3.60 (NA)	14.45 (NA)	315 (NA)	0.205 (NA)	201.9 (NA)

Table 4. Mean (1 SD) values of selected water chemistry parameters for phosphorus (total phosphorus [TP] and soluble reactive phosphorus [SRP]) and nitrogen (nitrate [NO_3^-], ammonia [NH_3], and total Kjeldahl nitrogen [TKN]) at the Middle Macatawa wetland restoration site during the 2018 period of record (Dec. 2017 – Nov. 2018). Data are divided into baseflow and stormflow conditions. Stormflow nutrient data included both storm events on 2/20/2018 and 10/2/2018.

Flow	Site	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
Base	Mac. Up	11	32 (27)	96 (64)	2.66 (0.88)	0.20 (0.13)	1.33 (0.32)
	Peter's Creek	11	22 (13)	49 (25)	9.45 (0.95)	0.33 (0.22)	1.14 (0.17)
	Mac. Down	11	38 (27)	87 (53)	5.50 (1.00)	0.19 (0.13)	1.23 (0.28)
Storm	Mac. Up	2	372 (12)	1090 (146)	4.99 (1.99)	0.33 (0.16)	2.74 (0.82)
	Peter's Creek	2	406 (151)	974 (199)	4.44 (0.01)	0.28 (0.25)	2.50 (0.50)
	Mac. Down	2	275 (63)	876 (176)	4.17 (0.32)	0.33 (0.04)	2.94 (0.45)

Table 5. Statistical analysis results comparing 2018 upstream vs. downstream water quality parameters at Middle Macatawa tributary sampling sites at baseflow and stormflow. Parameter column indicates water quality parameter and transformation used to meet assumptions of normality and variance. Data were analyzed using either 1-way ANOVA (1WA) or Kruskal-Wallis 1-way ANOVA on ranks (r). Significant differences (p-values < 0.050) between sites are indicated with bold text and not significantly (NS) different data are in plain text. TP, NO_3^-, NH_3, SRP, and TKN included both storm events on 2/20/2018 and 10/1/2018. Turbidity data included only the 2/20/2018 storm event due to YSI malfunction on 10/1/2018 and analysis was not applicable (NA).

Flow	Parameter	Test	p-value	Notes
Base	sqrt SRP	1WA	0.322	NS
	TP	**r**	**0.018**	**Mac. Up > Peter's Creek**
	NO_3^-	**1WA**	**<0.001**	**Peter's Creek > Mac. Up; Peter's Creek > Mac. Down; Mac. Down > Mac. Up**
	NH_3	1WA	0.236	NS
	sqrt TKN	1WA	0.277	NS
	Turbidity	1WA	0.207	NS
Storm	SRP	r	0.533	NS
	sqrt TP	r	0.667	NS
	NO_3^-	r	0.667	NS
	NH_3	r	1.000	NS
	TKN	r	0.800	NS
	Turbidity	-	-	NA

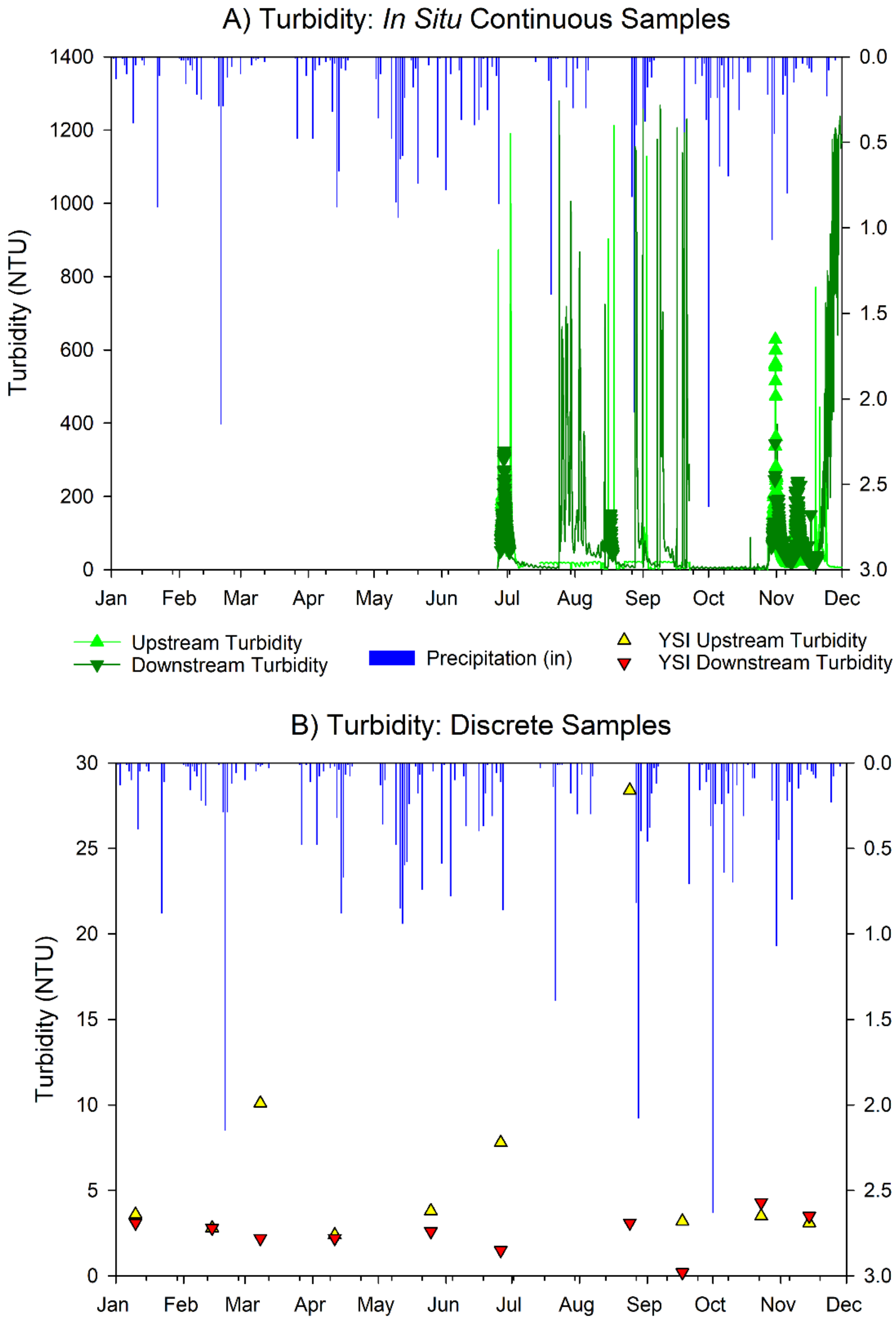

Figure 7. Daily precipitation and turbidity (NTU) during 2018 sampling season at the Middle Macatawa Upstream and Downstream sites. (A) Turbidity data were collected continuously every half hour via *in situ* YSI sensors. (B) Discrete baseflow and storm turbidity measurements were taken during monthly baseflow and storm sampling. Note that *in situ* turbidity sensor lines without symbols indicate observations recorded when conductivity was observed below 200 µS/cm, which is an indicator for whether the turbidity sensor is fully submerged (Fig. 8). Hourly precipitation data (panels A and B) were retrieved from the National Centers for Environmental Information website and summed by day. Note scales change on y-axes.

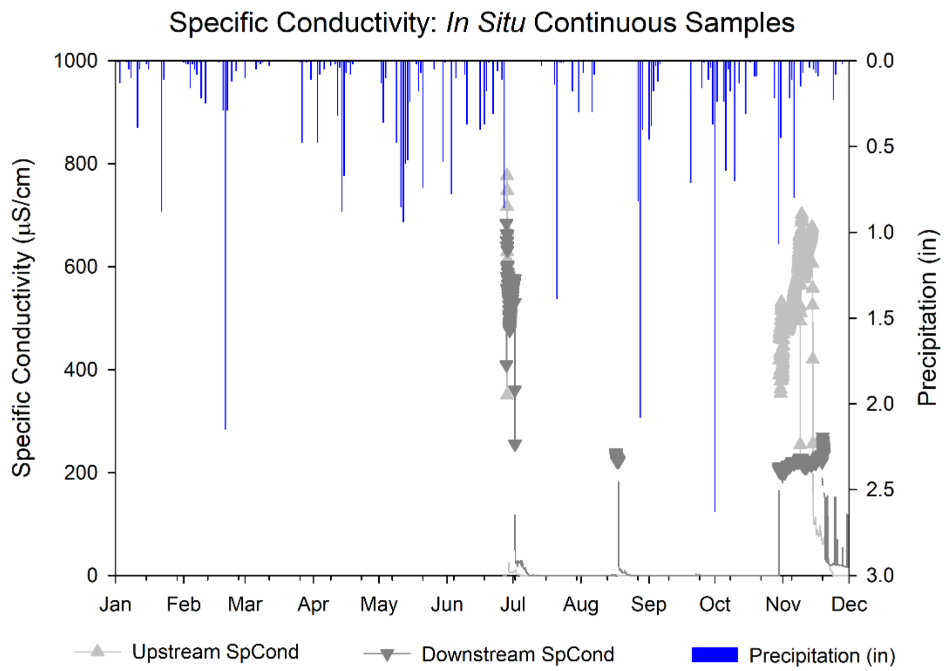

Figure 8. Specific conductivity and daily precipitation data during 2018 sampling season at the Middle Macatawa Upstream and Downstream sites. Rain data taken from National Centers for Environmental Information website. Specific conductivity data series were collected every half hour via *in situ* sensors. Note that lines without symbols indicate observations recorded when conductivity was observed below 200 µS/cm, which is indicative of the sensor being out of the water. *In situ* specific conductivity meter data gaps are due to coordination of sensor deployment with project partners and machine error.

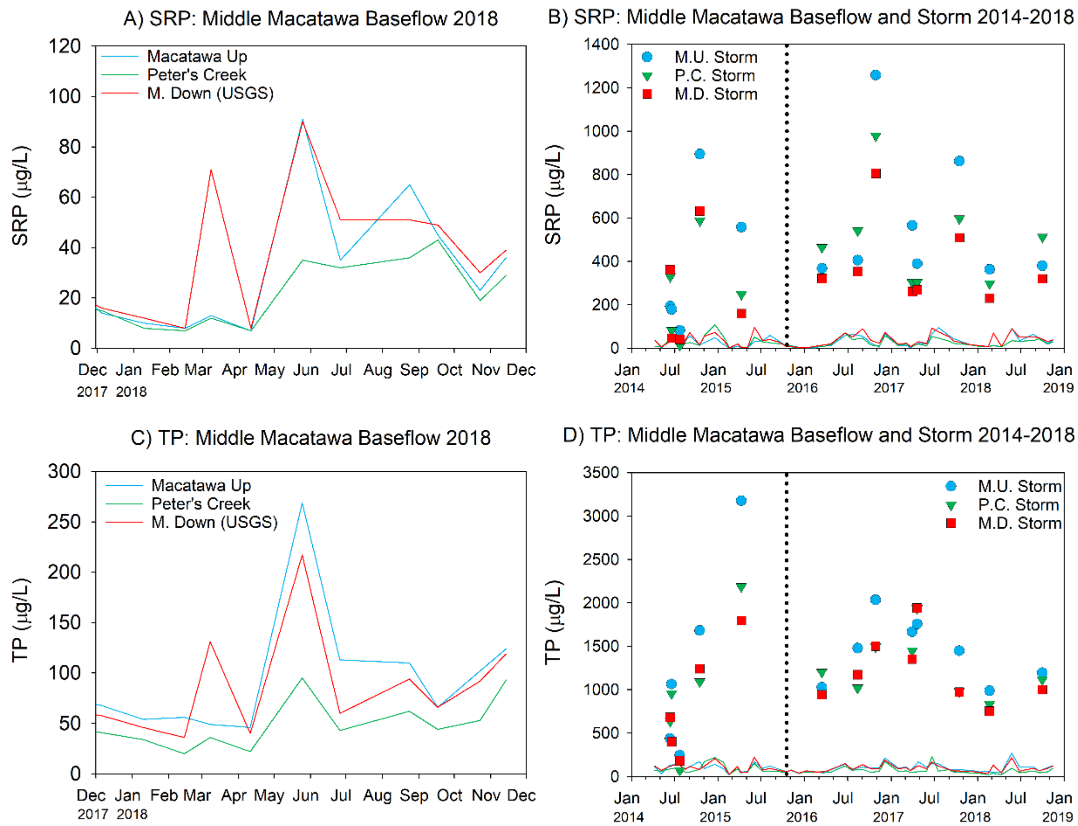

Figure 9. Soluble reactive phosphorus (SRP) (A, B) and total phosphorus (TP) (C, D) concentrations measured at Middle Macatawa restoration site in 2018 (A, C) and over total project history (B, D). Colored data lines in A and C magnify the 2018 baseflow data shown in B and D, which include both baseflow and storm event concentrations. Legend in A, C also applies to B, D; lines represent baseflow and symbols represent storm events. Vertical dotted lines represent approximate completion date of wetland restoration construction. Note changes to scales of y-axes. M.U.= Macatawa Upstream, P.C. = Peters Creek, M.D. = Macatawa Downstream (USGS).

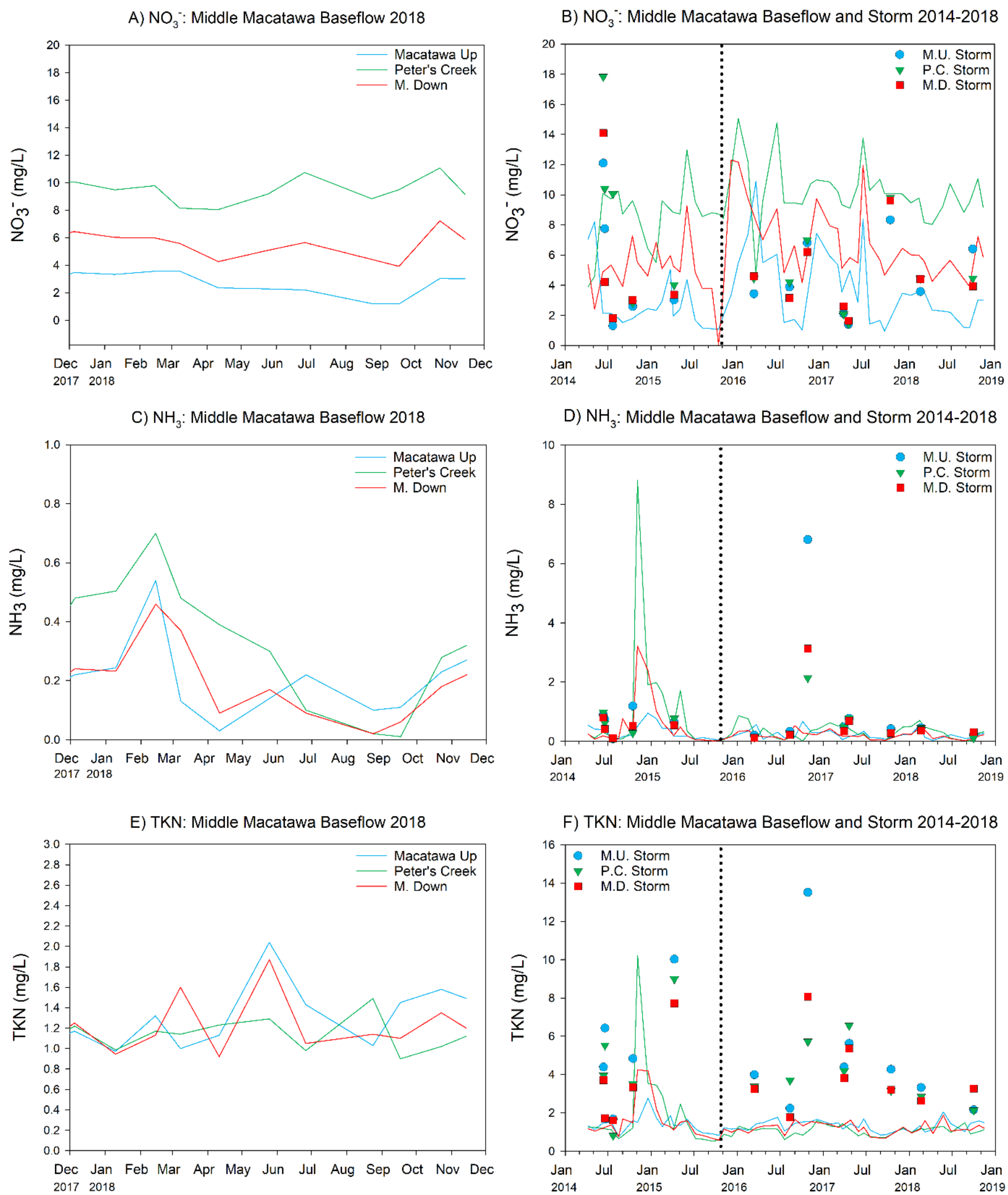

Figure 10. Nitrate (NO_3^-) (A, B), ammonia (NH_3) (C, D), and total Kjeldahl nitrogen (TKN) (E, F) concentrations measured at the Middle Macatawa restoration site in 2018 (A, C, E) and over total project history (B, D, E). Colored data lines in A, C, and E magnify 2018 baseflow data shown in B, D, and F, which include both baseflow and storm event concentrations. Legend in A, C, E also applies to B, D, F; lines represent baseflow and symbols represent storm events. Vertical dotted lines represent

approximate completion date of wetland restoration construction. Note changes to scales of y-axes. M.U.= Macatawa Upstream, P.C. = Peters Creek, M.D. = Macatawa Downstream (USGS).

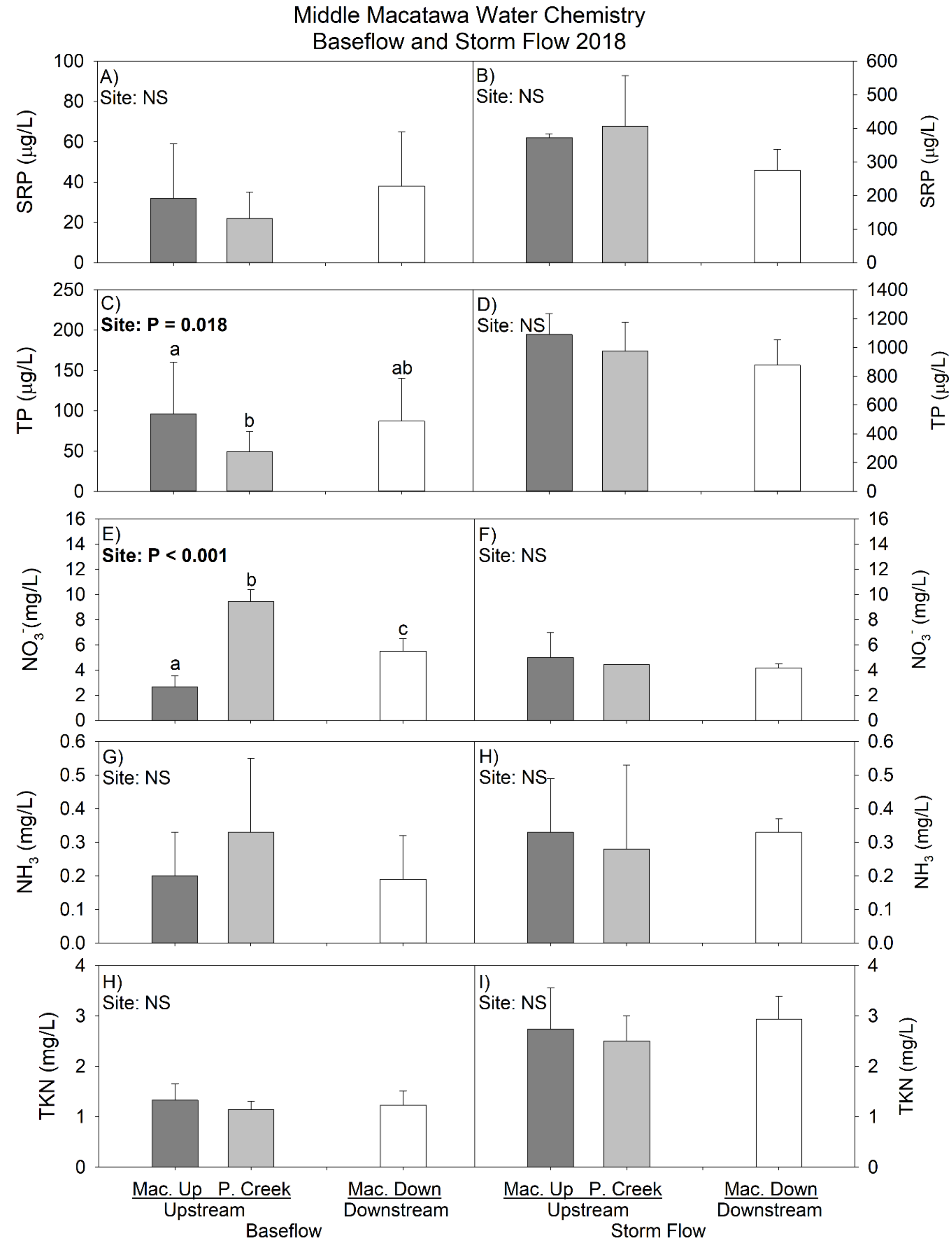

Figure 11. Middle Macatawa mean (1 SD) water chemistry at baseflow (A, C, E, G, I) and stormflow (B, D, F, H, J) for 2018 sampling year. River water from Macatawa Upstream and Peter's Creek sites flow together and combine before reaching Macatawa Downstream site. Note change in y-axis scale between baseflow (left side) and stormflow (right side). Lower case letters indicate significant differences between sites. NS = not significant.

