PROJECT CLARITY
2016 Annual Monitoring Report
(Dec. 2015 – Nov. 2016)

February 2017

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1. Overview

Project Clarity is a large-scale, multidisciplinary, collaborative watershed remediation project aimed at improving water quality in Lake Macatawa. A holistic approach that includes wetland restoration, in-stream remediation, Best Management Practices (BMPs), and community education is being implemented as part of a multimillion dollar public-private partnership. The project is expected to have many economic, social, and ecological benefits – while achieving the ultimate goal of improved water quality in Lake Macatawa.

Lake Macatawa is the terminus of a highly degraded watershed and has exhibited the symptoms of a hypereutrophic lake for more than 40 years (MWP 2012, Holden 2014). Extremely high nutrient and chlorophyll concentrations, excessive turbidity, low dissolved oxygen, and a high rate of sediment deposition 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). Through remediation projects and BMPs focused on key areas in the watershed, Project Clarity is focused on reducing P 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 2016, which represent the first year of post-restoration conditions, in combination with data reported previously from 2013-2015. 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 2014). We also briefly report on complementary studies conducted by AWRI that are not part of the monitoring program, and which are funded by sources external to Project Clarity.

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. Sampling locations (n=3), located on Peter's Creek and the Macatawa River, are indicated with red dots.

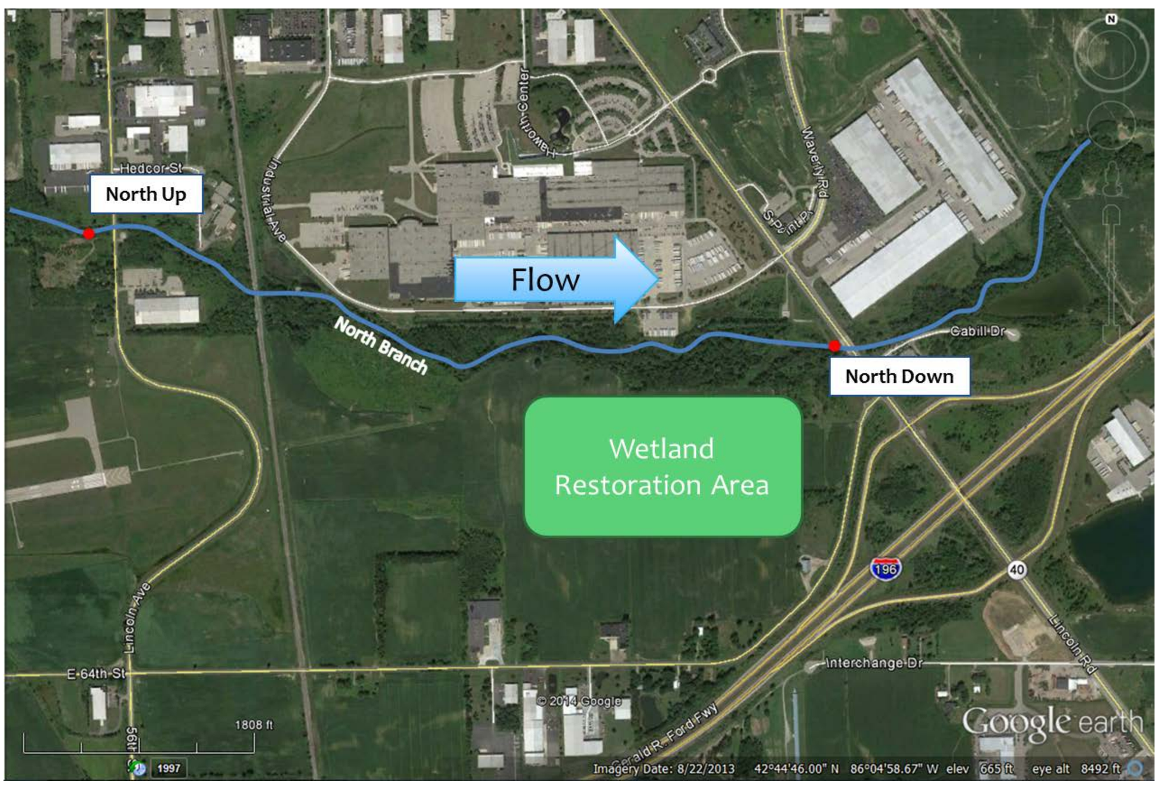

Figure 2. The Haworth wetland restoration study area. Sampling locations (n=2), located on the North Branch of the Macatawa River, are indicated with red dots.

2.2 Wetland Restoration: Middle Macatawa & Haworth Properties

<u>*2.2.1 Monitoring & Data Collection*</u>

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 flows into the Macatawa River) and one downstream site (Macatawa River at the USGS gauging station [Macatawa Down]). Sampling at Adams Street Landing was discontinued in March 2015 due to concerns that the Adams sampling site was too far downstream from the restoration area (~1.5 river miles) to accurately reflect the effect of restoration, so it has been dropped from this 2016 and all future reports. 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.

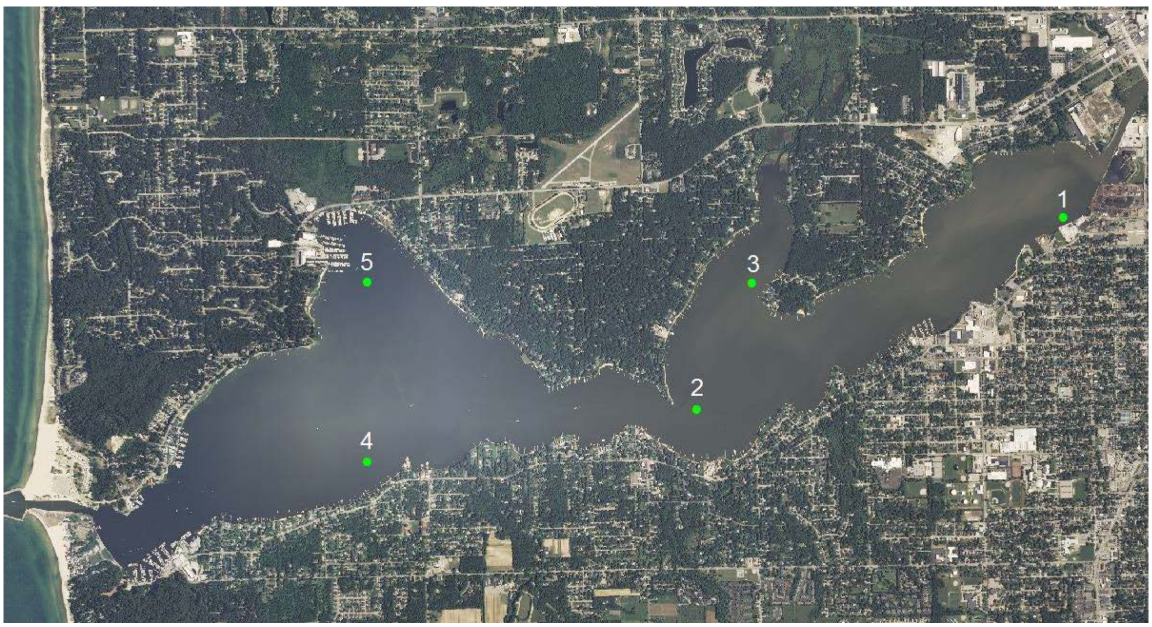

Figure 3. Map of Lake Macatawa showing the 5 sampling locations (green dots) for long-term water quality monitoring.

Water quality and hydrologic monitoring are ongoing and this report includes data from December 2015 through November 2016. Sampling occurred monthly during base flow conditions and during 3 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 base flow conditions and storm events. All samples were placed in a cooler on ice until received by the AWRI lab, usually within 4 hours, where they were stored and processed appropriately (see below).

Table 1. Precipitation summary for storm events sampled by AWRI in 2016.

	3/14/16	8/12/16	10/27/16
Rainfall (in)	0.63	2.78	0.82
Duration (h)	18.22	12.82	18.00
Intensity (in/h)	0.03	0.22	0.05

Water for SRP and NO_3 analysis 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, NH3, 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 installed at each monitoring location. Water level loggers and staff gauges were installed at permanently established transects at 4 of the monitoring locations (the Macatawa Down (USGS) 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 some sites to complete the discharge model; weather permitting, we anticipate having enough samples to complete the model after the 2017 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).

Suspended sediment load associated with high flow events was quantified using PVC sediment collection tubes, which were designed and used by Hope College in previous studies in the Macatawa watershed. Sediment collection tubes were installed near each of the monitoring locations. Sediment samples were collected from the tubes after each high flow event, defined when the USGS gauge station on the Macatawa River reaches 300 cfs, and processed by ODC and/or Hope College staff. The suspended sediment load results will be reported separately by the ODC.

Turbidity sensors (YSI 600OMS V2) were deployed at the upstream and downstream locations on the main branch of the Macatawa River before snowmelt in March 2016. The sensors log turbidity measurements every 30 minutes. These sensors will complement the sediment load data obtained from the passive PVC sediment sampler tubes, capturing smaller storm events and base flow events. The turbidity sensors were removed in December 2016 to avoid possible ice damage and will be returned to their former locations before the final snowmelt in spring of 2017. Concerns arose in the 2015 Project Clarity report from turbidity and precipitation data not consistently aligning; this was found to be caused by a graphical programming error in Microsoft Excel and all precipitation figures in the 2016 report were created in SigmaPlot 13.0 to remedy this.

2.2.2 Data Analysis

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

Upstream vs. Downstream:

Upstream-downstream differences between site pairs (e.g., North Up vs. North Down) within 2016 at baseflow and at storm flow 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.

Pre- vs. Post-Restoration:

Pre- and post-restoration differences were statistically tested separately for each site using two-tailed paired t-tests at baseflow and either two-tailed unpaired t-tests (normally distributed data) or Mann-Whitney rank sum tests (non-normally distributed data) at storm flow. In order to remove seasonality as a potentially biasing factor in analyses and because not all samples were taken at the same time from all sites, paired t-tests for baseflow incorporated an equal number of samples ($n = 10$) from identical months in pre- and post-restoration periods (Jan., Feb., Mar., Apr., Jun., Jul., Sep., Oct., Nov., Dec.). Storm flow analyses incorporated all possible sampled storm events (pre-restoration: $n = 4$ [North Up] or $n = 5$ [North Down, all Middle Macatawa sites]; post-restoration: $n = 3$ [all Haworth and Middle Macatawa sites]).

Normality was tested using the Shapiro-Wilk test and equal variance was tested using the Brown-Forsythe test. Data not meeting test assumptions of normality and equal variance were transformed prior to analysis. Statistical significance was indicated by p-values < 0.05. Trends of marginal significance were indicated by p-values < 0.10. All statistical tests were performed using SigmaPlot 13.0.

Upstream and downstream streambank reaches were analyzed with Light Detection and Ranging (LIDAR) technology to measure sediment erosion and deposition. A full report on this effort is included in Appendix A.

2.3 Lake Macatawa: Long-Term Monitoring

Water quality monitoring in the lake was conducted at 5 sites during spring, summer, and fall 2016 (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*, 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, and chlorophyll *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

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

The fish community was sampled in fall 2016. A full report on this effort is included in Appendix B.

This first year of post-restoration analysis of lake monitoring data is focused on characterizing the water quality status of the lake, including comparisons to established water quality targets, and identification of seasonal trends. Understanding and documenting these baseline characteristics will facilitate the detection of future changes due to restoration.

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 generate atmospheric deposition. As a consequence, it is of interest to know if changes in lake phosphorus concentrations are related more 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 total phosphorus (TP) concentrations near the Middle Macatawa restored wetland and in Lake Macatawa compared to precipitation data from the Tulip Airport in Holland using data from MDEQ, AWRI, the National Climatic Data Center (NCDC), and Weather Underground. Linear regressions on TP and precipitation data were conducted in SigmaPlot 13.0.