3.1.2 Pre- vs. Post-Restoration Comparison

Baseflow:

A qualitative comparison of general water quality parameters between pre- and post-restoration sampling periods showed a few consistent and distinct differences among all three sites: both mean temperature and mean turbidity were lower in post- vs. pre-restoration, although variance was high likely precluding any significant differences (Table 6). Lower post-restoration temperatures are most likely due to more winter sampling events than during the pre-restoration period, and not due to restoration, per se. Phosphorus showed very little difference between pre- vs. post-restoration periods, but nitrogen did show some patterns: mean nitrate was higher during the post-restoration period, but both mean ammonia and TKN were lower during post-restoration (Table 7, Fig. 12). Again, variance was relatively high in these parameters.

Stormflow:

Middle Macatawa stormflow water quality once again displayed the more complex and sometimes site dependent pre- and post-restoration trends that have been described in previous report years. Storm mean water temperature decreased from pre- to post-restoration by 4-7°C in post-restoration, again likely due to more winter sampling events; however, mean DO generally increased by ~3 mg/L at all sites during the same timeframe (Table 6). Conductivity, TDS, and turbidity all decreased in post-restoration, but variance ranges suggest it is unlikely that these differences are significant (Table 6, Fig. 13F). Mean SRP and TP concentrations increased from pre- to post-restoration, while NO_3^- and NH_3 decreased (Table 7, Figs. 13A-D). TKN decreased over time at Macatawa Up and increased over time at Peter's Creek and Macatawa Down, suggesting changing ratios of organic nitrogen between restoration periods (Table 7, Fig. 13E).

Table 6. Grand means (1 SD) of selected water quality parameters at the Middle Macatawa wetland restoration site. Each site has two rows per column: data in the top row represent entire pre-restoration period of record (Apr. 2014 – Sept. 2015); data in the bottom row represent entire post-restoration period of record (Oct. 2015 – Nov. 2018). Note that the number of observations (n) changes between flow regimes and restoration periods. Date of storm sampling events: Pre - 6/12/14; 6/18/14; 7/23/14; 10/15/14; 4/9/15. Post - 3/14/16; 8/12/16; 10/27/16; 3/30/17; 4/20/17; 10/15/17; 2/20/18.

Flow	Site	Period	n	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Base	Mac. Up	Pre	18	12.34 (7.50)	10.26 (2.23)	711 (184)	0.462 (0.119)	14.7 (12.4)
		Post	33	12.14 (8.30)	10.03 (2.60)	759 (120)	0.493 (0.078)	10.9 (7.7)
	Peter's Creek	Pre	18	12.35 (7.38)	10.45 (2.39)	665 (163)	0.432 (0.106)	11.3 (6.6)
		Post	33	11.65 (7.39)	10.62 (2.20)	664 (90)	0.431 (0.058)	7.4 (5.1)
	Mac. Down	Pre	18	12.17 (7.40)	10.53 (2.39)	765 (240)	0.497 (0.156)	10.5 (6.9)
		Post	33	11.43 (7.87)	10.59 (2.38)	717 (76)	0.466 (0.049)	7.9 (5.4)
Storm	Mac. Up	Pre	3	14.26 (6.78)	7.43 (2.68)	444 (207)	0.288 (0.135)	581.7 (697.8)
		Post	7	10.67 (7.32)	10.21 (2.88)	377 (120)	0.245 (0.078)	350.1 (193.3)
	Peter's Creek	Pre	2	17.00 (3.75)	7.49 (0.81)	460 (201)	0.299 (0.130)	141.6 (182.5)
		Post	7	10.68 (6.56)	10.54 (2.80)	319 (119)	0.207 (0.078)	361.3 (272.6)
	Mac. Down	Pre	3	14.00 (6.66)	7.88 (2.42)	481 (201)	0.313 (0.130)	462.2 (475.9)
		Post	7	10.75 (7.05)	10.33 (2.81)	357 (120)	0.232 (0.078)	319.2 (210.8)

Table 7. Grand means (1 SD) of selected water chemistry parameters at the Middle Macatawa wetland restoration site. Each site has two rows per column: data in the top row represent pre-restoration period of record (Apr. 2014 – Sept. 2015); data in the bottom row represent post-restoration period of record (Oct. 2015 – Nov. 2018). Data are divided into baseflow and stormflow conditions. Data are divided by baseflow and stormflow conditions and by pre- and post-restoration periods, respectively. Note that the number of observations (n) changes between flow regimes and restoration periods. Date of storm sampling events: Pre - 6/12/14; 6/18/14; 7/23/14; 10/15/14; 4/9/15. Post - 3/14/16; 8/12/16; 10/27/16; 3/30/17; 4/20/17; 10/15/17; 2/20/18; 10/1/2018.

Flow	Site	Period	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
Base	Mac. Up	Pre	18	27 (19)	101 (44)	2.90 (2.00)	0.32 (0.25)	1.41 (0.46)
		Post	33	31 (27)	97 (51)	3.72 (2.42)	0.22 (0.15)	1.31 (0.29)
	Peter's Creek	Pre	18	30 (26)	88 (53)	8.54 (2.19)	1.05 (2.06)	1.98 (2.26)
		Post	33	23 (18)	66 (41)	10.14 (1.93)	0.30 (0.24)	1.06 (0.25)
	Mac. Down	Pre	18	37 (27)	104 (51)	5.20 (1.51)	0.56 (0.87)	1.59 (1.02)
		Post	33	36 (28)	91 (44)	6.57 (2.61)	0.19 (0.13)	1.18 (0.30)
Storm	Mac. Up	Pre	5	381 (339)	1319 (1181)	5.35 (4.49)	0.71 (0.41)	5.47 (3.07)
		Post	8	574 (325)	1448 (366)	4.49 (2.43)	1.21 (2.27)	4.94 (3.65)
	Peter's Creek	Pre	4	254 (261)	687 (454)	10.28 (6.14)	0.49 (0.39)	3.45 (1.96)
		Post	8	500 (227)	1253 (356)	4.73 (2.66)	0.58 (0.66)	3.96 (1.49)
	Mac. Down	Pre	5	248 (251)	860 (657)	5.31 (4.99)	0.48 (0.25)	3.62 (2.48)
		Post	8	384 (191)	1203 (382)	4.52 (2.48)	0.68 (1.00)	3.92 (1.97)

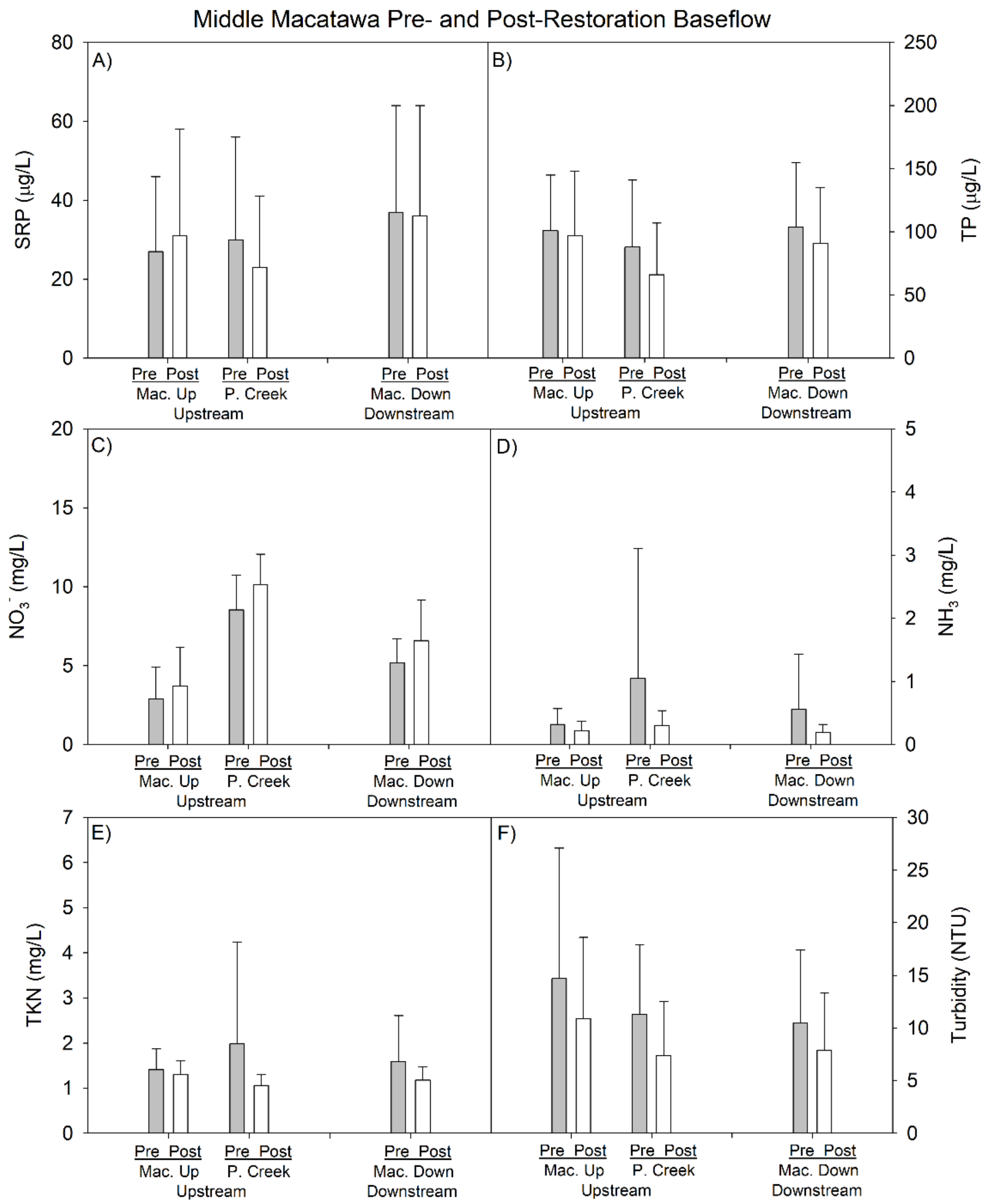

Figure 12. Middle Macatawa pre- and post-restoration water chemistry comparison at baseflow as of 2018 sampling year. Error bars represent 1 SD.

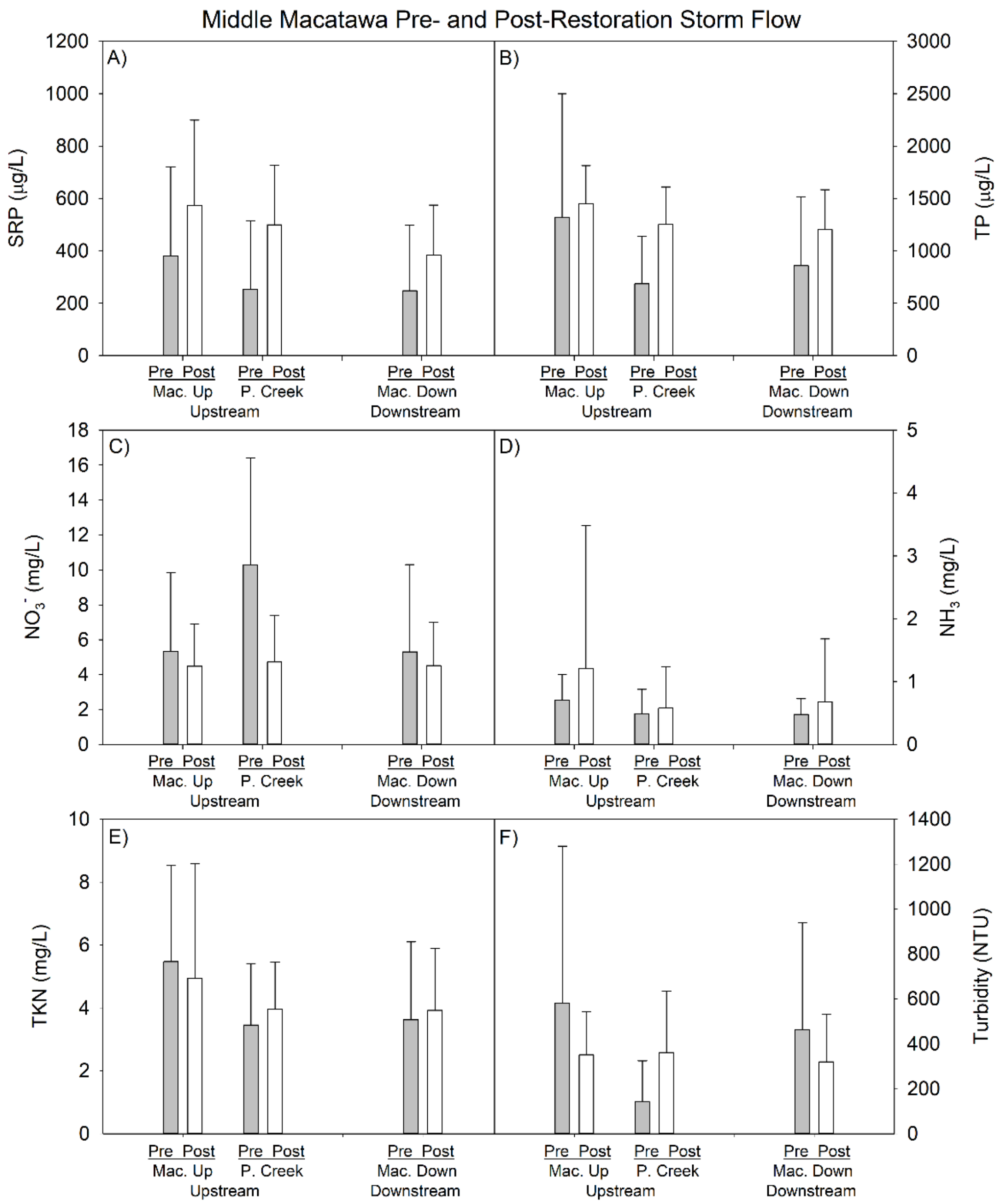

Figure 13. Middle Macatawa pre- and post-restoration water chemistry comparison at stormflow as of 2018 sampling year. Error bars represent 1 SD.

3.2 Wetland Restoration: Haworth Property

3.2.1 Sampling Year 2018

Baseflow:

Patterns of baseflow water quality were similar at the Haworth wetland tributary sites as were seen at Middle Macatawa. Mean temperatures (9.36-9.56°C) and DO (10.57-11 mg/L) were similar between sites (Table 9). Specific conductivity and TDS increased slightly between the upstream to downstream sites, while turbidity decreased (Table 9). Mean phosphorus concentrations were slightly lower at Haworth than at Middle Macatawa sites, with SRP increasing slightly from up to downstream (16 to 19 µg/L) but TP decreasing (41 to 34 µg/L, Table 10). Downstream N and P values were not consistently lower than upstream values throughout the year (Figs. 14 A, C; 15A, C, E). Given that the wetlands don't filter nutrients during baseflow, as the river doesn't enter them under those conditions, one would not expect lower downstream nutrient concentrations.

Stormflow:

YSI 6600 sonde general water quality grab samples from stormflow data at Haworth were similar to Middle Mac and reflective of the 2/20/2018 storm event. Mean water temperature, DO, and turbidity concentrations changed little between upstream and downstream sites (Table 9). Specific conductivity and TDS increased while moving downstream, although with only one observation, it is impossible to know if this was a pattern or not (Table 9). Much larger changes were evident between baseflow and stormflow, with once again, temperature, specific conductivity, and TDS declining dramatically during stormflow conditions but turbidity increasing ~25-fold (Table 9).

Nutrient concentrations from the two measured storm events (2/20/2018 and 10/1/2018) showed little difference between upstream and downstream sites (Table 10. Fig. 16). It may be that too much river volume bypasses the wetlands to detect an impact, or that the nutrient retention effect of the wetlands is more evident within the wetland than in the river (see Summary section).

3.2.2 Pre- vs. Post-Restoration Comparison

Baseflow:

Mean water temperature, DO, conductivity, TDS, and turbidity were slightly lower post-restoration compared to pre-restoration but clearly not significantly so given the high variance (Table 12). Whereas mean turbidity values declined clearly after restoration at the Middle Mac sites (Table 6), a similarly strong decline was not evident at the Haworth sites (Table 12). Most nutrients showed little difference between up- and downstream during baseflow except for nitrate, which similarly to the Middle Mac sites (Table 7), was higher in concentration following restoration (Table 13, Fig 17).

Stormflow:

Mean values of water temperature, specific conductivity, and TDS remained higher in pre-restoration samples during stormflow, while DO and turbidity were higher in post-restoration (Table 12). The distinct increase in mean P concentrations after restoration at the Middle Mac sites (Table 7) was evident at the Haworth North Down site but not at the Up site (Table 13, Figs. 18). Mean NO_3^-, NH_3, and TKN concentrations (Figs. 18A-E) increased in post-restoration, except again for North Up where mean TKN decreased from pre- to post-restoration (Table 13, Fig 18E).

Table 9. Mean (1 SD) values of selected water quality parameters at the Haworth wetland restoration site for the 2018 sampling year. Data are divided into baseflow and stormflow conditions. Stormflow general water quality data include only the storm event on 2/20/2018. NA = applicable.

Flow	Site	n	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Base	North Up	11	9.36 (8.17)	11.00 (2.46)	772 (160)	0.502 (0.104)	5.8 (7.7)
	North Down	11	9.56 (7.83)	10.57 (3.00)	831 (207)	0.540 (0.135)	3.3 (2.5)
Storm	North Up	1	5.89 (NA)	12.80 (NA)	338 (NA)	0.219 (NA)	116.4 (NA)
	North Down	1	6.54 (NA)	12.78 (NA)	392 (NA)	0.255 (NA)	103.5 (NA)

Table 10. Mean (1 SD) values of selected nutrient concentrations at the Haworth restoration site for the 2018 sampling year. Data are divided into baseflow and stormflow conditions. Stormflow included storm events on 2/20/2018 and 10/1/2018.

Flow	Site	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
Base	North Up	11	16 (8)	41 (34)	2.23 (0.88)	0.05 (0.03)	0.98 (0.31)
	North Down	11	13 (6)	34 (16)	1.99 (1.14)	0.04 (0.05)	0.91 (0.18)
Storm	North Up	2	136 (170)	498 (246)	1.82 (0.28)	0.13 (0.00)	2.16 (0.22)
	North Down	2	138 (132)	507 (319)	1.74 (0.24)	0.16 (0.01)	1.91 (0.20)

Table 11. Statistical analysis results of 2018 sampling at Haworth sites comparing upstream vs. downstream parameters at baseflow and stormflow. Parameter column indicates water quality parameter and transformation used to meet assumptions of normality and variance. All data were analyzed using either 2-tailed paired t-tests (T) or Wilcoxon signed-rank tests (W). Significant differences ($p < 0.05$) are indicated with bold text, marginally significant trends are indicated with italics, and not significantly (NS) different results are in plain text. TP, SRP, NO_3^-, NH_3, and TKN included both storm events on 2/20/2018 and 10/1/2018. Turbidity included only the 2/20/2018 storm due to YSI malfunction, so the statistical analysis was not applicable (NA).