3. Results and Discussion

3.1 Wetland Restoration: Middle Macatawa Property

3.1.1 Sampling Year 2016

Baseflow: Baseflow concentrations of dissolved oxygen (DO) were high (i.e., good), with both baseflow and storm conditions averaging 9-11 mg/L (Table 3). DO concentrations < 5 mg/L are indicative of impaired water quality and can be harmful to aquatic life, which we did not observe in our samples. Specific conductivity was high, > 600 µS/cm at all sites during baseflow (Table 3); concentrations above this level are generally indicative of human-induced stress in aquatic ecosystems (cf. Steinman et al. 2011). Turbidity measurements provide an indication of sediment levels in the system. Mean turbidity concentrations were < 10 NTU during baseflow (Table 3).

Nutrient concentrations were high during baseflow at all three sites, with SRP ranging between 22 and 32 µg/L, and TP ranging between 63 and 84 µg/L (Table 4, Fig. 6a,c), indicative of highly eutrophic conditions. Nitrate concentrations also were very high during baseflow (Table 4, Fig. 7a); the natural level of nitrate in surface water is typically low (less than 1 mg/L), but excess nitrates can lead to hypoxia (low levels of dissolved oxygen) and can become toxic to warm-blooded animals at higher concentrations (10 mg/L) under certain conditions. Baseflow concentrations of ammonia and TKN were much lower than nitrate (Table 4, Fig. 7c,e), but still potentially problematic. Ammonia 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). As seen in previous years, all ammonia concentrations measured at the Middle Macatawa sites were ≥ 0.1 mg/L and most were ≥ 0.2 mg/L (Figs. 7c,d). TKN is the sum of nitrogen as ammonia, ammonium, and organic substances. TKN reached a Project Clarity record high of 13.5 mg/L during the October 2016 storm sample at the Macatawa Up site, of which 50% was in the form of ammonia (Table 4, Figs. 7f and 8j).

With the exception of nitrate, the poorest water quality during baseflow generally was at the Macatawa Up site; while still degraded, Peter's Creek water was in relatively better shape than Macatawa Up, so after their confluence, there was dilution resulting in Macatawa Down water quality being intermediate between Peter's Creek and Macatawa Up on most sampling dates (Fig. 7a,c,e). However, the only two statistically significant differences among these three sites were for: (1) nitrate, where Macatawa Up had anomalously low concentrations indicating Peter's Creek continues to be a source of high nitrate concentrations to the Macatawa Down site (Table 4, Figs. 7a,b and 8e,f); and (2) TKN where Macatawa Up was greater than Peter's Creek, but neither was different than the downstream site (Table 5).

Storm Flow: There were no statistically significant differences in any of the water quality parameters (physical or chemical) among the three sites during our measured storm events (Table 5). This suggests that the effect of storms overwhelms this system so local effects are not distinguishable. Storm runoff increased water temperatures to a small degree relative to baseflow (Table 3), but diluted the concentrations of DO (although they still averaged > 9 mg/L), specific conductivity, and TDS. In contrast, turbidity increased dramatically at all sites compared to baseflow, as runoff liberated suspended sediment (Table 3).

Given the importance of sediment in the Macatawa watershed, we supplemented our discrete storm event sampling (n = 3) with *in situ* turbidity sensors. These *in situ* turbidity sensors provide a more thorough account of stream turbidity than can be provided by monthly baseflow sampling. Data gaps in summer and fall (Fig. 4a) were caused by equipment error and the natural formation of a sandbar at the turbidity sensor station. The *in situ* meters detected two classes of higher turbidity events that were not captured during monthly sampling: high turbidity events ranging ~700-1300 NTU and medium turbidity events ranging ~150-600 NTU (Fig. 4a). The turbidity peaks align well with storm events, as evidenced by 2016 precipitation data collected from the National Climatic Data Center (NCDC) website for Tulip City Airport (Fig. 4b). *In situ* sensors also measured specific conductivity in 2016, which peaked at ~600-800 µS/cm during storm events and declined to ~200-400 µS/cm during periods of low rain (Fig. 5).

Nutrient concentrations changed considerably with storm runoff, with SRP, TP, ammonia, and TKN increasing substantially relative to baseflow but nitrate declining (although still high) especially at the Peter's Creek and Macatawa down sites (Table 4, Figs. 6-8). Indeed, mean SRP concentrations ranged between 494 and 677 µg/L while mean TP concentrations were well above 1,000 µg/L (Table 4, Fig. 6), which is 20× the interim TMDL target (Fig. 6b). These data are clear indications that storm events can have disproportionately large impacts on water quality at these sites.

Table 3. Mean (1 SD) values of selected water quality parameters at the Middle Macatawa wetland restoration site during the 2016 post-restoration sampling year (Dec. 2015 – Nov. 2016). Note that the number of observations (n) changes between baseflow and storm flow regimes.

Flow	Site	N	Temp. (C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Base	Mac. Up	10	12.35 (8.80)	10.15 (3.02)	806 (100)	0.524 (0.065)	9.8 (3.7)
	Peter's Creek	10	11.75 (7.93)	10.68 (2.51)	636 (240)	0.459 (0.058)	9.1 (5.2)
	Mac. Down	10	11.45 (8.23)	10.56 (2.73)	747 (80)	0.486 (0.052)	7.7 (3.6)
Storm	Mac. Up	3	12.82 (9.56)	9.07 (3.08)	456 (128)	0.296 (0.083)	264.3 (62.4)
	Peter's Creek	3	12.88 (9.16)	9.43 (3.49)	344 (135)	0.224 (0.088)	264.0 (48.3)
	Mac. Down	3	12.82 (9.23)	9.34 (2.92)	393 (164)	0.256 (0.106)	243.6 (41.6)

Table 4. Mean (1 SD) values of selected water chemistry parameters at the Middle Macatawa wetland restoration site during the 2016 period of record (Dec. 2015 – Nov. 2016). Data are divided into baseflow and storm flow conditions.