Flow	Parameter	Test	p-value	Notes
Base	**SRP**	**W**	**0.002**	**North Up > North Down**
	1/sqrt TP	T	0.900	NS
	NO_3^-	*T*	*0.085*	*North Up > North Down*
	NH_3	T	0.390	NS
	1/x TKN	T	0.458	NS
	sqrt Turbidity	T	0.309	NS
Storm	SRP	T	0.960	NS
	TP	T	0.895	NS
	NO_3^-	T	0.228	NS
	NH_3	W	0.500	NS
	TKN	T	0.557	NS
	Turbidity	-	-	NA

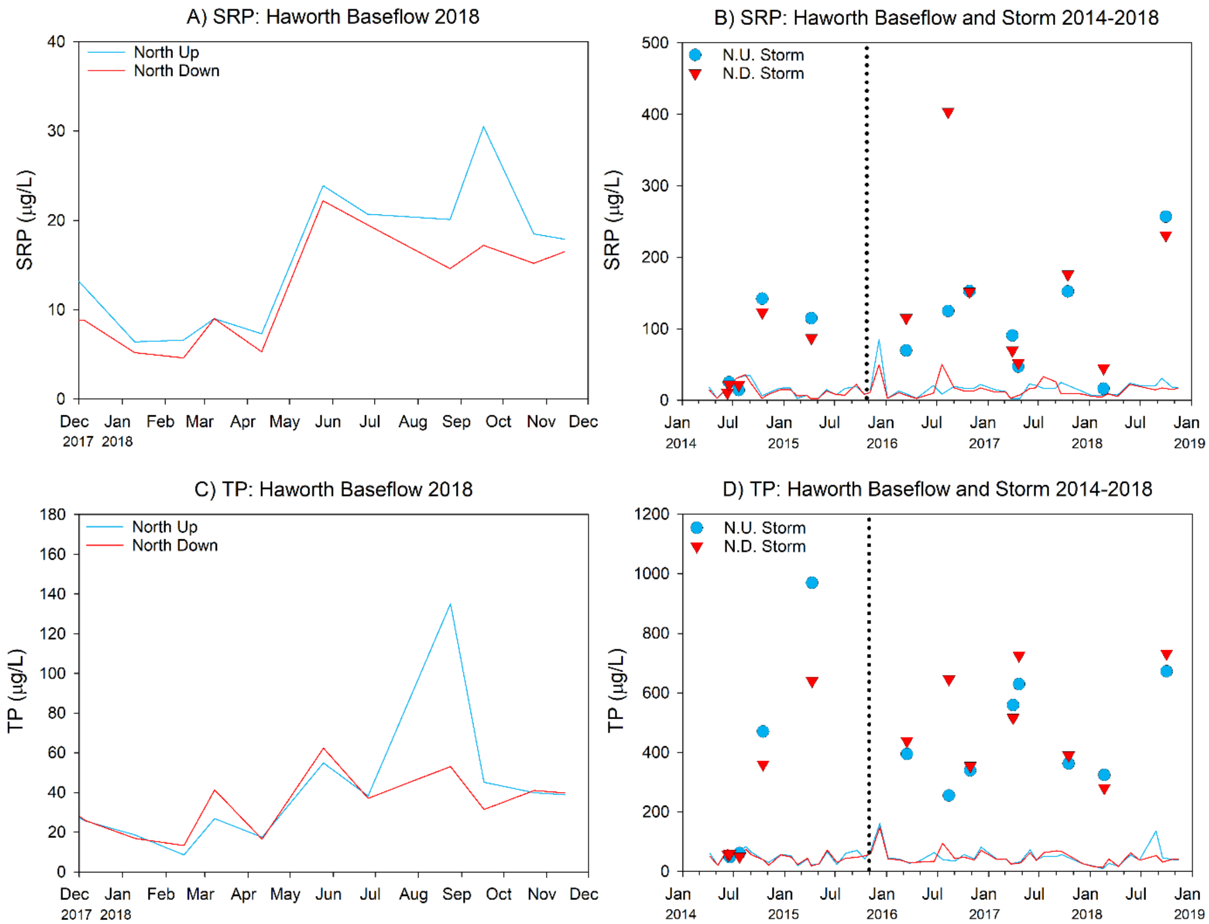

Figure 14. Soluble reactive phosphorus (SRP) (A, B) and total phosphorus (TP) (C, D) concentrations measured at Haworth wetland for 2018 (A, C) and total project history (B, D). Colored data lines in A and C magnify 2018 baseflow data shown in B and D, which include both baseflow and storm event concentrations in same graph. Legend in A, C also applies to B, D; lines represent baseflow and symbols represent storm events. Vertical dotted lines represent approximate completion date of wetland restoration construction. Note changes to scales of y-axes.

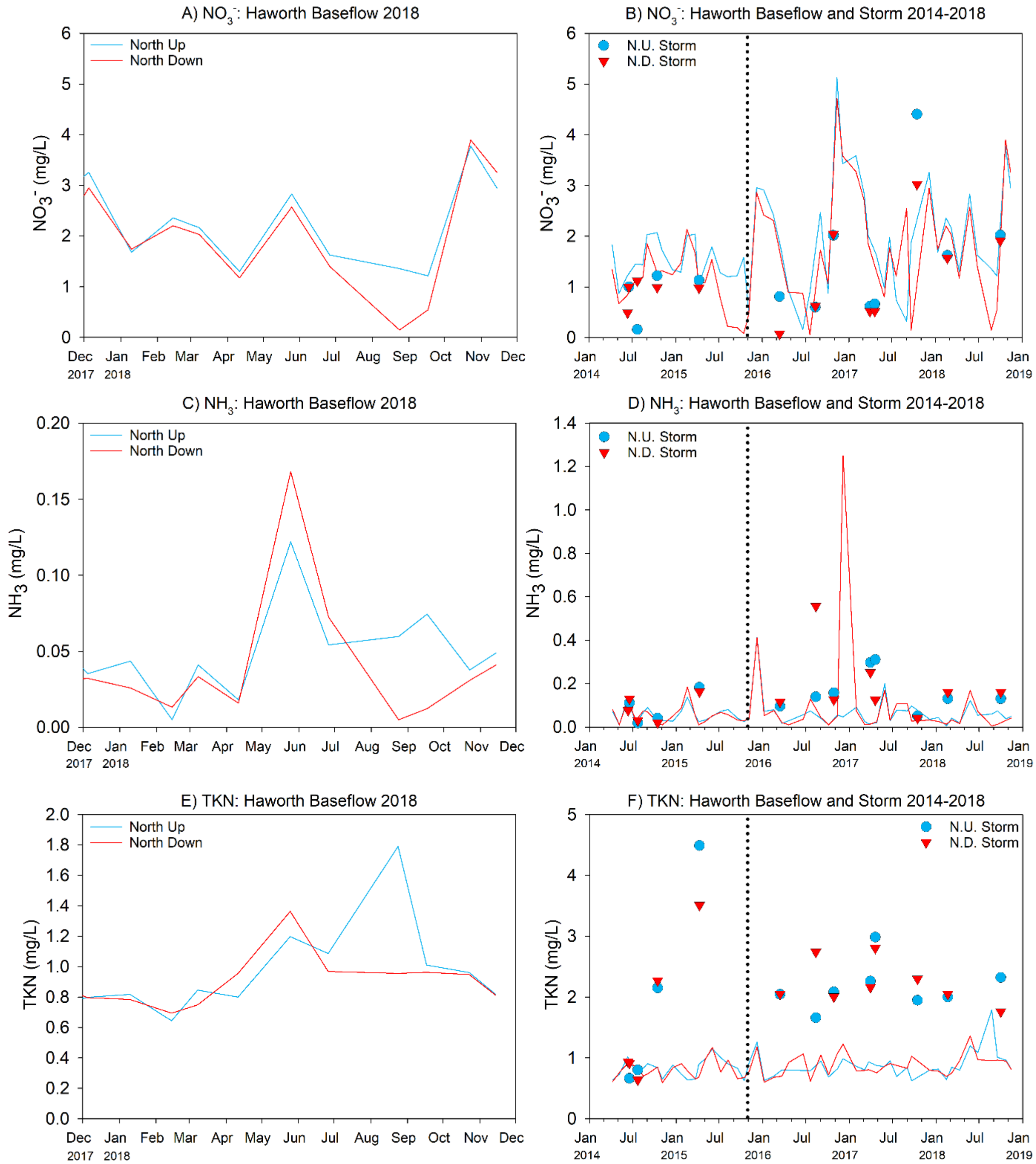

Figure 15. Nitrate (NO_3^-) (A, B), ammonia (NH_3) (C, D), and total Kjeldahl nitrogen (TKN) (E, F) concentrations measured at the Haworth wetland for 2018 (A, C, E) and total project history (B, D, E). Colored data lines in A, C, E magnify 2018 baseflow data shown in B, D, F, which include both baseflow and storm event concentrations in same graph. Legend in A, C, E also applies to B, D, F; lines represent baseflow and symbols represent storm events. Vertical dotted lines represent approximate completion date of wetland restoration construction. Note changes to scales of y-axes; and that y-axis scales are lower than at Middle Macatawa sites (Fig. 7).

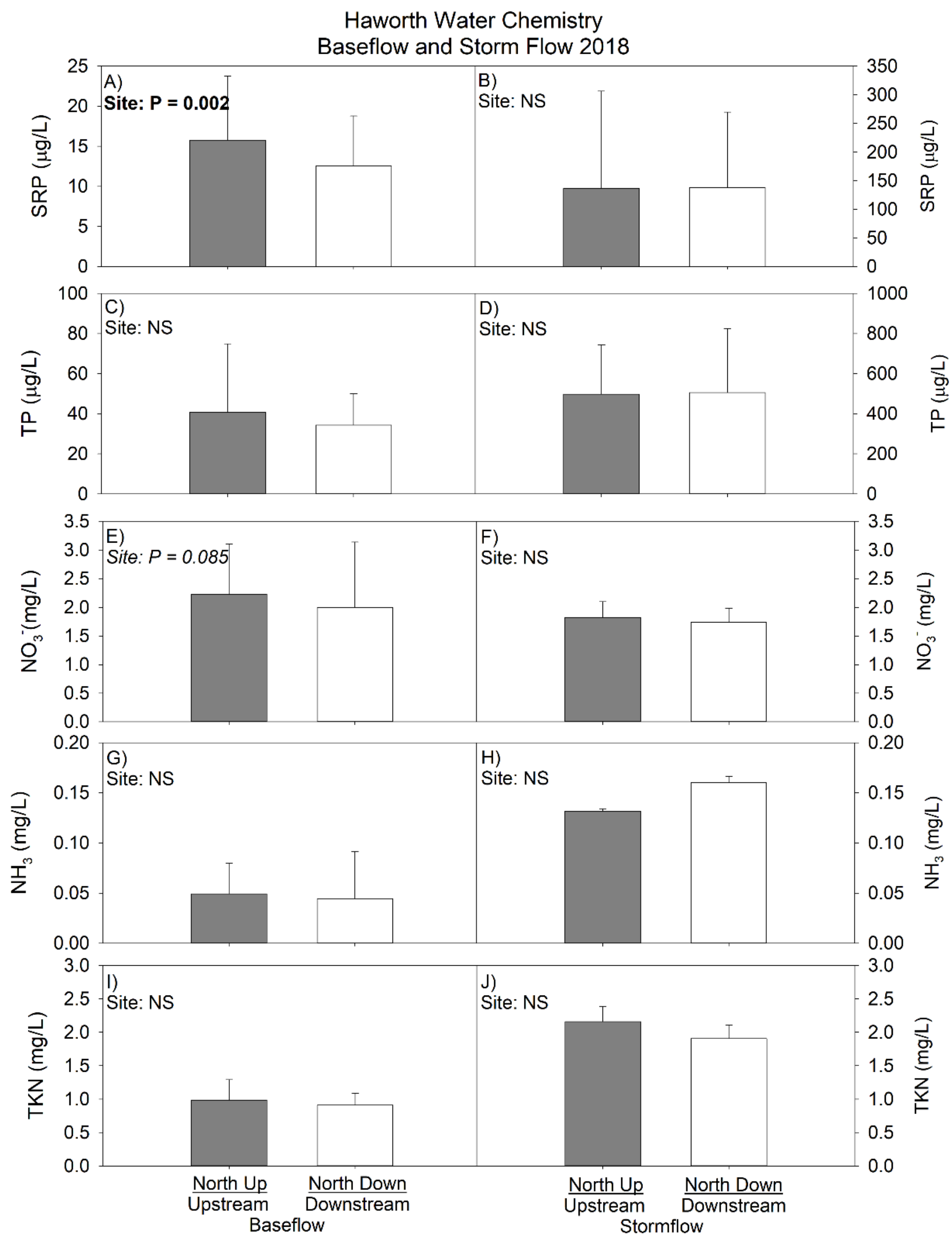

Figure 16. Mean (1 SD) water quality values at Haworth sites for 2018 sampling year at baseflow (A, C, E, G, I) and stormflow (B, D, F, H, J). Note that scales change in y-axes between flow regimes and water quality parameters.

Table 12. Grand mean (1 SD) values of selected water quality parameters at the Haworth wetland restoration site in pre- and post-restoration sampling periods. Sites have two rows per column: data in the top row represent pre-restoration sampling (Apr. 2014 – Sept. 2015) and data in bottom row represent post-restoration sampling (Oct. 2015 –Nov. 2018). Data are divided into baseflow and stormflow conditions. Note that the number of observations (n) changes between flow regimes and restoration periods. Date of storm sampling events: Pre - 6/12/14; 6/18/14; 7/23/14; 10/15/14; 4/9/15. Post - 3/14/16; 8/12/16; 10/27/16; 3/30/17; 4/20/17; 10/15/17; 2/20/18.

Flow	Site	Period	n	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Base	North Up	Pre	18	12.38 (7.11)	11.02 (3.89)	843 (144)	0.548 (0.093)	6.4 (3.6)
		Post	33	10.77 (7.78)	10.14 (2.71)	791 (186)	0.514 (0.121)	6.3 (5.8)
	North Down	Pre	18	11.93 (6.96)	10.32 (3.36)	844 (194)	0.549 (0.126)	5.6 (3.0)
		Post	33	10.88 (7.69)	9.87 (2.84)	827 (167)	0.538 (0.108)	5.3 (5.3)
Storm	North Up	Pre	3	13.80 (5.92)	7.77 (2.29)	432 (283)	0.281 (0.184)	200.7 (223.6)
		Post	7	11.25 (6.77)	9.72 (2.76)	382 (99)	0.248 (0.064)	222.4 (318.6)
	North Down	Pre	3	13.80 (6.06)	7.84 (2.32)	478 (150)	0.310 (0.098)	143.6 (146.0)
		Post	7	11.60 (6.81)	9.51 (2.96)	412 (90)	0.268 (0.058)	146.3 (109.5)

Table 13. Grand mean (1 SD) values of selected nutrient concentrations at the Haworth restoration site in pre- and post-restoration sampling periods. Sites have two rows per column: data in the top row represent pre-restoration sampling (Apr. 2014 – Sept. 2015) and data in bottom row represent post-restoration sampling (Oct. 2015 – Nov. 2018). Data are divided into baseflow and stormflow conditions. Note that the number of observations (n) changes between flow regimes and restoration periods. Date of storm sampling events: Pre - 6/12/14; 6/18/14; 7/23/14; 10/15/14; 4/9/15. Post - 3/14/16; 8/12/16; 10/27/16; 3/30/17; 4/20/17; 10/15/17; 2/20/18; 10/1/2018.

Flow	Site	Period	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
Base	North Up	Pre	18	14 (11)	48 (21)	1.51 (0.38)	0.06 (0.04)	0.84 (0.15)
		Post	33	16 (14)	48 (30)	2.02 (1.13)	0.06 (0.07)	0.88 (0.22)
	North Down	Pre	18	13 (10)	44 (19)	1.17 (0.50)	0.06 (0.04)	0.80 (0.15)
		Post	33	15 (11)	47 (25)	1.82 (1.19)	0.10 (0.22)	0.88 (0.18)
Storm	North Up	Pre	3	90 (67)	500 (455)	0.84 (0.59)	0.08 (0.09)	2.48 (1.87)
		Post	9	104 (77)	398 (196)	1.53 (1.23)	0.16 (0.09)	2.00 (0.62)
	North Down	Pre	5	53 (49)	233 (263)	0.92 (0.24)	0.08 (0.06)	1.65 (1.22)
		Post	8	156 (119)	511 (173)	1.28 (1.01)	0.19 (0.16)	2.23 (0.37)

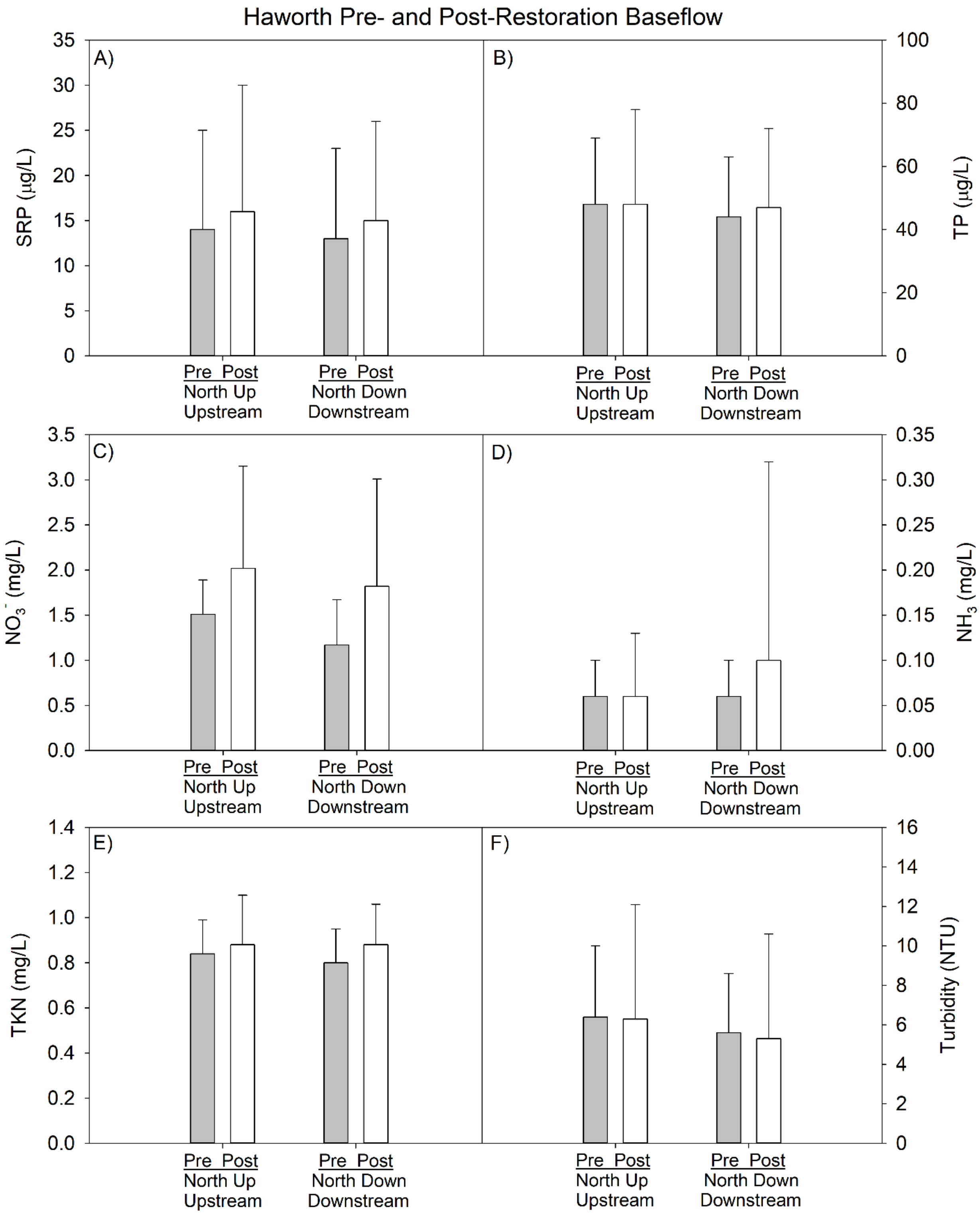

Figure 17. Haworth pre- and post-restoration water chemistry comparison at baseflow as of 2018 sampling year. Error bars represent 1 SD.

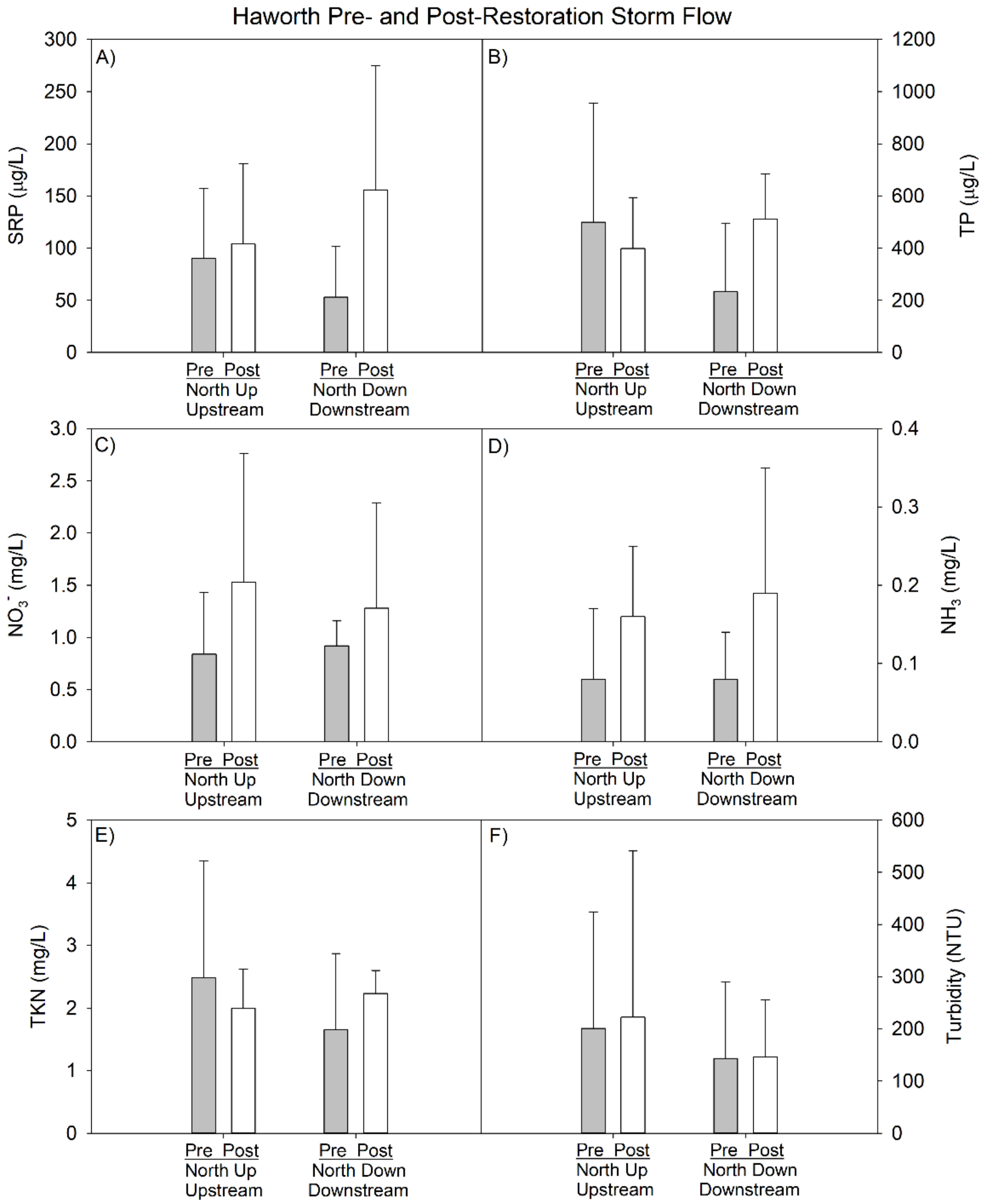

Figure 18. Haworth pre- and post-restoration water chemistry comparison at stormflow as of 2018 sampling year. Error bars represent 1 SD.

3.3 Lake Macatawa: Long-Term Monitoring

3.3.1. Sampling Year 2018

Lake Macatawa's water column was well mixed during spring and fall 2018 sampling, as mean water temperature and DO remained generally consistent from top to near bottom sampling depths (Table 15). Summer sampling provided evidence of stratification, as bottom mean DO was 5.35 mg/L with summer readings from sites 2 and 3 of 3.7 and 3.3 mg/L, respectively, suggesting possible stress to support warm water fish (Table 15). Low DO in this range has been previously seen at the bottom of sites 1 and 4 in 2014 and 2015 and build on the body of evidence that hypoxia can establish in the deeper areas of Lake Macatawa during parts of the summer and fall (Hassett et al. 2018). Lake-wide means of specific conductivity varied seasonally and by depth, but notably exceeded 600 µS/cm in spring, suggesting human-induced stress (Table 15). Higher specific conductivity and turbidity in spring may be associated with increased runoff from the watershed or increased wind activity, resulting in sediment resuspension.

Mean SRP, TP, and NO_3^- concentrations were lowest in the summer and highest in spring and fall, similar to what has been seen in previous years (Table 16, Figs. 19, 20, 21). This likely reflects high phytoplankton demand of these dissolved nutrients in the summer, when algal growth is highest. As noted in our Lake Macatawa dashboard (Appendix B), caution should be exercised when looking at inorganic nutrient values (such as SRP or NO_3^-), simply because these bioavailable forms may be low at certain times of year due to uptake by algae. In that sense, TP gives a better indication of lake trophic status than SRP. Mean surface TP ranged 42-99 µg/L and concentrations generally declined when considering sites and moving from east to west ("uplake" to "downlake") along the lake's surface (Table 16, Fig. 19). The average surface TP concentration throughout the year was ~112 µg/L. If this value is plugged into well-known TP-Chl relationships developed for clear and humic lakes (Havens and Nürnberg 2004), the surface chlorophyll concentrations in Lake Macatawa actually exceeded the expected concentration based on the Havens and Nürnberg regression; this suggests that at least in 2018, turbidity on an annual basis was not limiting algal growth to any great extent.

Perhaps most significantly from a lake management perspective, TP and chl *a* concentrations continue to exceed the 50 µg TP/L and 22 µg chl *a*/L restoration goals for Lake Macatawa (Tables 15, 16).

ELISA tests detected microcystin less than 0.06 µg/L in spring 2018, which was not previously detected at this time in 2017. Summer microcystin concentrations were 0.33 µg/L and 0.59 µg/L at site 4 (top and bottom, respectively) and 0.87 µg/L at site 5 (top only), while the remaining sites had < 0.05 µg/L. Neither spring nor summer had detectable microcystin in 2017. Fall samples had lower concentrations in 2018 than in 2017, with all values < 0.08 µg/L. In summary, 2018 microcystin values are below both WHO and US EPA recreational exposure thresholds but their detection warrants future testing and vigilance.

<u>3.3.2 Pre- vs. Post Restoration Comparison</u>

A qualitative assessment of lake condition reveals only minor evidence that lake condition has improved (Table 17, Fig. 20). This is not surprising as it often takes years, if not decades, for lake conditions to improve once the stressors are removed, and in many cases, the stressors remain in place but at reduced levels, exacerbating lake impairment (Sharpley et al. 2013). The sharp increase in SRP concentrations seen in 2017 has been softened when averaged with 2018 data, but still represents a mean SRP increase of up to ~20 µg/L from pre- to post-restoration (Table 17, Figs. 19A, 20A). Given that the large spike in SRP previously observed in 2017 did not reoccur in 2018, it's possible that similar spikes did not occur in 2018, but it's more likely that seasonal sampling is not capturing the full range of lake nutrient concentration values.

Two apparent nutrient concentration trends have emerged from our sampling: 1) in general, the highest concentrations in Lake Mac occur in the spring; and 2) site 1 (easternmost) generally has the highest concentrations. The high spring concentrations are potentially most problematic, as they provide critical resource supplies for algal growth in summer, as temperatures warm. Controlling nutrients in the spring runoff would be one way to help reduce summer algal blooms.

Table 15. Lake-wide means (1 SD) of select general water quality parameters recorded during 2018 monitoring year. Within 2018, "n" is the number of lake sites composing the seasonal mean at each depth. Data are shaded for readability.

Season	Depth	N	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Spring	Top	5	16.51 (1.20)	11.91 (0.90)	635 (88)	0.413 (0.057)	8.7 (2.9)
	Middle	5	16.13 (1.30)	11.01 (1.95)	632 (88)	0.411 (0.057)	10.5 (4.2)
(5/8)	Bottom	5	15.03 (1.59)	9.06 (3.77)	610 (109)	0.397 (0.071)	14.1 (4.8)
Summer	Top	5	24.14 (0.59)	12.66 (0.69)	454 (28)	0.295 (0.018)	8.4 (1.3)
	Middle	5	21.88 (2.77)	10.22 (2.63)	441 (49)	0.287 (0.032)	8.3 (1.1)
(7/25)	Bottom	5	17.80 (4.64)	5.35 (2.16)	413 (64)	0.268 (0.041)	11.9 (6.1)
Fall	Top	5	9.88 (0.07)	11.03 (0.57)	497 (60)	0.323 (0.039)	9.3 (1.9)
	Middle	5	9.83 (0.08)	10.65 (0.71)	500 (65)	0.325 (0.042)	9.0 (1.5)
(10/24)	Bottom	5	9.87 (0.17)	10.15 (0.99)	544 (142)	0.353 (0.093)	12.4 (5.6)

Table 16. 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 2018 monitoring year. Within 2018, "n" is the number of lake sites composing the seasonal mean at each depth. Data are shaded coded for readability. Sampling dates listed in Table 15.

Season	Depth	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)	ext. Chl *a* (µg/L)	Secchi depth (m)
Spring	Top	5	7 (1)	96 (19)	2.14 (0.19)	0.65 (0.76)	2.60 (1.13)	52 (23)	0.7 (0.4)
	Bottom	5	6 (1)	75 (12)	1.74 (0.35)	0.07 (0.04)	1.40 (0.33)	40 (13)	
Summer	Top	5	4 (3)	42 (11)	0.29 (0.02)	0.33 (0.23)	1.37 (0.24)	44 (19)	0.7 (0.0)
	Bottom	5	4 (4)	49 (11)	0.25 (0.05)	0.21 (0.19)	1.15 (0.16)	36 (14)	
Fall	Top	5	14 (2)	99 (10)	2.23 (0.61)	0.62 (0.35)	2.05 (0.35)	40 (20)	0.5 (0.0)
	Bottom	5	12 (2)	74 (8)	1.54 (0.26)	0.14 (0.14)	1.40 (0.19)	52 (9)	

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Table 17. 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. 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 2018). Data are color coded for readability. ND = no data. Sampling dates listed in Table 15.

Season	Depth	Period	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)	ext. Chl *a* (µg /L)	Secchi Depth (m)
Spring	Top	Pre	2	3 (0)	66 (4)	ND	ND	ND	25 (4)	0.6 (0.1)
		Post	3	22 (29)	131 (79)	1.87 (0.38)	0.62 (0.05)	1.93 (0.95)	43 (9)	0.7 (0.1)
	Bottom	Pre	2	3 (1)	98 (30)	ND	ND	ND	24 (3)	
		Post	3	23 (27)	130 (78)	1.70 (0.05)	0.30 (0.32)	1.29 (0.15)	36 (9)	
Summer	Top	Pre	3	6 (3)	110 (66)	ND	ND	ND	67 (39)	0.4 (0.1)
		Post	3	7 (4)	73 (29)	0.27 (0.02)	0.32 (0.01)	1.38 (0.02)	70 (36)	0.7 (0.1)
	Bottom	Pre	3	17 (18)	107 (49)	ND	ND	ND	32 (13)	
		Post	3	10 (5)	87 (34)	0.33 (0.12)	0.39 (0.26)	1.30 (0.22)	33 (4)	
Fall	Top	Pre	3	10 (12)	134 (23)	ND	ND	ND	63 (43)	0.4 (0.1)
		Post	3	7 (6)	85 (14)	1.19 (1.46)	0.69 (0.10)	1.79 (0.37)	67 (30)	0.5 (0.0)
	Bottom	Pre	3	11 (13)	158 (19)	ND	ND	ND	61 (35)	
		Post	3	8 (4)	74 (7)	0.86 (0.97)	0.44 (0.42)	1.32 (0.11)	53 (3)	

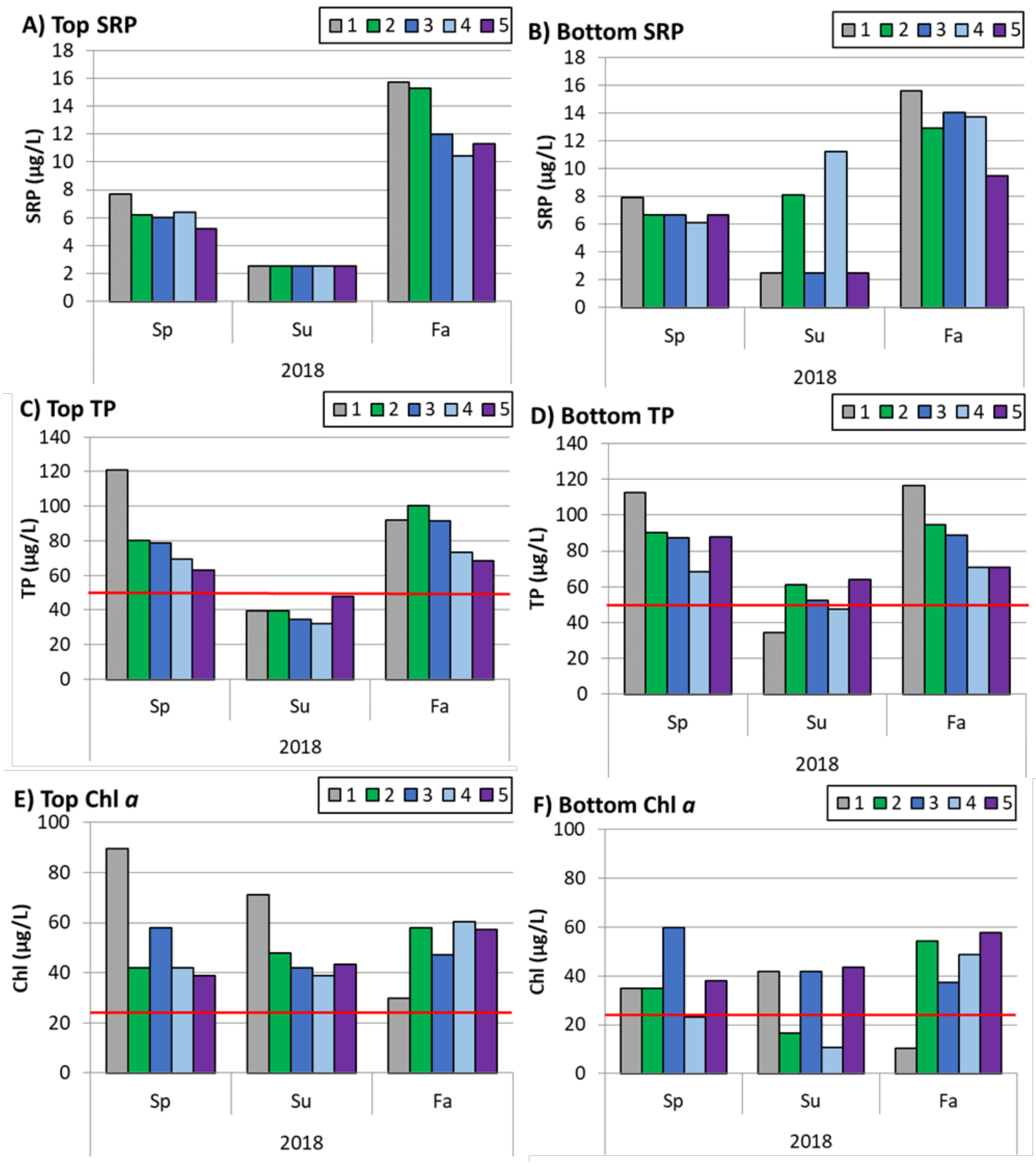

Figure 19. Soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); and chlorophyll *a* ([chl *a*]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2018. The red horizontal lines on TP figures (C, D) indicate the interim total maximum daily load (TMDL) 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 MDEQ for assessing chl *a* in Lake Macatawa (Holden 2014). Note scales change on y-axes.

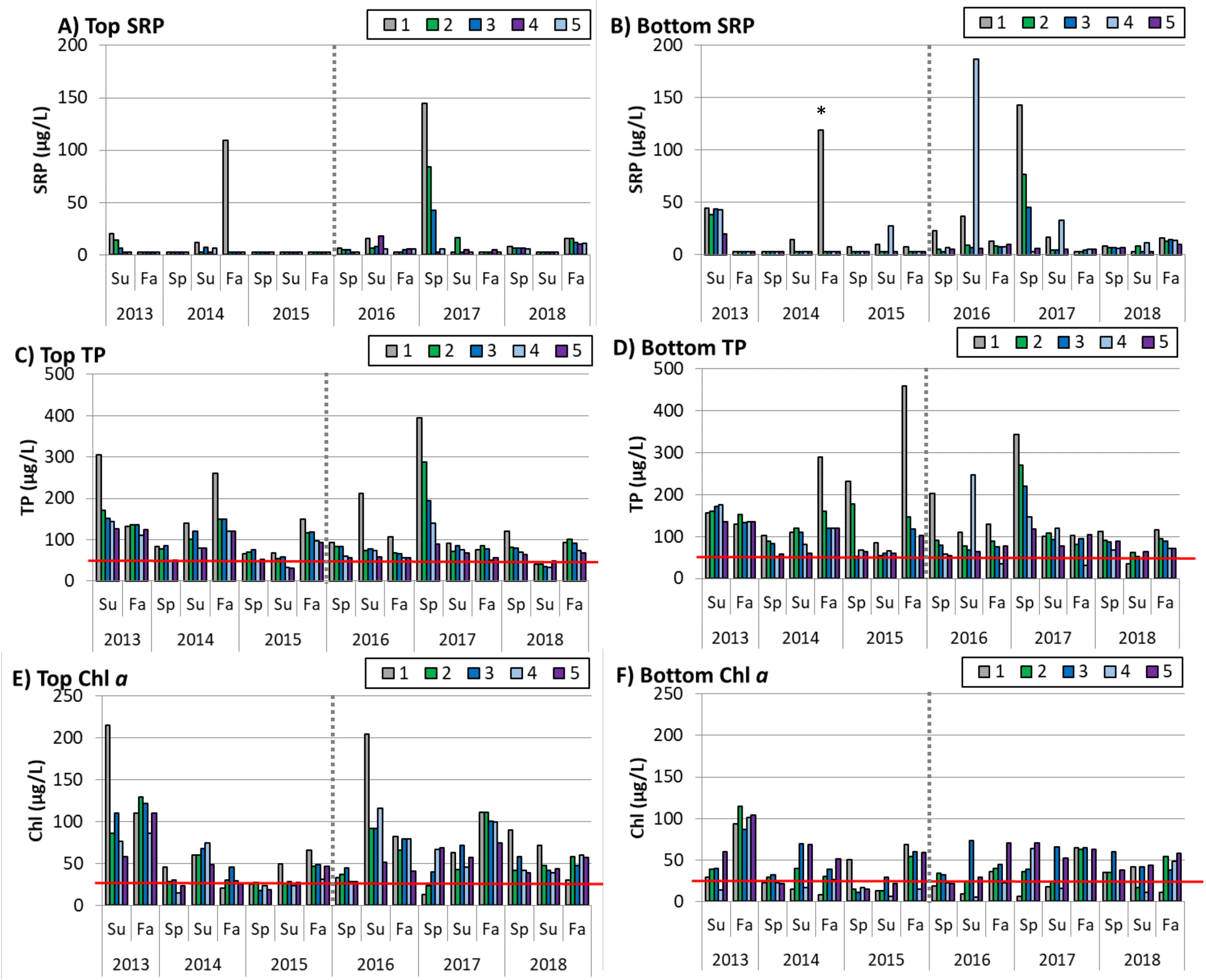

Figure 20. Soluble reactive phosphorus ([SRP]: A, B); total phosphorus ([TP]: C, D); and chlorophyll *a* ([chl *a*]*:* E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2013 through 2018. The red horizontal lines on TP figures (C, D) indicate the interim total daily maximum 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 MDEQ for assessing chl *a* in Lake Macatawa (Holden 2014). Summer 2016 site 4 SRP bottom depth sample (B, asterisked) is a likely outlier due to sediment disturbance. Note scales change on y-axes. Vertical dotted lines represent approximate restoration construction completion dates for Middle Macatawa and Haworth wetlands.