Flow	Site	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
Base	Mac. Up	10	24 (25)	80 (34)	4.78 (3.03)	0.29 (0.20)	1.37 (0.24)
	Peter's Creek	10	22 (22)	63 (24)	10.72 (2.98)	0.31 (0.30)	1.02 (0.22)
	Mac. Down	10	32 (30)	84 (36)	8.17 (2.75)	0.24 (0.14)	1.23 (0.27)
Storm	Mac. Up	3	677 (504)	1512 (504)	4.70 (1.84)	2.45 (3.78)	6.58 (6.07)
	Peter's Creek	3	661 (278)	1238 (238)	5.23 (1.55)	0.84 (1.12)	4.27 (1.28)
	Mac. Down	3	494 (271)	1204 (282)	4.65 (1.53)	1.15 (1.71)	4.36 (3.30)

Table 5. Statistical analysis results of 2016 sampling at Middle Macatawa sites at baseflow and storm flow. 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 < 0.05) between sites are indicated with bold text and not significantly different data are in plain text.

Flow	Parameter	Test	Site	Notes
Base	log SRP	1WA	0.735	NS
	TP	1WA	0.314	NS
	NO_3^-	1WA	**< 0.001**	**P. Creek > Mac Up** **Mac Down > Mac Up**
	log NH_3	1WA	0.767	NS
	TKN	1WA	**0.012**	**Mac Up > P.Creek**
	log Turbidity	1WA	0.581	NS
Storm	SRP	r	0.439	NS
	TP	1WA	0.553	NS
	NO_3^-	1WA	0.896	NS
	NH_3	1WA	0.716	NS
	TKN	1WA	0.743	NS
	Turbidity	1WA	0.857	NS

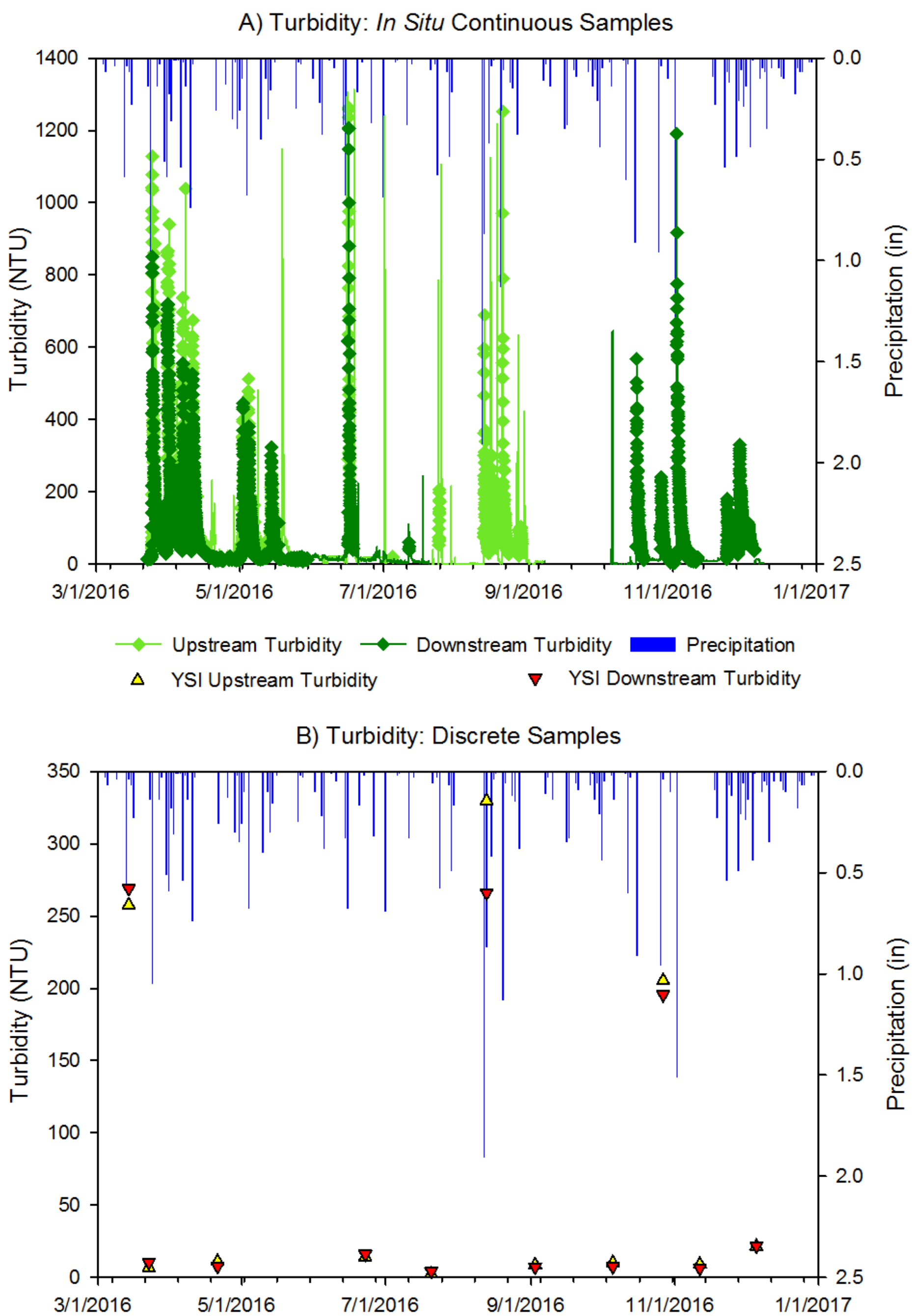

Figure 4. Daily precipitation and turbidity (NTU) during 2016 sampling season at the Middle Macatawa Upstream and Downstream sites. (A) Turbidity data were collected continuously every half hour via *in situ* sensors. (B) Discrete monthly baseflow and storm turbidity measurements taken with YSI 6600. Turbidity lines indicate that sensors were actively recording data, but turbidity symbols represent time points verified to be submerged in river water by conductivity meter (Fig. 5). *In situ* turbidity meter data gaps in summer and fall are due to both the natural formation of a sandbar at the sonde location and sensor error. Hourly precipitation data (panels A and B) were retrieved from the National Climatic Data Center website and summed by day. Note different scales for turbidity on y-axes in panels.

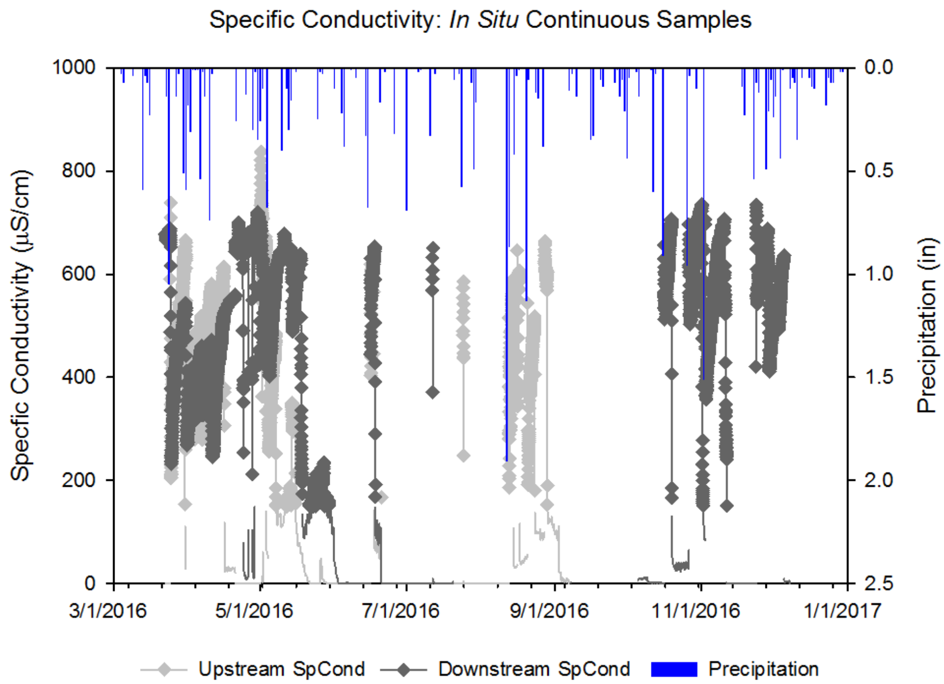

Figure 5. Specific Conductivity and daily precipitation data during 2016 sampling season at the Middle Macatawa Upstream and Downstream sites. Rain data taken from National Climatic Data Center website. Specific conductivity data series were collected every half hour via *in situ* sensors. Conductivity lines indicate that sensors were actively recording data, but conductivity symbols represent time points verified to be submerged in river water. *In situ* specific conductivity meter data gaps in early summer and fall are due to both the natural formation of a sandbar at the sonde location and sensor error.

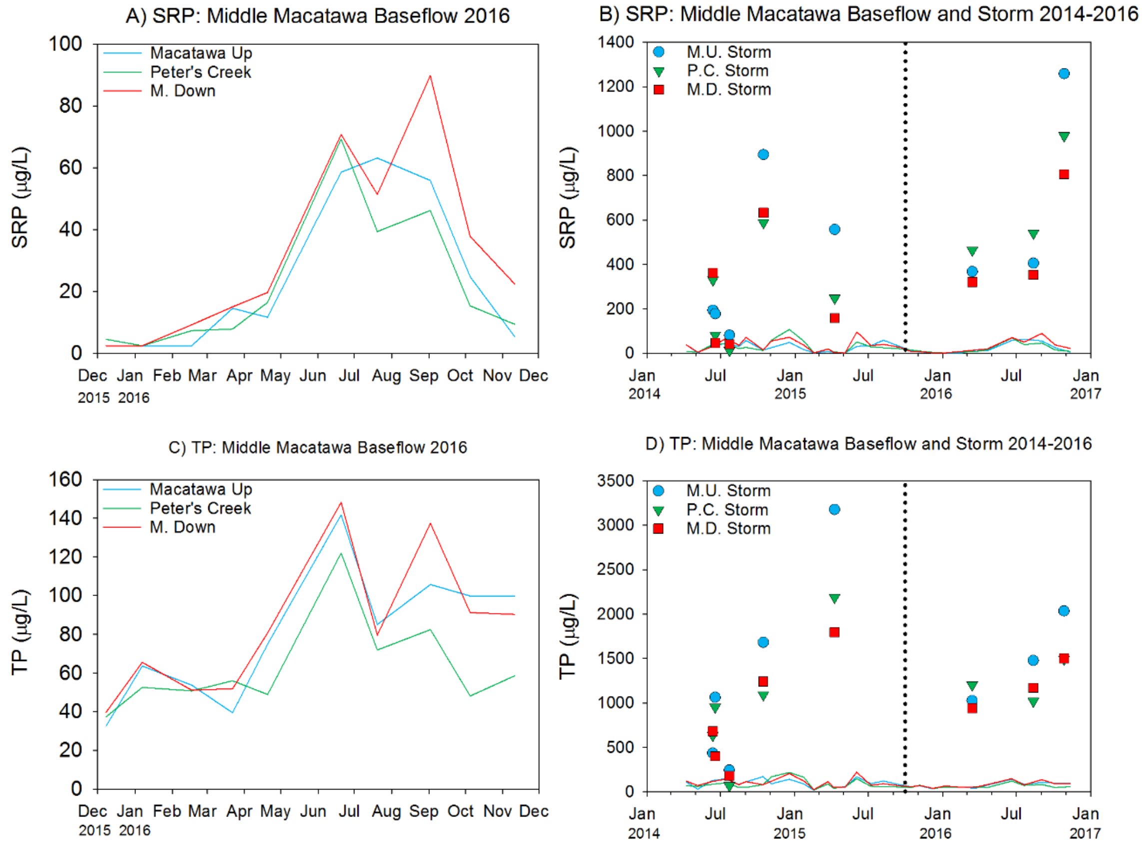

Figure 6. Soluble reactive phosphorus (SRP) (A, B) and total phosphorus (TP) (C, D) concentrations measured at Middle Macatawa wetland within 2016 (A, C) and total project history (B, D). Colored data lines in A and C magnify the 2016 baseflow data shown in B and D, which allow us to include both baseflow and storm event concentrations in same graph; Symbols represent storm events. Note changes to scales of y-axes. Legend in A, C also applies to B, D. Vertical dotted line in October 2015 represents approximate completion date of wetland restoration construction.