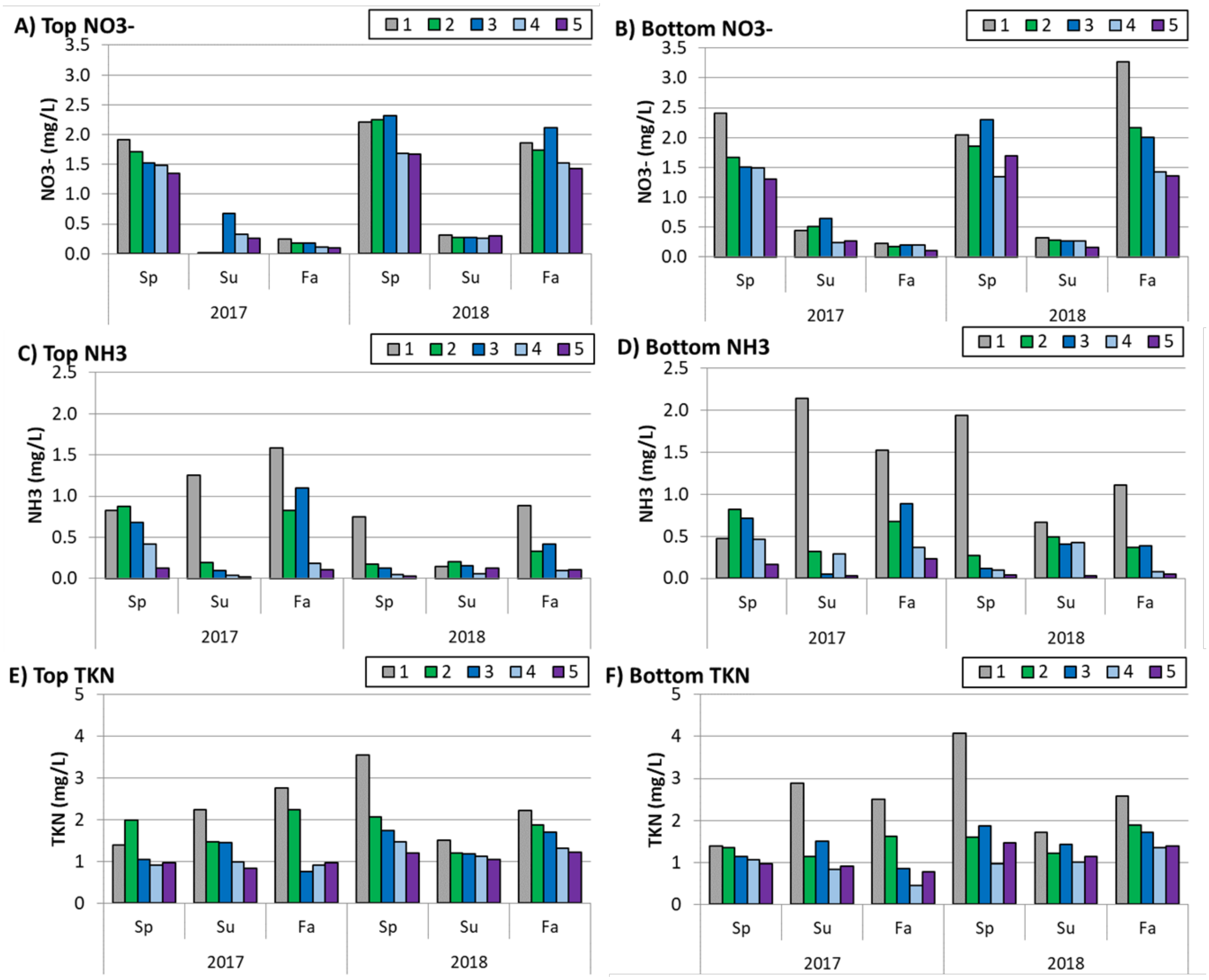

Figure 21. Nitrate ([NO_3^-]: A, B); ammonia ([NH_3]: C, D); and Total Kjeldahl Nitrogen ([TKN]: E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa from 2017 through 2018. Note scales change on y-axes.

3.4 Lake Macatawa Watershed: Phosphorus – Precipitation Analysis

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 clearly shown in the western basin of Lake Erie, where heavy spring rains transported recently applied soluble phosphorus 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 and precipitation.

In Lake Macatawa, the relationship between lake TP and precipitation has not been clear-cut. Between 1972 and 2018, the relationship between precipitation and TP concentration in the lake was not statistically significant (Figs. 19, 20; $R^2 = 0.004$; $p = 0.788$). For example, some years have very high TP concentrations and relatively low precipitation (e.g., 2000 and 2004), whereas other years have modest levels of TP and relatively high precipitation (e.g., 2017). Interestingly, the relationship between TP and precipitation is much improved since 2013 ($R^2 = 0.384$; $p = 0.190$) but is still not statistically significant. This relationship is based on only 6 data points, so it should be viewed cautiously. We view these data as appropriate for screening purposes only, as the TP concentrations are single sampling events, which may miss pulses of high phosphorus concentrations after storm events.

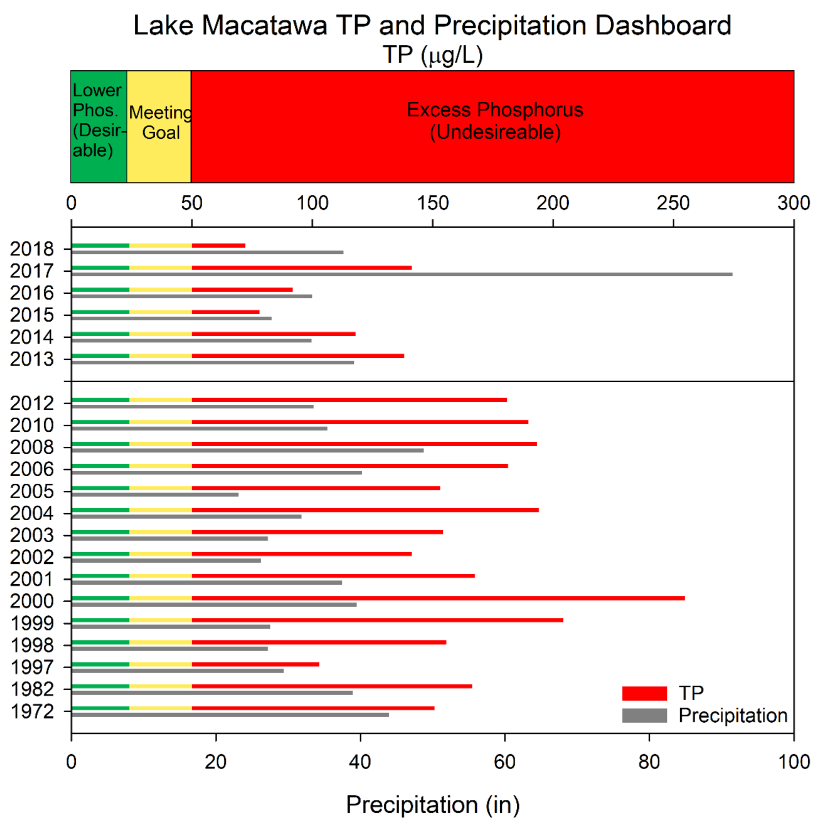

Figure 22. Lake Macatawa total phosphorus (TP) and precipitation dashboard summary. TP bars average data from top depths at sites 1, 2, and 4 to represent a continuum of water moving through Lake Macatawa in the east, central, and west basins, respectively. Yellow and red portions of the TP axis indicate averages meeting or exceeding the interim total maximum daily limit (TMDL) goal of 50 µg/L, respectively. Precipitation data represent annual sums of hourly precipitation at Tulip Airport in Holland. Historical TP data sources include U.S. EPA (1972; STORET), Michigan Department of Environmental Quality (1982, 1997-2012; S. Holden, personal communication), and AWRI (since 2013). Precipitation data sources include the National Climatic Data Center/National Centers for Environmental Information (2005-2018; NOAA) and Weather Underground (1972-2004; The Weather Channel Company).

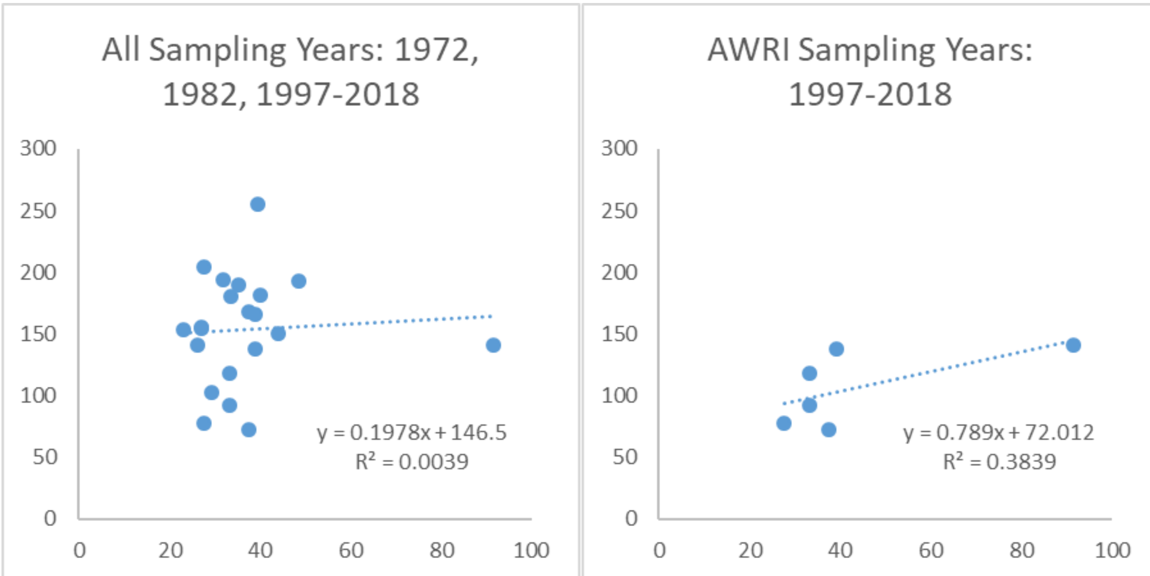

Figure 23. Linear regressions plotting annual precipitation vs. mean total phosphorus (TP) concentration in Lake Macatawa. Historical TP data sources include U.S. EPA (1972; STORET), Michigan Department of Environmental Quality (1982, 1997-2012; S. Holden, personal communication), and AWRI (since 2013). Precipitation data sources include the National Climatic Data Center/National Centers for Environmental Information (2005-2018; NOAA) and Weather Underground (1972-2004; The Weather Channel Company).

3.5 Iron Slag Pre-Construction Sampling

Slag sites were sampled during three baseflow events in 2018: 9/20, 10/23, and 11/14. As site construction has yet to begin, we present preliminary data here in order to better characterize these potential restoration sites. Note that tile drain samples are all independent samples flowing into the same drainage ditch, unlike the wetland restoration monitoring site. Mean water temperatures varied between sites and ranged from 9.34 to 17.10°C (Table 18). Mean DO ranged from 6.88 to 10.50 mg/L (Table 18). Specific conductivity and TDS were both highest at the Goldie West site, which may be related to the site's highly channelized shape allowing for more local sediment to be swept up into the current (Table 18). Phosphorus concentrations varied widely among groups and individual sites and are likely reflective of field management and drainage. Mean SRP and TP concentrations were highest in Oak Grove, with 411 and 436 µg/L, respectively (Table 19), which are generally consistent with previous measurements of tile drainage P in the Macatawa watershed (Clement and Steinman 2017).

Table 18. Mean (1 SD) values of selected water quality parameters for tile drain outflow iron slag pre-construction monitoring. Data are shaded to improve readability. N= number of successful sampling events per site.

Site	n	Temp. (°C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Behind Mill 1	3	14.52 (4.70)	9.19 (1.47)	936 (206)	0.533 (0.264)	15.7 (27.0)
Behind Mill 2	3	14.64 (5.97)	9.47 (2.49)	780 (373)	0.582 (0.112)	2.7 (6.4)
Behind Mill 3	1	9.34 (NA)	10.50 (NA)	940 (NA)	0.611 (NA)	0.0 (NA)
Goldie West 1	3	15.45 (5.82)	7.31 (0.48)	1277 (177)	0.830 (0.115)	1.9 (6.6)
Goldie West 2	2	17.10 (8.78)	6.88 (0.42)	964 (341)	0.627 (0.222)	11.6 (18.5)
Oak Grove 1	3	14.40 (5.43)	7.81 (0.36)	613 (23)	0.398 (0.014)	0.0 (0.8)
Oak Grove 2	3	15.46 (6.97)	9.22 (3.01)	620 (208)	0.403 (0.136)	1.8 (8.7)
Oak Grove 3	3	14.16 (4.61)	8.87 (0.99)	662 (29)	0.430 (0.019)	0.0 (1.7)

Table 19. Mean (1 SD) values of soluble reactive phosphorus (SRP) and total phosphorus (TP) for tile drain outflow iron slag pre-construction monitoring. Data are shaded coded to improve readability. N= number of successful sampling events per site.

Site	n	SRP (µg/L)	TP (µg/L)
Behind Mill 1	3	172 (146)	210 (170)
Behind Mill 2	3	117 (104)	162 (141)
Behind Mill 3	1	23 (NA)	33 (NA)
Goldie West 1	3	21 (11)	59 (55)
Goldie West 2	2	76 (88)	132 (162)
Oak Grove 1	3	39 (8)	67 (21)
Oak Grove 2	3	411 (485)	436 (486)
Oak Grove 3	3	140 (46)	191 (59)

4. Summary

The results of the 2018 monitoring revealed that the main indicators of water quality: total phosphorus, chlorophyll a, and Secchi disk depth (water clarity) all showed improved conditions compared to 2017. While this is certainly more encouraging than the 2017 data, when these indicators showed worsening conditions, our results indicate that water quality in Lake Macatawa is still severely impaired. We expect to see 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.

As noted previously, the lack of more immediate improvement can be attributed to at least three reasons: 1) restoration is still very recent, and until the restored sites are fully functional, which should take a number of years, it is unreasonable to expect a demonstrable change; 2) the restoration sites have relatively small footprints and volume holding capacity, so given the volume of water moving through the Macatawa River, especially during storm events, the ability to detect a signal from the noise may be very difficult at any one particular site; and 3) the natural environment is variable, so it will take a number of years to detect a robust trend at any site, regardless of direction.

In addition to elevated P concentrations, high nitrate concentrations continue to be a concern in the watershed. We have previously found that at least some algae in Lake Macatawa are co-limited by phosphorus and nitrogen (Steinman et al. 2016), and the summer drawdown of nitrate in the lake, presumably due to phytoplankton uptake, is another indicator that nitrogen is a critical element for algal growth in Lake Macatawa. We strongly recommend the agricultural community to focus on both nitrogen and phosphorus controls.

The implementation of new agricultural structural BMPs, such as two-stage ditches and slag filters, are important steps to reduce nutrient and sediment loading. Our previous research findings, conducted as part of MS theses and not directly funded by Project Clarity, show that tile drain effluent can be an important source of P (and maybe N) (Clement and Steinman 2017); the slag filter projects have potential to strip out P from the tile drain effluent before reaching the drainage ditches. Analyses in 2018 of these projects will give us a better understanding of their efficacy. In addition, work by Kindervater and Steinman (in press), has shown that sediment in 2-stage ditches has the potential to store a considerable amount of phosphorus. Where feasible, and assuming the landforms are stable, implementing more 2-stage ditches is recommended.

Last year, we began working on a computational SWAT model for the Macatawa watershed. This work was done in concert with Project Clarity but through independent funding sources. Unfortunately, the postdoctoral research associate working on this project took a job at Penn State University, which has slowed down the completion of this model. However, she continues to work on it as time allows, and we expect to see it completed in 2019.

Discussions with the Project Clarity Management Team regarding future sampling resulted in a mutual decision to stop the upstream-downstream monitoring of the Middle Mac and Haworth wetland restoration projects in April 2019. The monitoring design did not allow us to discern the effectiveness of the wetlands, and given the cost, we decided to replace it with sediment P analyses. Starting in 2019, we will sample these wetlands (n = 4 per wetland) for measurement of sediment equilibrium phosphorus concentration (EPC), which indicates whether the sediment acts as a P source (from the sediment to the overlying water) or a sink (from the water column into the sediment; cf. Oldenborg and Steinman 2019). In addition, we will fractionate the sediment, which will allow us to determine how the P is bound within the sediment profile; some fractions bind P very loosely, so it is mobile and can easily leach out of the sediment and into the overlying water. Conversely, some fractions bind the P very tightly, forming a stable and more permanent sink. This information will give us a better understanding of whether the P is likely to be released or retained in the sediment of the restored wetlands, and at what depth.

5. Acknowledgements

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Appendices

Appendix A. Long-Term Fish Monitoring of Lake Macatawa: Results from Year 5 (Ruetz, Oudsema and Ellens).

Appendix B. Lake Macatawa Dashboard (Hassett and Steinman).

Appendix A.

Long-Term Fish Monitoring of Lake Macatawa: Results from Year 5

Carl R. Ruetz III[1], Maggie Oudsema, and Travis Ellens
Annis Water Resources Institute
Grand Valley State University
740 W. Shoreline Drive, Muskegon, Michigan 49441

25 February 2018

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to the
Outdoor Discovery Center
Holland, Michigan 49423

[1] Corresponding author; Office: 616-331-3946; E-mail: ruetzc@gvsu.edu

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. Although we do not expect the benefits of the restoration activities in the watershed to be expressed in Lake Macatawa immediately, establishing baseline conditions in Lake Macatawa will be critical for evaluating ecological change over time. In autumn 2014, we initiated a long-term monitoring effort of the littoral fish assemblage of Lake Macatawa. 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 fifth year of sampling was to continue to characterize the pre-restoration (baseline) littoral fish assemblage. We made preliminary comparisons with our ongoing 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). However, the true value of this fish monitoring effort will come in future years as we 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). Fish sampling was conducted at four littoral sites in Lake Macatawa that represented a gradient from the mouth of the Macatawa River to the connecting channel with Lake Michigan (Figure 1; Table 1). In 2016, much of the riparian vegetation was removed at site #2 for a construction project. The clearing of most trees and woody vegetation that were flooded by high Great Lakes water levels at site #2 (most were cut off at the water level) provided habitat structure for fish that could be more easily accessed by sampling gear (especially with respect to boat electrofishing) than prior to removal.

Fish sampling.—At each study site, we sampled fish via fyke netting and boat electrofishing. Using both sampling gears should better characterize the littoral fish assemblage than either gear by itself because small-bodied fishes are better represented in fyke netting and large-bodied fishes are better represented in nighttime boat electrofishing (Ruetz et al. 2007). Fyke nets were set on 4 September 2018 during daylight hours (i.e., between 1100 and 1600) and fished for about 22.0 h (range = 21.8-22.3 h). 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 6 September 2018. 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 preserved 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. Note that the probe used to measure ORP on our YSI sonde malfunctioned during 2018 sampling, so we do not report that variable in our 2018 data. We made one measurement at each fyke net (n = 12) and one measurement at the beginning of each electrofishing transect (n = 4). 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). In previous years, we also visually estimated the percent macrophyte cover for the length of each electrofishing transect during fish sampling; however, we were unable to see the lake bottom during electrofishing transects and were unable to make such an assessment in 2018.

Results and Discussion

We characterized water quality variables at each site during fish sampling (Tables 2 and 3). The mean water depth at fyke nets was 91 cm (Table 2). Mean water temperature was similar during fyke netting (25.5 °C; Table 2) and boat electrofishing (24.2 °C; Table 3). At fyke nets, mean % cover of macrophytes was zero at site #1 and approached zero at site #2 (<1%), whereas mean % cover of macrophytes was 17% and 23% at sites #3 and #4, respectively. Unfortunately, we were unable to estimate macrophyte cover at electrofishing transects because we could not see the lake bottom. The trend is an increase in % macrophyte cover over time, although we observed lower % macrophyte cover during fyke netting in 2018 than in 2017 (Figure 2). 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;

both turbidity from inflowing sediment and abundant phytoplankton growth in the lake water column can reduce light penetration.