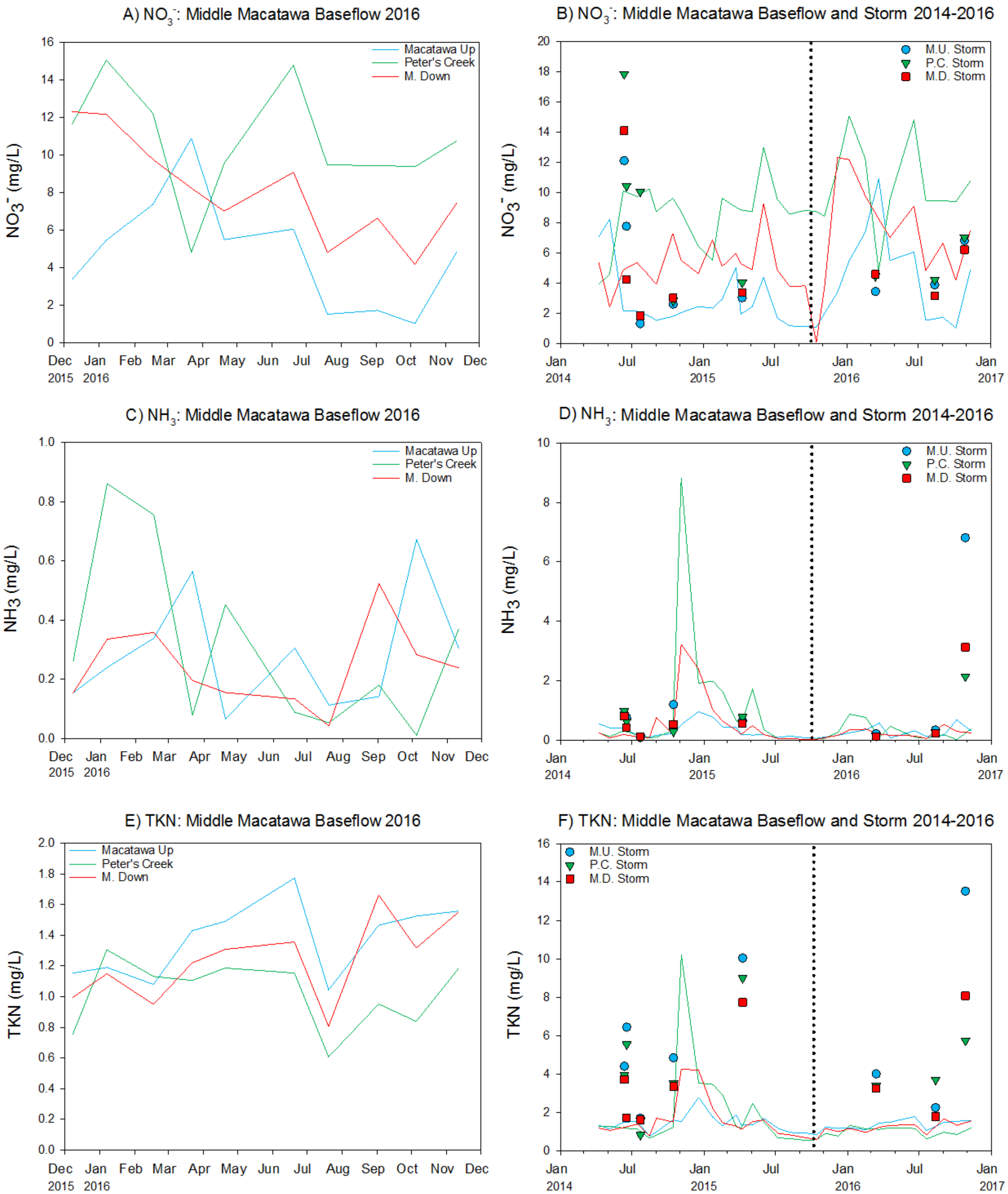

Figure 7. Nitrate (NO_3^-) (A, B), ammonia (NH_3) (C, D), and total Kjeldahl nitrogen (TKN) (E, F) concentrations measured at the Middle Macatawa wetland for 2016 (A, C, E) and total project history (B, D, E). Colored data lines in A, C, and E magnify 2016 baseflow data shown in B, D, and F, which allow us to include both baseflow and storm event concentrations in same graph; dots represent storm events. Vertical dotted lines at October 2015 date represent approximate completion date of wetland restoration construction. Note changes to scales of y-axes. Legend in A, C, E also applies to B, D, F.

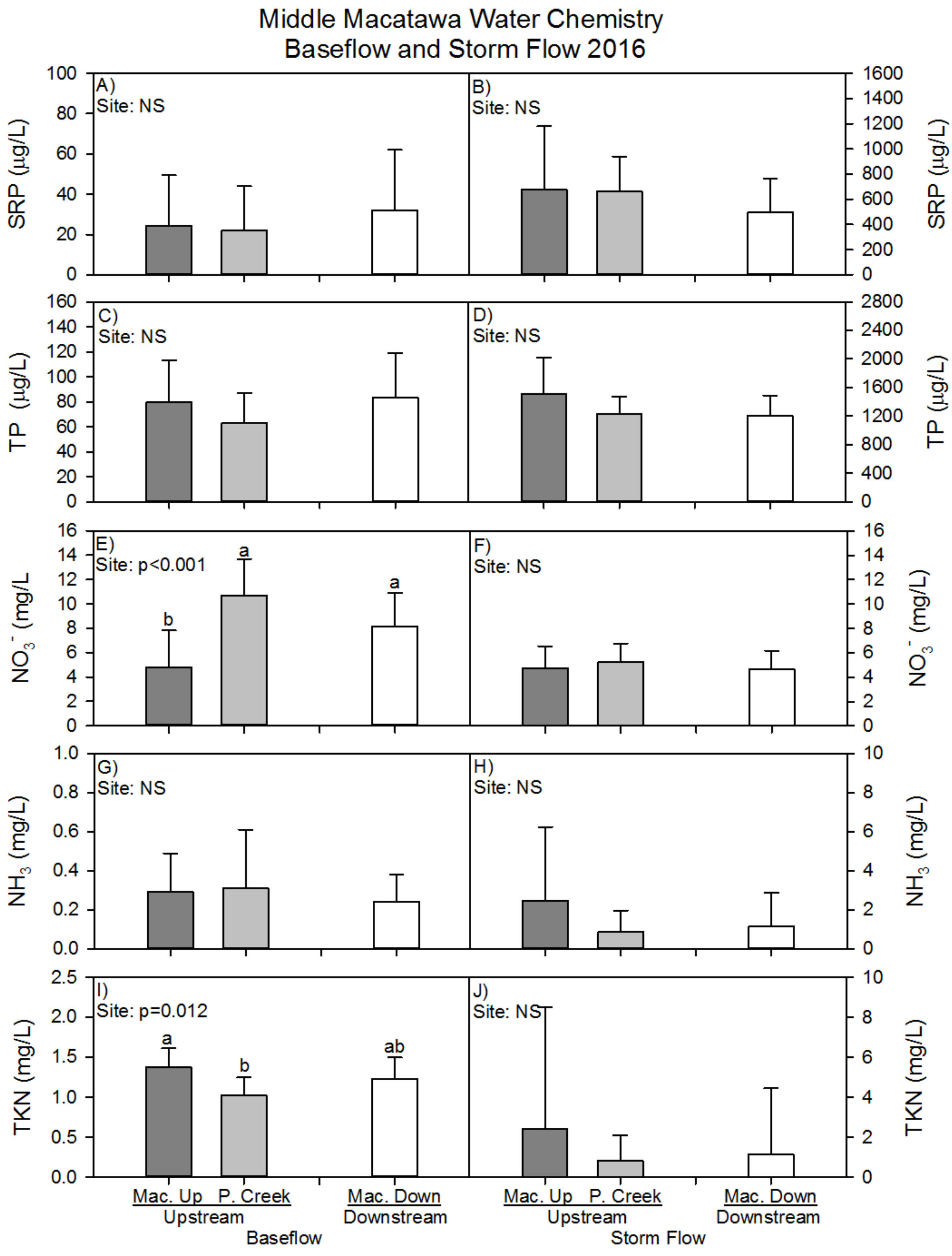

Figure 8. Middle Macatawa mean (1 SD) water chemistry at baseflow (A, C, E, G, I) and storm flow (B, D, F, H, J) for 2016 sampling year. Note that scales change in y-axes between flow regimes and water quality parameters. River water from Macatawa Up and Peter's Creek sites flow together and combine before reaching Macatawa Downstream site.
Note change in y-axis scale between baseflow (left side) and storm flow (right side).

3.1.2 Pre- vs. Post-Restoration Comparison

Baseflow: A qualitative review of the mean water quality values during baseflow, based on the pre-restoration and post-restoration time periods, reveals generally similar patterns at all three sites (Tables 6,7; Figs. 9,10). Temperature, DO, specific conductivity, and TDS were all slightly lower in the post-restoration period compared to the pre-restoration period (Table 6). In addition, turbidity SRP, TP, ammonia, and TKN concentrations all had more substantial declines following restoration (Tables 6,7) during baseflow. Only nitrate showed an increase following restoration, which was evident at all three sites (Table 7).

Storm flow: Water quality trends were more complex when comparing pre- vs. post-restoration periods during storm events. All three sites had lower temperature and higher DO in the post-restoration period (Table 6), but specific conductivity and TDS were slightly higher following restoration at the Macatawa Up site, whereas they were substantially lower at the other two sites (Table 6). Turbidity, on the other hand, was higher at the Peter's Creek site during the post-restoration period, but lower at the other two sites following restoration (Table 6). Indeed, Peter's Creek appears to behave like an outlier in the post-restoration period, showing a decline in TP and TKN, but only a slight increase in ammonia, in contrast to the other two sites (Table 7). All three sites did show a substantial increase in SRP and a relatively small decline in nitrate during the post-restoration period (Table 7).

We used a subset of our overall data set to determine if the differences in water quality between the pre- vs. post-restoration periods were statistically significant (Table 8). We chose not to use the entire data set for this analysis because there were differences in the number of sampling dates in the pre- and post-restoration periods, which could introduce bias due to season. Instead, we selected 10 baseflow sampling dates and 3-5 stormflow sampling dates that corresponded in sampled date between the pre- and post-restoration monitoring periods at each site, and compared differences using inferential statistics. The results show few statistically significant differences, which is not surprising given that the wetland restoration was only recently completed. For baseflow periods, TP was marginally greater ($p < 0.10$) in the pre- vs. post-restoration period at the Peter's Creek site, but was not different at the other two sites (Fig. 9b); nitrate was significantly greater in the post- compared to the pre-restoration period at the Macatawa Up and Down sites (Table 8; Fig. 9c). Ammonia and TKN were marginally greater in pre- vs. post-restoration periods at Peter's Creek, but not different at the other two sites. The only difference for turbidity was at Macatawa Up, where it was significantly greater in the pre- vs. post-restoration period.

To summarize baseflow, out of 18 possible results, only 6 were even marginally statistically different—4 of the 6 were lower following restoration and of those four only one was the downstream site (where we would expect to see a decline) but at this site, nitrate levels actually increased following restoration. During stormflow, there was only one significant result, with SRP greater post-restoration vs pre-restoration ($p < 0.10$) (Table 8). The small number of observations combined with the variability that accompanies storm events contributed to our limited ability to detect change.