As stated in past reports, aquatic macrophytes are important habitat for fish (e.g., Radomski and Goeman 2001), and their return is an important goal for the restoration of the fish community in Lake Macatawa. The presence of macrophyte beds in the vicinity of our fish sampling sites were likely related to the lower turbidity that we observed in the lake (2016-2018) compared with 2014-2015 (Figure 3B). A detailed macrophyte survey, conducted on a 3-5 year interval, would provide useful information for Lake Macatawa's ecological status (see Ogdahl and Steinman 2014).

Compared to six Lake Michigan drowned river mouths, water quality in Lake Macatawa was 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 Muskegon Lake, the drowned river mouth lake for which we have the longest time series of water quality observations (Bhagat and Ruetz 2011). 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). Nevertheless, turbidity and specific conductivity were lower in 2018 than in 2014 and 2015 (Figure 3). Within the lake itself, there was a gradient in specific conductivity and turbidity, with higher levels closer at the east end and lower levels closer to Lake Michigan (Tables 2 and 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.

We captured 1,503 fish comprising 28 species in Lake Macatawa during 2018 sampling surveys (Table 4), which was similar to most years (Figure 4). The most abundant fishes in the combined catch (i.e., fyke netting and boat electrofishing in 2018) were bluegill (34%), gizzard shad (32%), and yellow perch (6%), which composed 72% of the total catch (Figure 5A). Four of the 28 species captured during 2018 were non-native to the Great Lakes basin (Bailey et al. 2004)—alewife, common carp, white perch, and round goby—which composed 9% of the total catch (Table 4).

In fyke netting, bluegill (41%), gizzard shad (34%), spotfin shiner (5%), and alewife (4%) were the most abundant fishes in the catch, composing 84% of all fish captured (Figure 5B). Bluegill was the most abundant or second most abundant species in the catch at all sites (Table 5). Gizzard shad was most abundant in the catch at site #2 (Table 5). Although not the most abundant species in the catch, alewife was the next most abundant species at site #3, and spotfin shiner was the next most abundant species at site #4 (Table 5). The number of fish captured also varied among sites, with the most fish captured at sites #2 and #1 (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 differences in the relative abundance (i.e., percentage of a fish species in the total catch for a given year) were that we captured more bluegill in 2018 than previous years (Figure 7). The relative abundance of gizzard shad and alewife in 2018 also was high compared with most other years, whereas brook silverside was much lower than in 2017 (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 (24%), yellow perch (22%), white perch (13%), largemouth bass (12%), pumpkinseed (8%), and bluegill (7%), which composed 86% of the total catch (Figure 5C). Yellow perch was most abundant in the catch at sites #2 and #4, and gizzard shad was most abundant in the catch at sites #1 and #3 (Table 6). The next most abundant species in the catch was gizzard shad at site #2, largemouth bass at site #4, and white perch at sites #1 and #3 (Table 6). Total catch also varied among sites in 2018, with the higher catch at sites #2 and #4 and lower catch at sites #3 and #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., 2016-2018; Figure 8). Overall, there appears to be less variability in species composition for boat electrofishing surveys compared with fyke netting surveys (see Figure 8 vs. Figure 7). The main difference in the littoral fish assemblage among annual electrofishing surveys was that gizzard shad, largemouth bass, and bluegill were more common and spottail shiner and pumpkinseed were less common in 2016-2018 compared with 2014-2015 (Figure 8).

In conclusion, the observations reported here are the fifth year of an effort to characterize the littoral fish assemblage of Lake Macatawa. This monitoring effort will provide a baseline to assess how the fish assemblage responds to restoration activities in the Lake Macatawa watershed. Although we have completed only 5 years of fish monitoring, we observed differences in total catch (Figure 6) and relative abundance among years (Figures 7 and 8). 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.

Acknowledgements

We thank Dr. Alan Steinman for facilitating our role in fish monitoring as part of Project Clarity as well as comments on this report. Rachel Orzechowski assisted with boat electrofishing in 2018. Andrya Whitten was a coauthor on previous reports (years 1 and 2), and this report is an update of those.

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Table 1. Locations (latitude and longitude) for each 2018 fish sampling site; coordinates are the mean of the three fyke nets and the start and end of each boat electrofishing transect. Site locations are depicted in Figure 1.

			Electrofishing			
	Fyke netting		Start		End	
Site	Lat (°)	Long (°)	Lat (°)	Long (°)	Lat (°)	Long (°)
1	42.79559	-86.12270	42.79578	-86.12104	42.79568	-86.12351
2	42.78843	-86.14423	42.78807	-86.14469	42.79000	-86.14377
3	42.78651	-86.17490	42.78402	-86.17302	42.78671	-86.17510
4	42.77990	-86.19661	42.77902	-86.19801	42.78053	-86.19601

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 4 September 2018 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	95±1	26.49±0.10	13.50±0.15	168.0±0.7	504±1	0.33±0.00	14.8±1.5	8.67±0.04	--	77.8±2.7
2	93±17	25.72±0.01	13.43±0.59	164.9±7.2	482±0	0.31±0.00	11.8±0.4	8.71±0.00	--	103.7±4.4
3	96±1	24.96±0.04	11.69±0.23	141.5±2.7	410±1	0.27±0.00	12.5±3.3	8.89±0.01	--	50.7±3.6
4	83±5	24.72±0.05	12.49±0.18	150.5±2.0	406±0	0.26±0.00	11.1±3.6	8.96±0.00	--	44.8±7.0

Table 3. Water quality variables at fish sampling sites in Lake Macatawa. Measurements were made during nighttime boat electrofishing on 6 September 2018 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	24.59	8.88	106.8	530	0.345	15.6	7.92	--	80.3
2	24.30	8.99	107.5	493	0.320	12.9	8.22	--	76.6
3	24.02	10.27	122.2	430	0.280	11.6	8.71	--	74.2
4	23.82	10.73	127.2	415	0.270	5.9	8.81	--	44.8

Table 4. Number and mean total length (TL; ranges reported parenthetically) of fish captured by fyke netting (*n* = 12 nets) on 5 September 2018 and boat electrofishing (*n* = 4 transects) on 6 September 2018 at four sites in Lake Macatawa. Total catch combined both gears.

		Total	Fyke netting		Electrofishing	
Common name	Scientific name	Catch	Catch	TL (cm)	Catch	TL (cm)
alewife	*Alosa pseudoharengus*	51	51	6.7 (4.8-10.0)	0	--
bowfin	*Amia calva*	4	3	52.9 (41.9-64.1)	1	37.5
freshwater drum	*Aplodinotus grunniens*	3	0	--	3	18.5 (9.9-23.0)
white sucker	*Catostomus commersonii*	26	13	41.1 (27.5-47.7)	13	41.6 (36.2-48.0)
spotfin shiner	*Cyprinella spiloptera*	63	63	7.2 (3.5-9.8)	0	--
common carp	*Cyprinus carpio*	4	0	--	4	58.3 (55.4-60.3)
gizzard shad	*Dorosoma cepedianum*	475	401	8.2 (4-14.9)	74	11.7 (7.4-18.2)
muskellunge	*Esox masquinongy*	1	1	13.1	0	--
banded killifish	*Fundulus diaphanus*	3	2	6.5 (6.3-6.7)	1	9.4
channel catfish	*Ictalurus punctatus*	10	9	45.2 (39.4-51.2)	1	54.9
brook silverside	*Labidesthes sicculus*	13	12	5.9 (5.0-7.0)	1	5.1
pumpkinseed	*Lepomis gibbosus*	53	29	11.2 (4.3-16.8)	24	14.3 (5.9-16.5)
bluegill	*Lepomis macrochirus*	505	482	3.8 (2.1-18.6)	23	15.5 (5.9-19.5)
largemouth bass	*Micropterus salmoides*	49	11	19.7 (4.7-45.1)	38	19.6 (5.7-48.8)
white perch	*Morone americana*	64	23	12.0 (9.0-21.1)	41	10.3 (8.9-17.8)
white bass	*Morone chrysops*	1	0	--	1	16.3
silver redhorse	*Moxostoma anisurum*	2	0	--	2	63.9 (63.9-63.9)
shorhead redhorse	*Moxostoma macrolepidotum*	1	1	47.5	0	--
round goby	*Neogobius melanostomus*	11	11	5.8 (3.7-12.1)	0	--
golden shiner	*Notemigonus crysoleucas*	16	13	5.2 (3.7-9.4)	3	16.9 (14.0-21.3)
emerald shiner	*Notropis atherinoides*	4	3	9.1 (8.9-9.5)	1	5.1
spottail shiner	*Notropis hudsonius*	16	7	7.1 (3.7-10.6)	9	9.6 (8.1-11.9)
mimic shiner	*Notropis volucellus*	1	1	4.3	0	--
yellow perch	*Perca falvescens*	97	27	15.0 (8.2-20.3)	70	14.4 (8.4-19.5)
bluntnose minnow	*Pimephales notatus*	26	26	5.7 (4.2-8.9)	0	--
black crappie	*Pomoxis nigromaculatus*	1	1	9.2	0	--
flathead catfish	*Pylodictis olivaris*	1	1	86.0	0	--
walleye	*Sander vitreus*	2	0	--	2	53.3 (47.3-59.3)
	Total	**1503**	**1191**		**312**	

Table 5. Number and mean total length (TL; range reported parenthetically) of fish captured by fyke netting (n = 3 nets per site) at four sites in Lake Macatawa on 5 September 2018. Site locations are depicted in Figure 1.

		Site #1		Site #2		Site #3		Site #4	
Common name	Scientific name	Catch	TL (cm)	Catch	TL (cm)	Catch	TL (cm)	Catch	TL (cm)
alewife	*Alosa pseudoharengus*	0	--	0	--	50	6.7 (4.8-10.0)	1	6.4
bowfin	*Amia calva*	0	--	0	--	2	58.5 (52.8-64.1)	1	41.9
white sucker	*Catostomus commersonii*	4	38.2 (27.5-44.0)	1	42.3	4	41.0 (35.6-47.7)	4	43.8
spotfin shiner	*Cyprinella spiloptera*	1	8.1	17	6.8 (3.5-8.9)	5	8.4 (6.8-9.8)	40	7.1 (4.4-9.0)
gizzard shad	*Dorosoma cepedianum*	9	11.0 (7.1-14.4)	386	8.2 (6.1-13.6)	5	9.1 (4.0-11.0)	1	14.9
muskellunge	*Esox masquinongy*	1	13.1	0	--	0	--	0	--
banded killifish	*Fundulus diaphanus*	0	--	0	--	0	--	2	6.5 (6.3-6.7)
channel catfish	*Ictalurus punctatus*	3	41.2 (39.4-42.5)	3	48.9 (47.6-51.2)	1	44.6	2	45.9 (45.6-46.2)
brook silverside	*Labidesthes sicculus*	2	6.2 (6.1-6.3)	0	--	0	--	10	5.8 (5.0-7.0)
pumpkinseed	*Lepomis gibbosus*	10	11.3 (5.7-15.4)	5	14.8 (11.2-16.8)	4	13.0 (5.4-16.0)	10	8.5 (4.3-15.3)
bluegill	*Lepomis macrochirus*	209	3.9 (2.1-18.6)	96	3.8 (2.6-17.7)	92	3.6 (2.7-5.6)	85	4.0 (2.8-15.9)
largemouth bass	*Micropterus salmoides*	3	33.3 (12.8-45.1)	0	--	3	19.9 (4.7-44.1)	5	11.3 (7.2-24.3)
white perch	*Morone americana*	4	10.3 (9.7-11.2)	12	13.9 (9.1-21.1)	2	10.3 (9.8-10.7)	5	9.7 (9.0-10.7)
shorhead redhorse	*Moxostoma macrolepidotum*	1	47.5	0	--	0	--	0	--
round goby	*Neogobius melanostomus*	1	5.4	2	6.6 (6.6-6.6)	1	4.0	7	5.9 (3.7-12.1)
golden shiner	*Notemigonus crysoleucas*	9	4.8 (3.7-9.4)	0	--	1	4.1	3	6.9 (4.6-8.5)
emerald shiner	*Notropis atherinoides*	1	8.9	0	--	1	9.5	1	9.0
spottail shiner	*Notropis hudsonius*	1	7.7	2	3.7 (3.7-3.7)	3	9.8 (8.3-10.6)	1	5.3
mimic shiner	*Notropis volucellus*	0	--	0	--	0	--	1	4.3
yellow perch	*Perca falvescens*	9	13.4 (8.6-19.6)	6	15.7 (9.7-18.4)	8	15.4 (8.2-20.3)	4	46.8 (14.9-19.1)
bluntnose minnow	*Pimephales notatus*	4	7.5 (6.2-8.7)	0	--	0	--	22	5.4 (4.2-8.9)
black crappie	*Pomoxis nigromaculatus*	1	9.2	0	--	0	--	0	--
flathead catfish	*Pylodictis olivaris*	1	86.0	0	--	0	--	0	--
	Total	**274**		**530**		**182**		**205**	

Table 6. Number and mean total length (TL; range reported parenthetically) of fish captured by nighttime boat electrofishing (n = 1 transect per site) at four sites in Lake Macatawa on 6 September 2018. Site locations are depicted in Figure 1.

		Site #1		Site #2		Site #3		Site #4	
Common name	Scientific name	Catch	TL (cm)	Catch	TL (cm)	Catch	TL (cm)	Catch	TL (cm)
bowfin	*Amia calva*	0	--	0	--	0	--	1	37.5
freshwater drum	*Aplodinotus grunniens*	0	--	1	9.9	0	--	2	22.9 (22.7-23.0)
white sucker	*Catostomus commersonii*	0	--	2	40.9 (38.0-43.8)	2	40.9 (39.7-42.0)	9	42.0 (36.2-48.0)
common carp	*Cyprinus carpio*	1	55.4	1	57.4	2	60.3 (60.2-60.3)	0	--
gizzard shad	*Dorosoma cepedianum*	10	9.1 (7.4-12.0)	25	11.5 (10.3-17.8)	33	12.7 (8.6-18.2)	6	11.8 (9.3-13.2)
banded killifish	*Fundulus diaphanus*	0	--	0	--	0	--	1	9.4
channel catfish	*Ictalurus punctatus*	0	--	0	--	0	--	1	54.9
brook silverside	*Labidesthes sicculus*	0	--	1	5.1	0	--	0	--
pumpkinseed	*Lepomis gibbosus*	3	13.2 (10.6-16.0)	13	14.5 (11.0-16.5)	1	14.7	7	14.2 (5.9-16.2)
bluegill	*Lepomis macrochirus*	3	16.4 (16.0-16.6)	17	15.5 (5.9-19.5)	1	13.2	2	15.8 (15.0-16.6)
largemouth bass	*Micropterus salmoides*	7	23.1 (14.0-48.8)	15	24.4 (14.9-33.8)	0	--	16	13.7 (5.7-34.0)
white perch	*Morone americana*	8	12.0 (9.5-17.8)	17	9.8 (8.9-10.3)	4	9.5 (9.2-9.8)	12	10.2 (9.0-16.7)
white bass	*Morone chrysops*	0	--	0	--	1	16.3	0	--
silver redhorse	*Moxostoma anisurum*	1	63.9	0	--	0	--	1	63.9
golden shiner	*Notemigonus crysoleucas*	0	--	0	--	1	14	2	18.4 (15.5-21.3)
emerald shiner	*Notropis atherinoides*	1	5.1	0	--	0	--	0	--
spottail shiner	*Notropis hudsonius*	0	--	4	8.7 (8.2-9.1)	2	9.1 (8.1-10.1)	3	11.2 (10.8-11.9)
yellow perch	*Perca flavescens*	3	17.6 (16.7-19.1)	26	14.7 (9.1-17.6)	2	17.3 (16.1-18.4)	39	13.7 (8.4-19.5)
walleye	*Sander vitreus*	0	--	0	--	2	53.3 (47.3-59.3)	0	--
	Total	**37**		**122**		**51**		**102**	

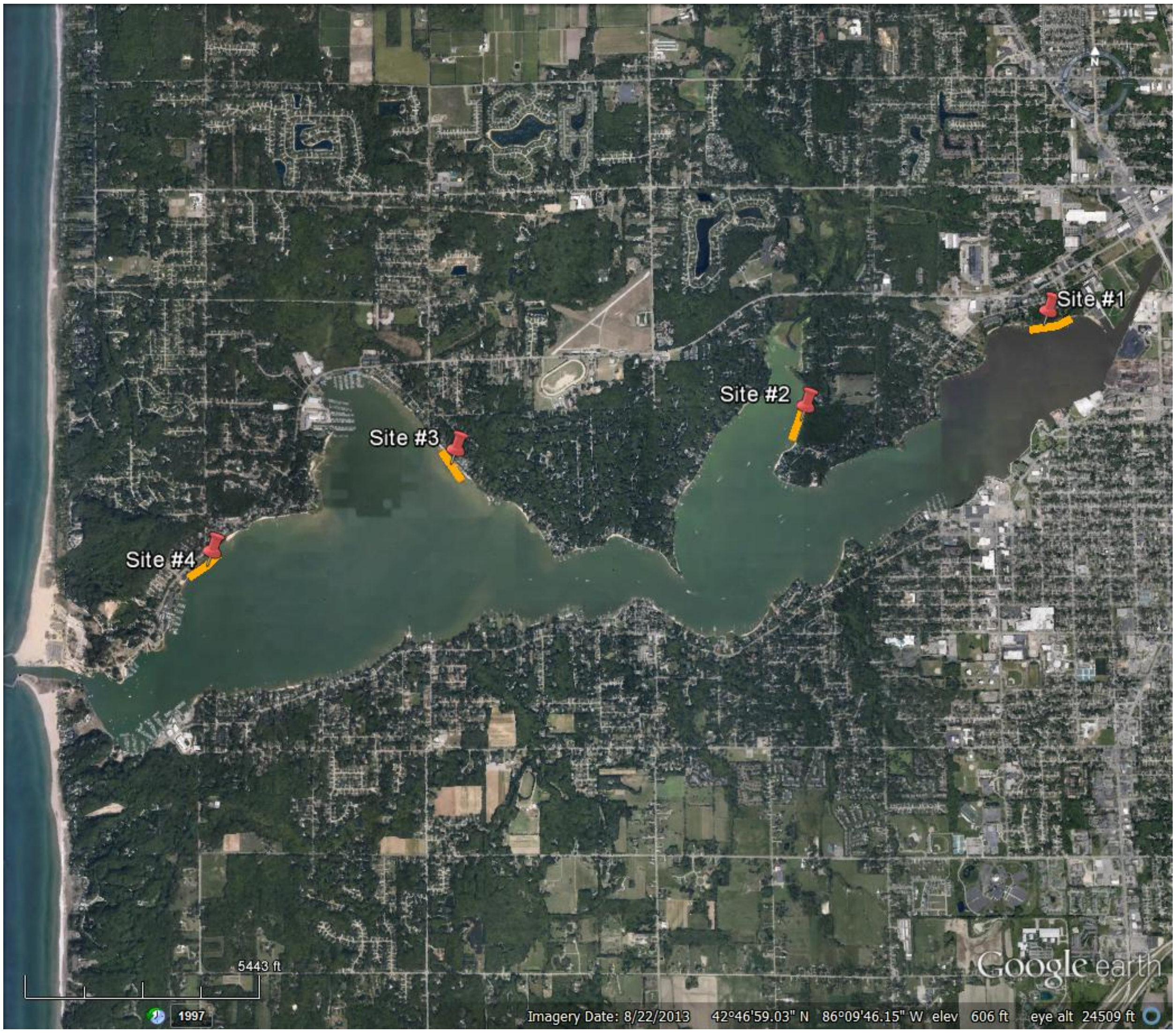


Figure 1. Map of Lake Macatawa (Ottawa County, Michigan) showing fish sampling sites. The orange transects depict approximately where boat electrofishing was conducted at each site. Site #1 is closest to the Macatawa River and site #4 is closest to Lake Michigan.

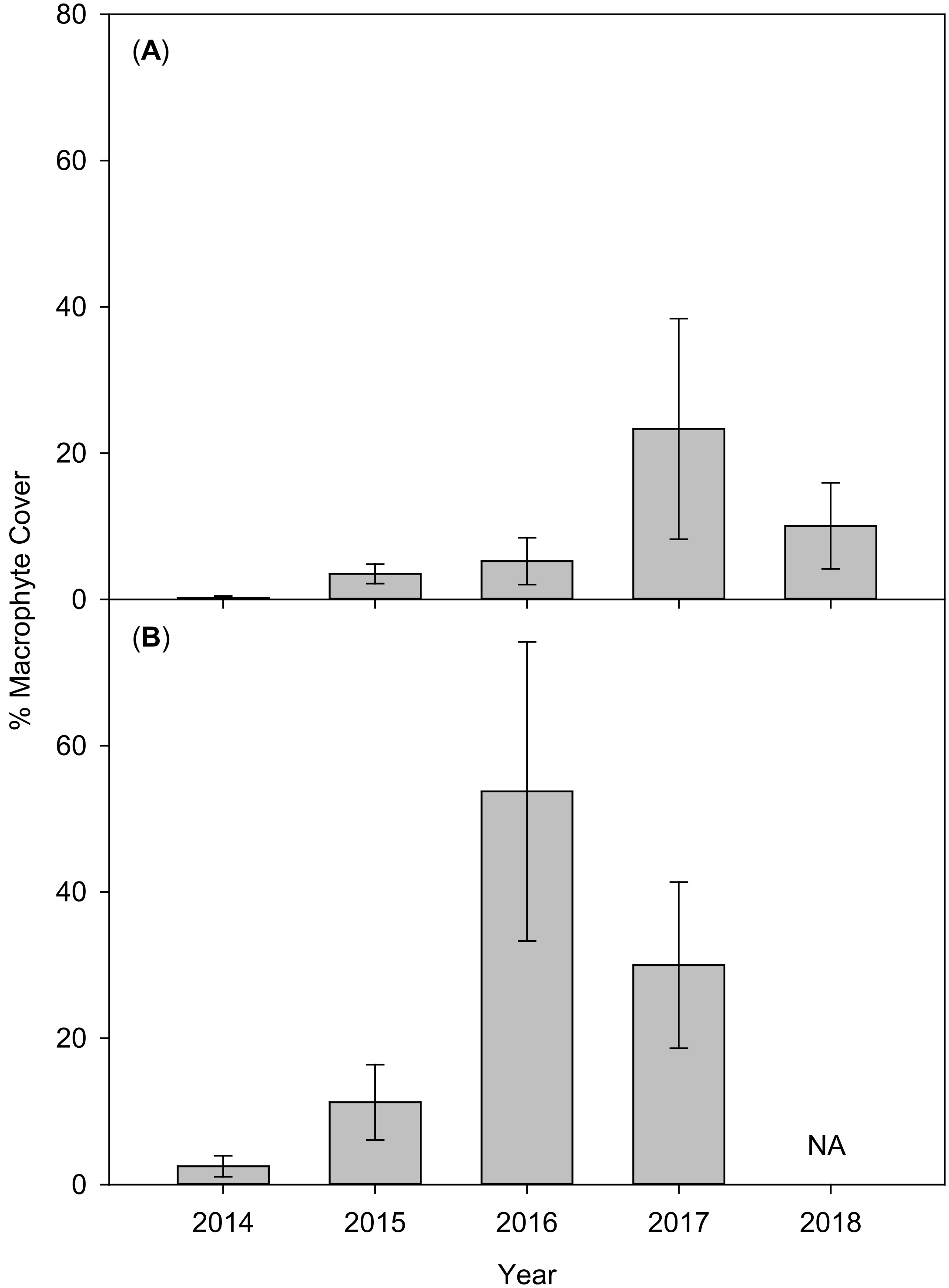


Figure 2. Mean (±1 standard error) % macrophyte cover visually estimated at (**A**) fyke net locations and (**B**) boat electrofishing transects in Lake Macatawa (*n* = 4 sites per year). Note that

the area where macrophyte cover is assessed during fyke netting is much less compared with a boat electrofishing transect. NA means data were not available.

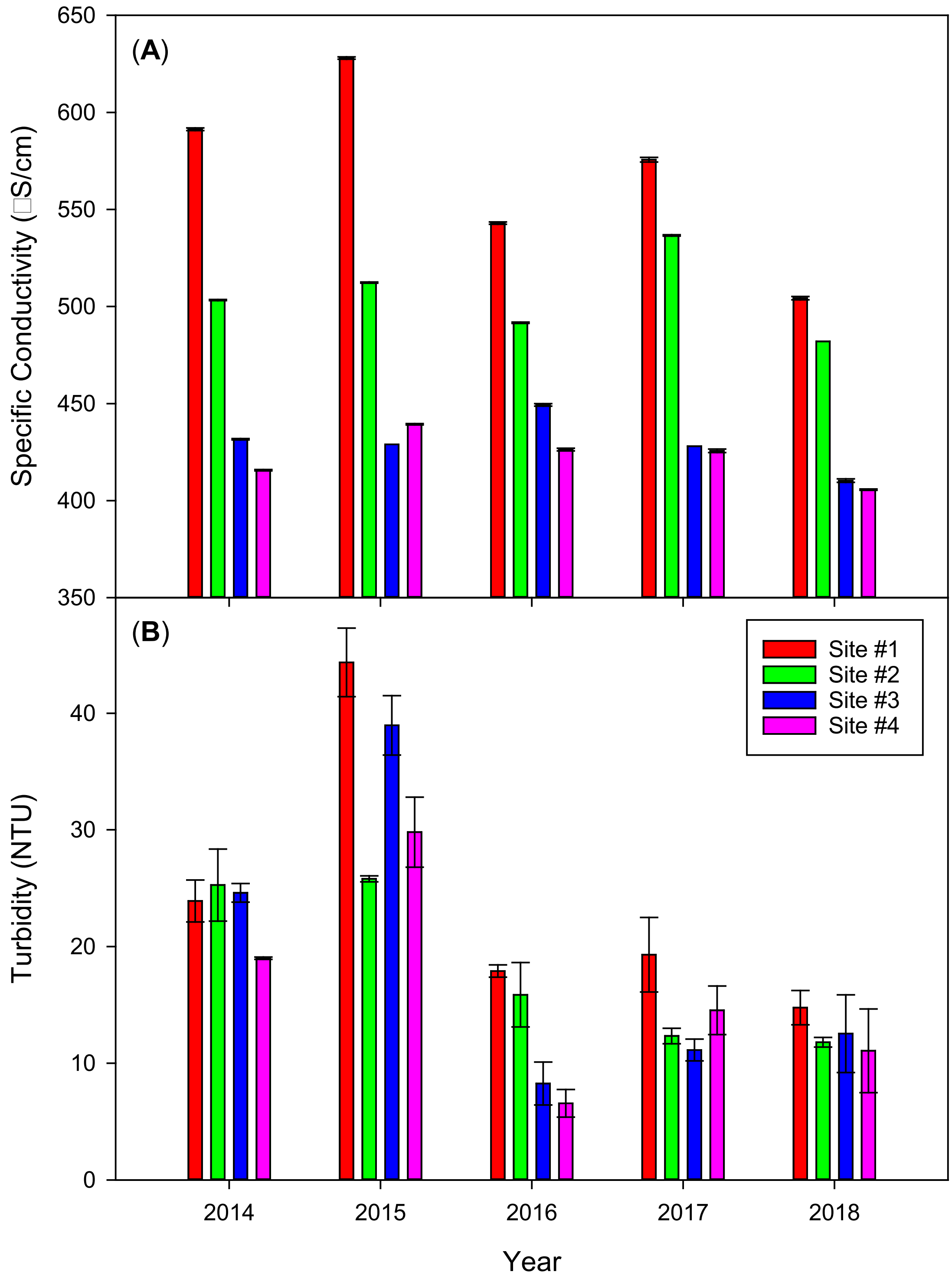


Figure 3. Mean (**A**) specific conductivity and (**B**) turbidity measured during fyke netting in Lake Macatawa. Error bars represent ±1 standard error (*n* = 3 nets per site), although they may be too small to be visible for some means.

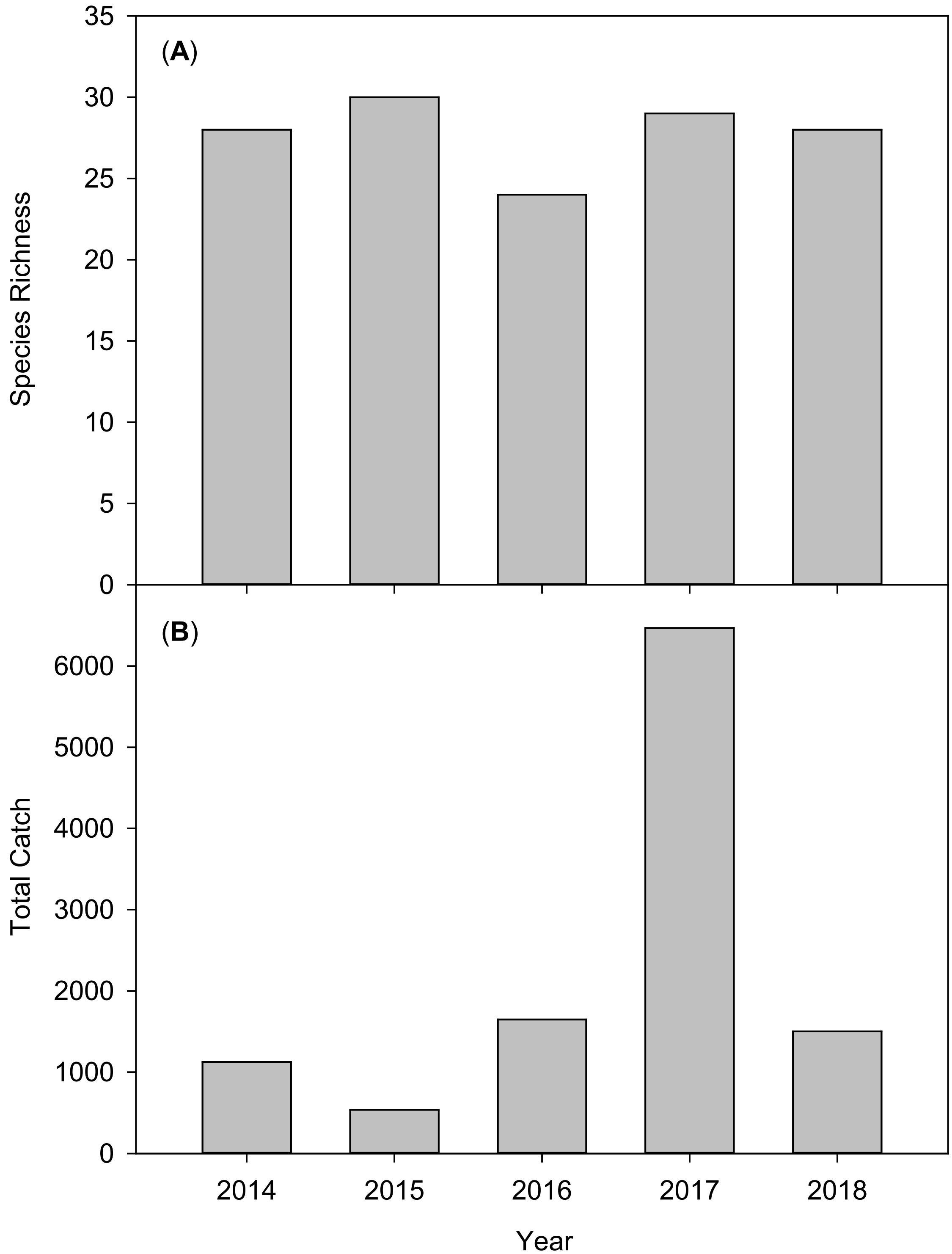


Figure 4. (**A**) Number of fish species captured and (**B**) total number of fish captured using both fyke netting and boat electrofishing each year in Lake Macatawa. *Note*: the high catch in 2017 was due to 5,288 brook silversides captured from a single fyke net at site #4.

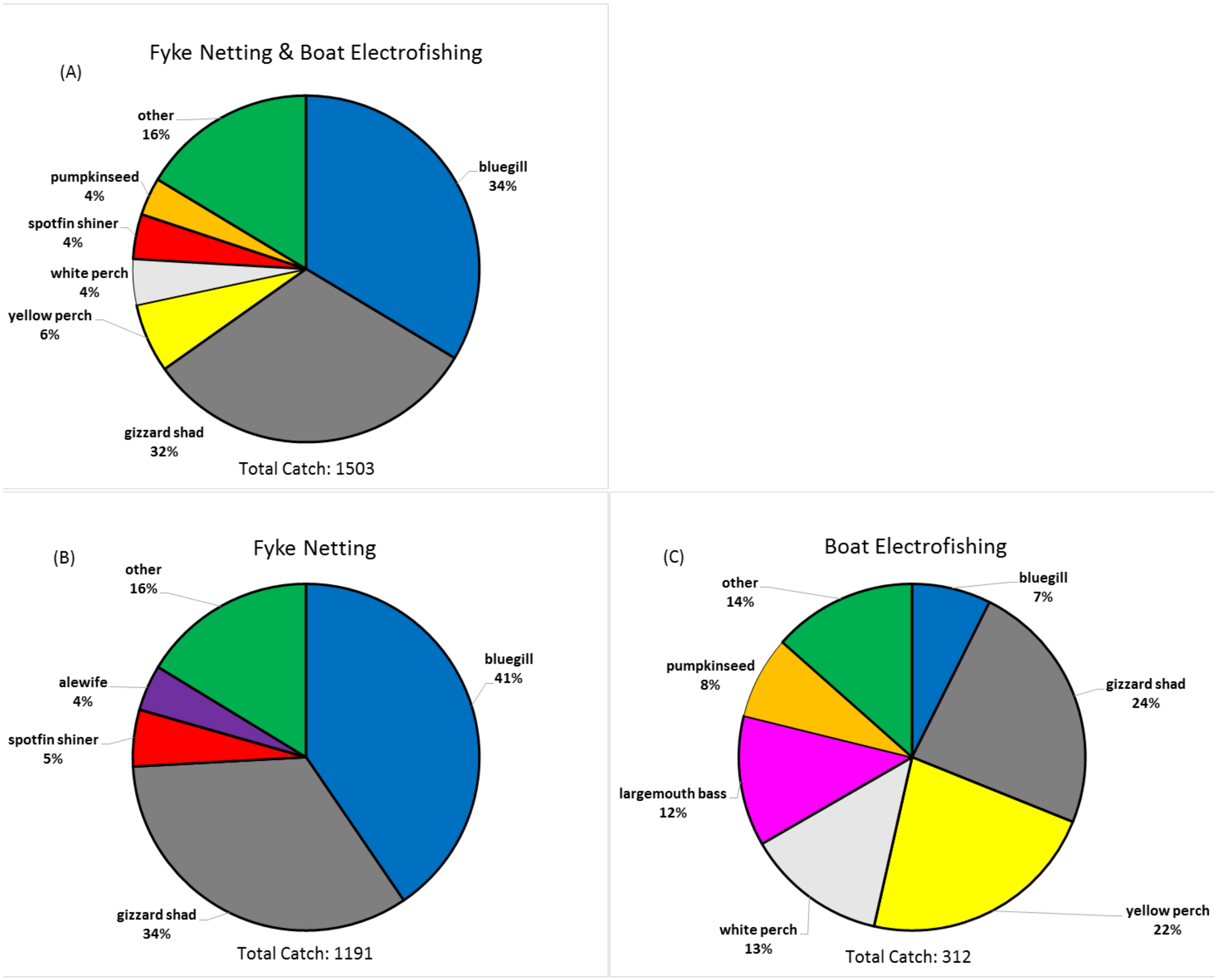


Figure 5. Fish species captured in littoral habitats of Lake Macatawa by (**A**) fyke netting and boat electrofishing (i.e., combined catch), (**B**) fyke netting (n = 12 nets), and (**C**) boat electrofishing (n = 4 transects) during September 2018. Catch data, including the species pooled in the "other" category, are reported in Table 4.

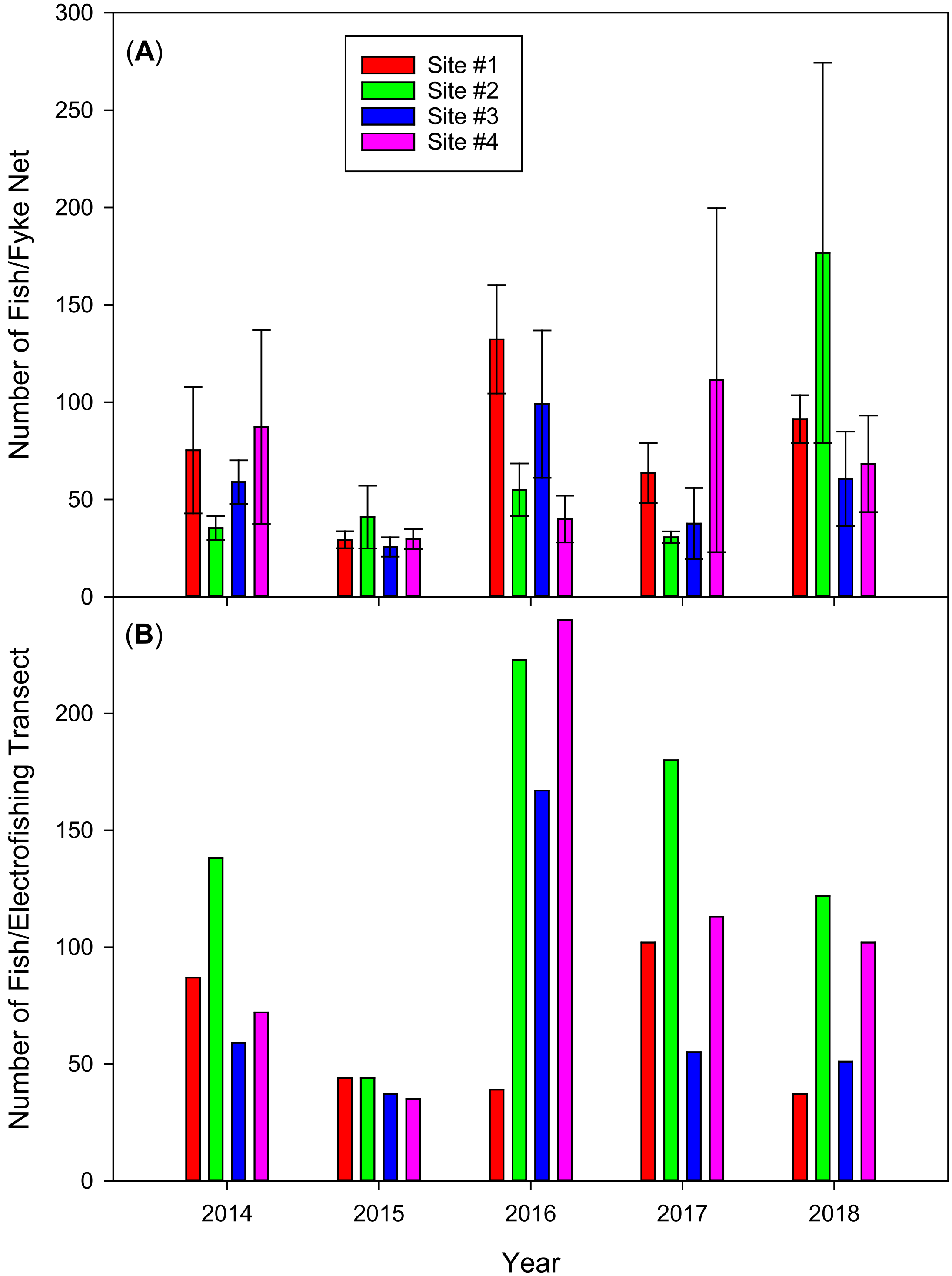


Figure 6. (**A**) Mean number (±1 standard error) of fish captured in fyke nets (*n* = 3 nets per site) and (**B**) number of fish captured during a boat electrofishing transect (*n* = 1 transect per site) in Lake Macatawa. *Note*: 5,288 brook silversides captured in a single fyke net at site #4 in 2017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

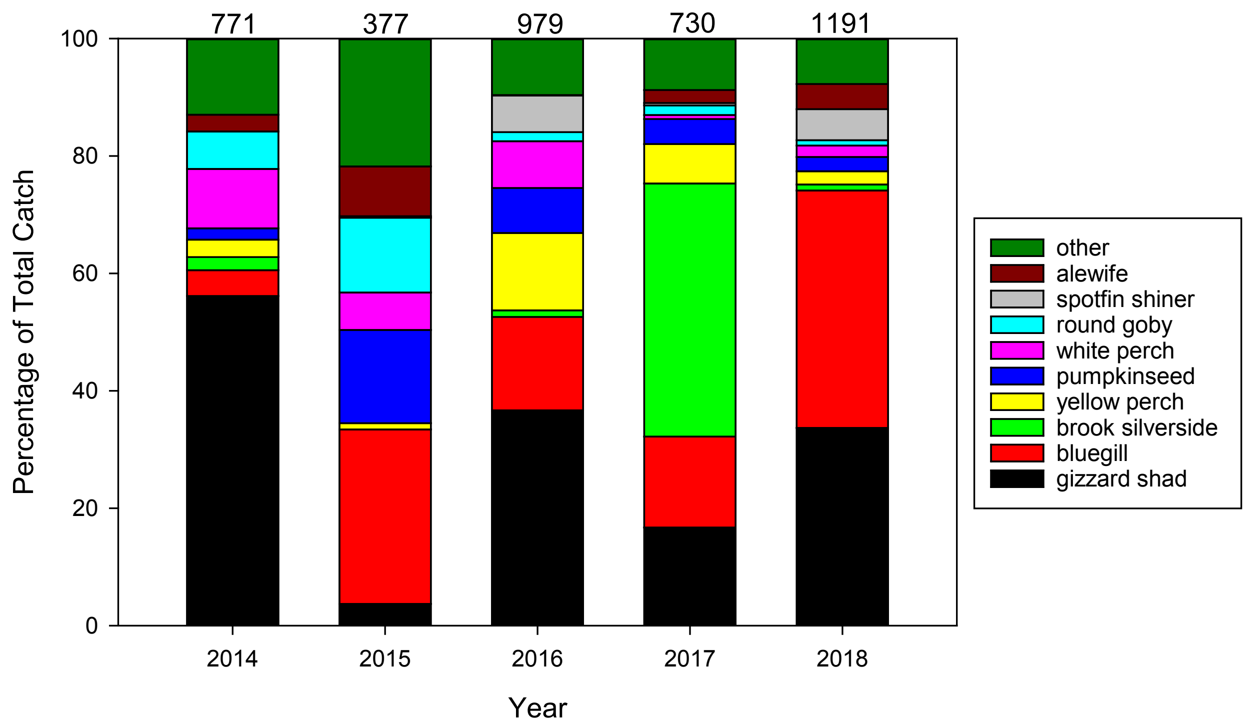


Figure 7. Fish species composition (pooled across sites) in fyke netting surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar. *Note*: 5,288 brook silversides captured in a single fyke net at site #4 in 2017 were excluded from the percentage of total catch.

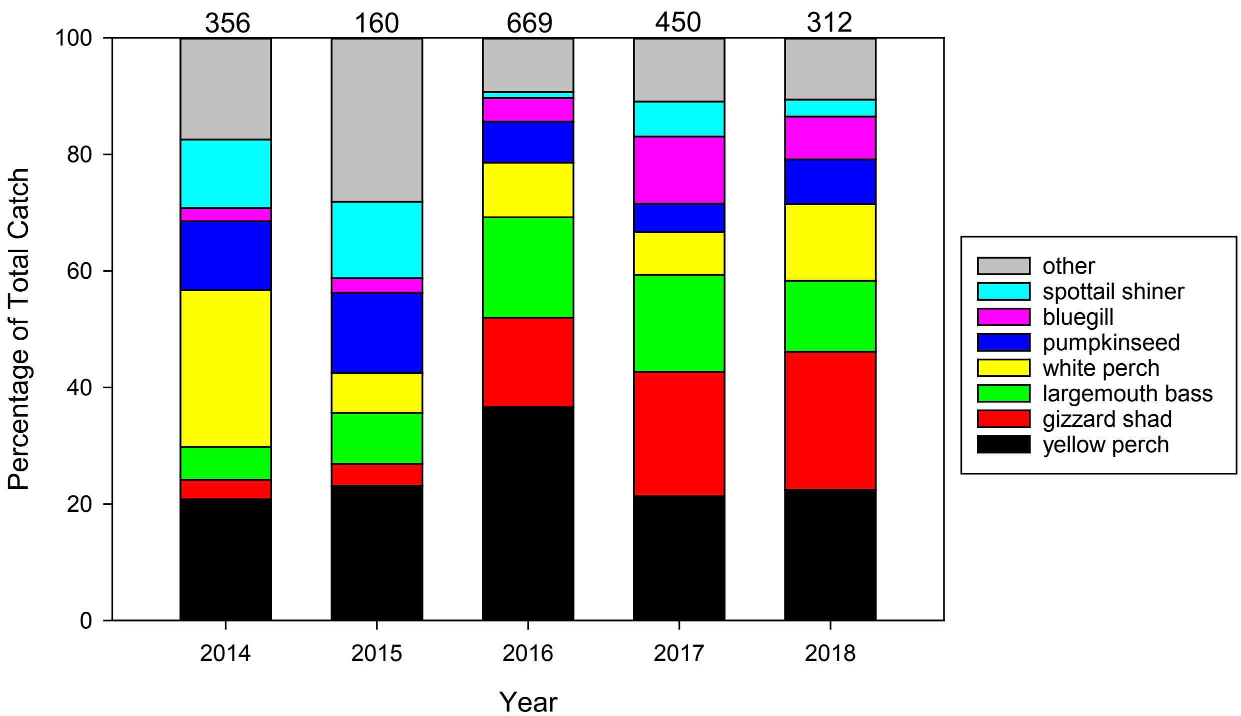


Figure 8. Fish species composition (pooled across sites) in nighttime boat electrofishing surveys for each sampling year. The number of fish captured differed among years, which is reported at the top of each bar.

Appendix B.

Lake Macatawa Water Quality Dashboard

2018

Prepared: February 2019

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

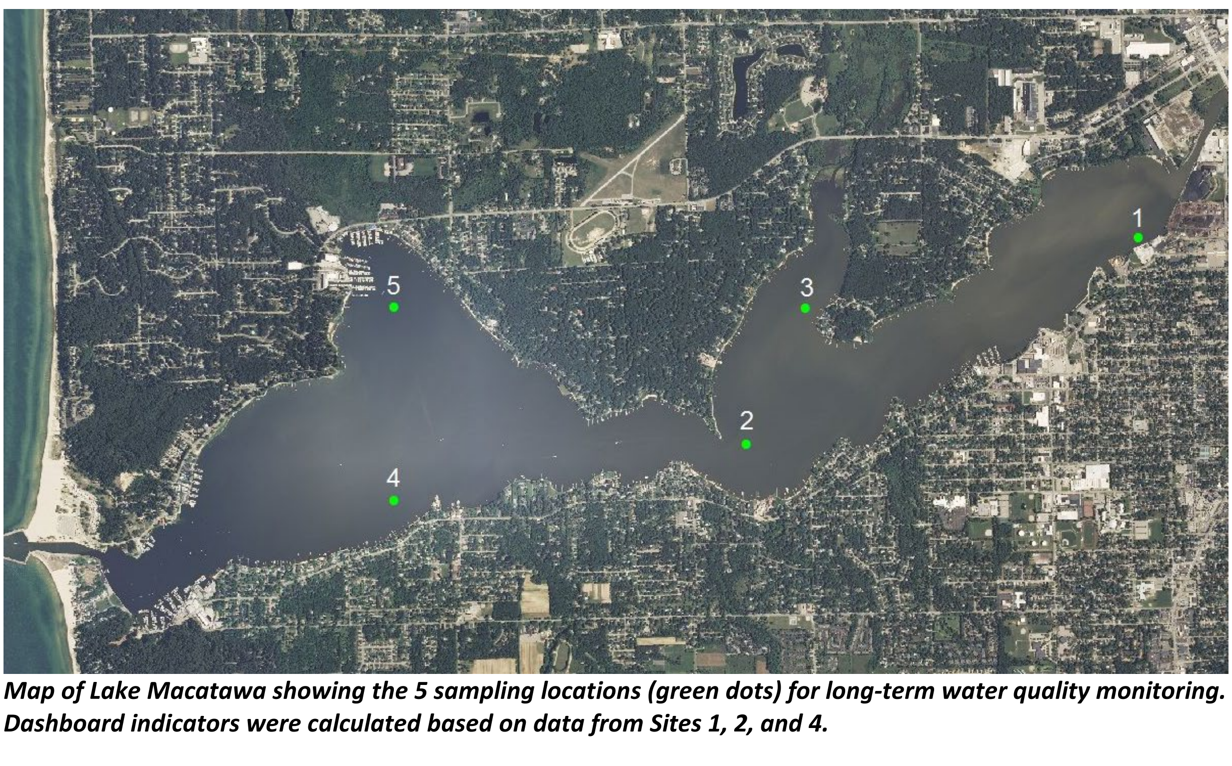
Grand Valley State University
Robert B. Annis Water Resources Institute

Introduction

As part of Project Clarity, Grand Valley State University's Annis Water Resources Institute (AWRI) established a monitoring program on Lake Macatawa in 2013. The goal of the monitoring program is to evaluate and document the progress toward achieving Project Clarity's goal of improved water quality in Lake Macatawa. The monitoring program involves sampling the lake 3 times per year for a suite of biological, physical, and chemical parameters.

Key water quality indicators were selected from the many parameters that are monitored to create a water quality dashboard for Lake Macatawa (please 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.

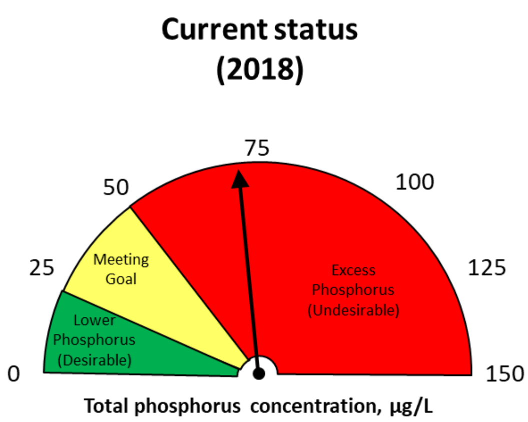
Historical data are included in the dashboard to facilitate comparison of current findings with past status of the selected water quality indicators. Sources for historical data include U.S. EPA (1972; STORET), Michigan Department of Environmental Quality (1982-2012; S. Holden, personal communication), 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).

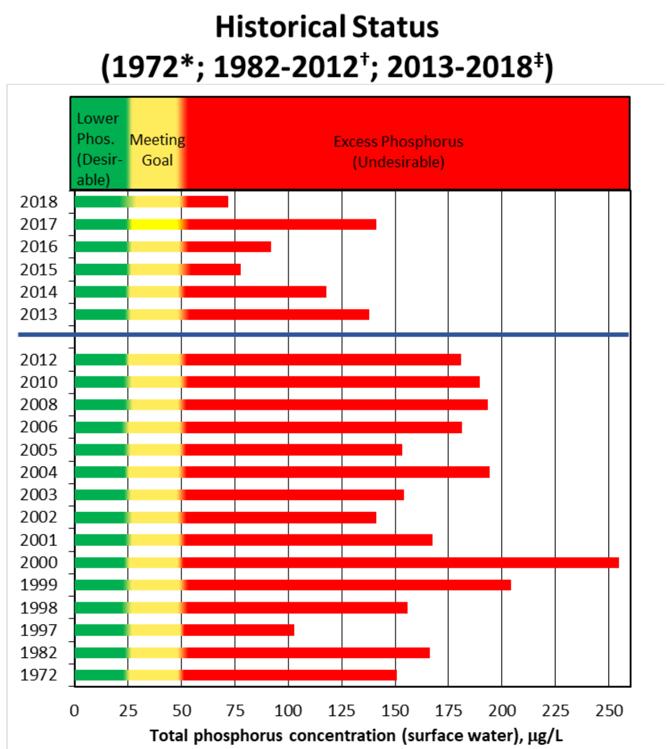


Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring. Dashboard indicators were calculated based on data from Sites 1, 2, and 4.

Total Phosphorus

2018 Mean Concentration: 72 µg/L
Target Concentration: 50 µg/L





*U.S. EPA; †MDEQ; ‡AWRI

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

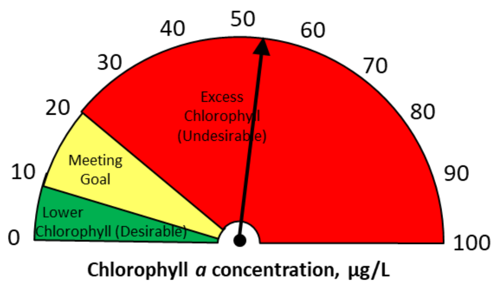
Lake Macatawa has a history of extremely high TP concentrations (i.e., > 100 µg/L), placing it in the "hypereutrophic" trophic state. As a result of this nutrient enrichment, the State of Michigan has established an interim target TP concentration of 50 µg/L in Lake Macatawa. Thus, the TP dashboard shows 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 2018 exceeded the water quality goal. Some annual variation in TP concentration should be expected and although mean 2018 TP concentrations remain above the target concentration observed in Lake Macatawa, it is encouraging to see that mean 2018 concentrations were considerably lower than those in 2017.

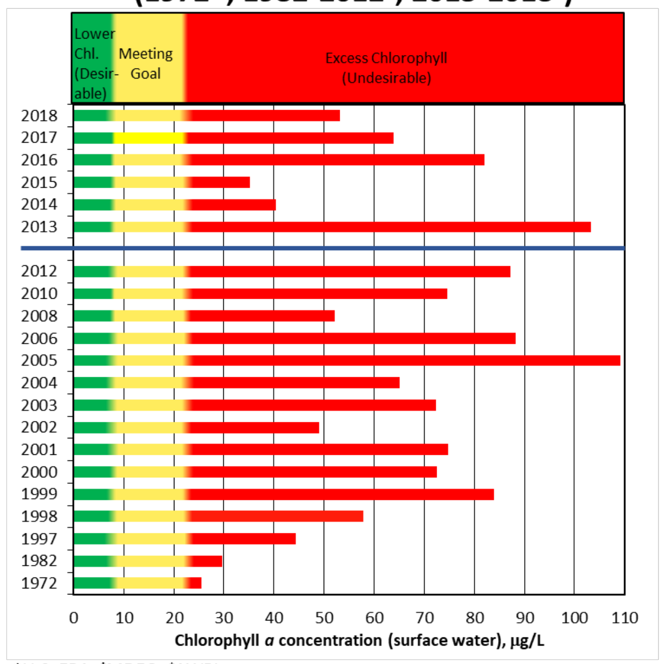
Chlorophyll *a*

2018 Mean Concentration: 53 µg/L
Target Concentration: 20 µg/L

Current status (2018)



Historical Status (1972*; 1982-2012†; 2013-2018‡)



*U.S. EPA; †MDEQ; ‡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, so the measurement may give an underestimate of how much algal biomass would otherwise be present.

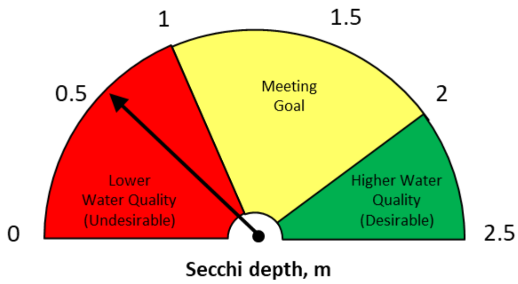
Lake Macatawa has a history of excess algal biomass and high chlorophyll *a* concentrations, typically exceeding the "hypereutrophic" threshold commonly used by MDEQ (22 µg/L) in its assessments of the lake. The chlorophyll *a* dashboard shows that the concentration will meet the water quality goal once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

The current status for the chlorophyll *a* indicator is **Undesirable**, meaning that the average chlorophyll *a* concentration in 2018 exceeded the water quality goal. While 2018 mean chlorophyll concentration continues the declining trend started in 2016, levels remain unacceptably high.

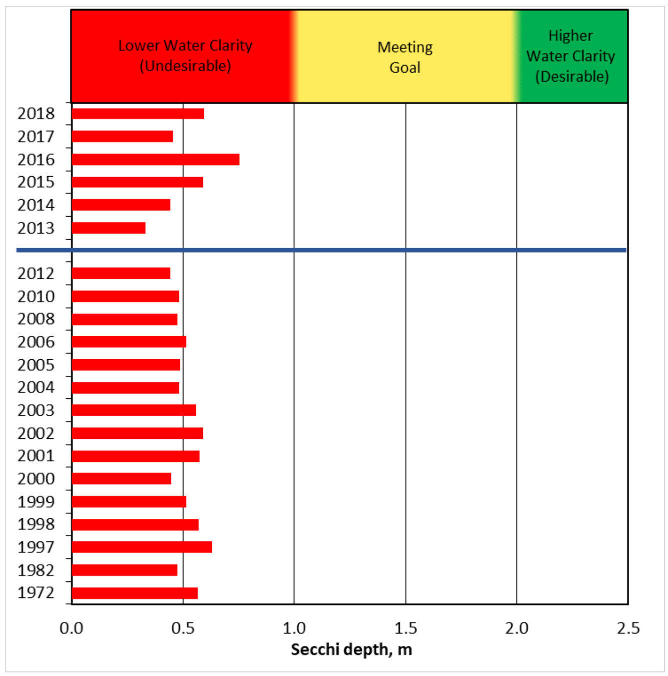
Secchi Disk Depth (Water Clarity)

2018 Mean Depth: 0.6 m (~ 2ft)
Target Depth: 1.0 m (~ 3.3 ft)

Current status (2018)



Historical Status (1972*; 1982-2012†; 2013-2018‡)



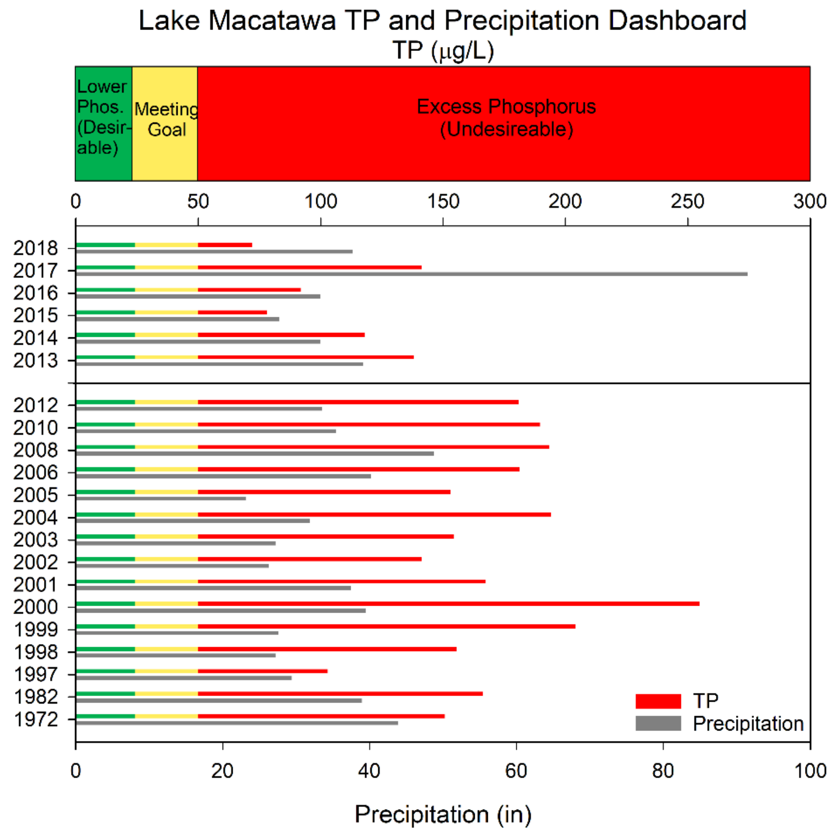
*U.S. EPA; †MDEQ; ‡AWRI

Secchi disk depth is an estimate of water clarity. It is measured using a standard black and white disk, named after 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. The water clarity goal for Lake Macatawa is modest, with a Secchi depth > 1 m. Because Secchi depths between 1 and 2 m are indicative of a eutrophic state, a desirable Secchi depth is > 2 m.

The current status for the Secchi depth indicator is **Undesirable**, meaning that the average Secchi depth in 2018 was shallower (i.e., less clear) than the water quality goal. The small improvement in water clarity from 2017 to 2018 may be related to the decrease in chlorophyll concentration during the same timeframe.

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 also 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 MDEQ 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 2018, the relationship between precipitation and TP concentration in the lake was not statistically significant ($R^2 = 0.004$; $p = 0.788$). 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). Interestingly, the relationship between TP and precipitation is much improved since 2013 ($R^2 = 0.384$; $p = 0.190$) but is still not statistically significant. This relationship is based on only 6 data points, so it should be viewed cautiously. We view these data as appropriate for screening purposes only, as the TP concentrations are means of seasonal lake sampling events, which likely miss pulses of high P concentrations after storm events.