Table 6. Grand means (1 SD) of selected water quality parameters at the Middle Macatawa wetland restoration site. Each cell 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. 2016). Note that the number of observations (n) changes between flow regimes and restoration periods.

Flow	Site	Period	N	Temp. (C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Base	Mac. Up	Pre	18	12.17 (7.40)	10.53 (2.39)	765 (240)	0.497 (0.156)	10.5 (6.9)
		Post	12	11.55 (7.46)	10.45 (2.48)	746 (75)	0.485 (0.048)	6.9 (3.8)
	Peter's Creek	Pre	18	12.35 (7.38)	10.45 (2.39)	665 (163)	0.432 (0.106)	11.3 (6.6)
		Post	12	11.79 (7.19)	10.43 (2.34)	633 (217)	0.449 (0.057)	7.8 (5.5)
	Mac. Down	Pre	18	12.17 (7.40)	10.53 (2.39)	765 (240)	0.497 (0.156)	10.5 (6.9)
		Post	12	11.55 (7.46)	10.45 (2.48)	746 (75)	0.485 (0.048)	6.9 (3.8)
Storm	Mac. Up	Pre	3	14.26 (6.78)	7.43 (2.68)	444 (207)	0.288 (0.135)	581.7 (697.8)
		Post	3	12.82 (9.56)	9.07 (3.08)	456 (128)	0.296 (0.083)	264.3 (62.4)
	Peter's Creek	Pre	2	17.00 (3.75)	7.49 (0.81)	460 (201)	0.299 (0.130)	141.6 (182.5)
		Post	3	12.88 (9.16)	9.43 (3.49)	344 (135)	0.224 (0.088)	264.0 (48.3)
	Mac. Down	Pre	3	14.00 (6.66)	7.88 (2.42)	481 (201)	0.313 (0.130)	462.2 (475.9)
		Post	3	12.82 (9.23)	9.34 (2.92)	393 (164)	0.256 (0.106)	243.6 (41.6)

Table 7. Grand means (1 SD) of selected water chemistry parameters at the Middle Macatawa wetland restoration site. Each cell has two rows per column: data in the top row represent pre-restoration period of record (Dec. 2014 – Sept. 2015); data in the bottom row represent post-restoration period of record (Oct. 2015 – Nov. 2016). Data are divided into baseflow and storm flow conditions. Data are divided by baseflow and storm flow conditions and by pre- and post-restoration periods, respectively.

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	12	22 (24)	77 (31)	4.24 (3.03)	0.25 (0.20)	1.31 (0.27)
	Peter's Creek	Pre	18	30 (26)	88 (53)	8.54 (2.19)	1.05 (2.06)	1.98 (2.26)
		Post	12	20 (20)	63 (23)	10.36 (2.82)	0.27 (0.29)	0.97 (0.24)
	Mac. Down	Pre	18	37 (27)	104 (51)	5.20 (1.51)	0.56 (0.87)	1.59 (1.02)
		Post	12	28 (29)	81 (33)	7.12 (3.57)	0.21 (0.15)	1.17 (0.31)
Storm	Mac. Up	Pre	5	381 (339)	1320 (1181)	5.35 (4.49)	0.71 (0.41)	5.47 (3.07)
		Post	3	677 (504)	1512 (504)	4.70 (1.84)	2.45 (3.78)	6.58 (6.07)
	Peter's Creek	Pre	5	381 (339)	1320 (1181)	5.35 (4.49)	0.71 (0.41)	5.47 (3.07)
		Post	3	661 (278)	1238 (238)	5.23 (1.55)	0.84 (1.12)	4.27 (1.28)
	Mac. Down	Pre	5	248 (251)	860 (657)	5.31 (4.99)	0.48 (0.25)	3.62 (2.48)
		Post	3	494 (271)	1204 (282)	4.65 (1.53)	1.15 (1.71)	4.36 (3.30)

Table 8. Pre- and post-restoration statistical analyses of water quality at Middle Macatawa sites at baseflow (pre-, post- n = 10, 10) and storm flow (pre-, post water chemistry n = 5, 3 and turbidity n = 2, 3). In order to remove potential bias of pre- vs. post-restoration samples collected from different time periods, baseflow tests incorporated an equal number of samples from identical months in pre- and post-restoration periods (Jan., Feb., Mar., Apr., Jun., Jul., Sep., Oct., Nov., Dec.). Storm flow tests incorporated all possible sampled storm events. All tests performed are either paired t-tests (baseflow) or unpaired t-tests (storm flow), with the exception of storm flow turbidity at Peter's Creek (Mann-Whitney rank-sum test). Parameter indicates water quality metric. Transformation column indicates pre- and post- data that were transformed to meet test assumptions. Significant differences ($p < 0.05$) are indicated with bold text, marginally significant differences are indicated with italics, and not significantly different results are in plain text.

		Mac. Up			Peter's Creek			Mac. Down		
Flow	Parameter	Transform	p-value	Notes	Transform	p-value	Notes	Transform	p-value	Notes
Base	SRP	-	0.768	NS	sqrt	0.625	NS	-	0.702	NS
	TP	-	0.186	NS	-	*0.089*	*pre > post*	-	0.277	NS
	NO_3^-	-	**0.009**	**post > pre**	-	0.151	NS	-	**0.041**	**post > pre**
	NH_3	-	0.447	NS	log	*0.066*	*pre > post*	sqrt	0.186	NS
	TKN	-	0.275	NS	log	*0.052*	*pre > post*	-	0.135	NS
	Turbidity	-	**0.050**	**pre > post**	log	0.240	NS	sqrt	0.185	NS
Storm	SRP	sqrt	0.318	NS	-	*0.062*	*post > pre*	-	0.241	NS
	TP	-	0.803	NS	-	0.617	NS	-	0.433	NS
	NO_3^-	-	0.824	NS	-	0.336	NS	sqrt	0.988	NS
	NH_3	-	0.322	NS	-	0.588	NS	-	0.394	NS
	TKN	-	0.736	NS	-	0.881	NS	-	0.727	NS
	Turbidity	-	0.476	NS	-	0.400	NS	-	0.472	NS

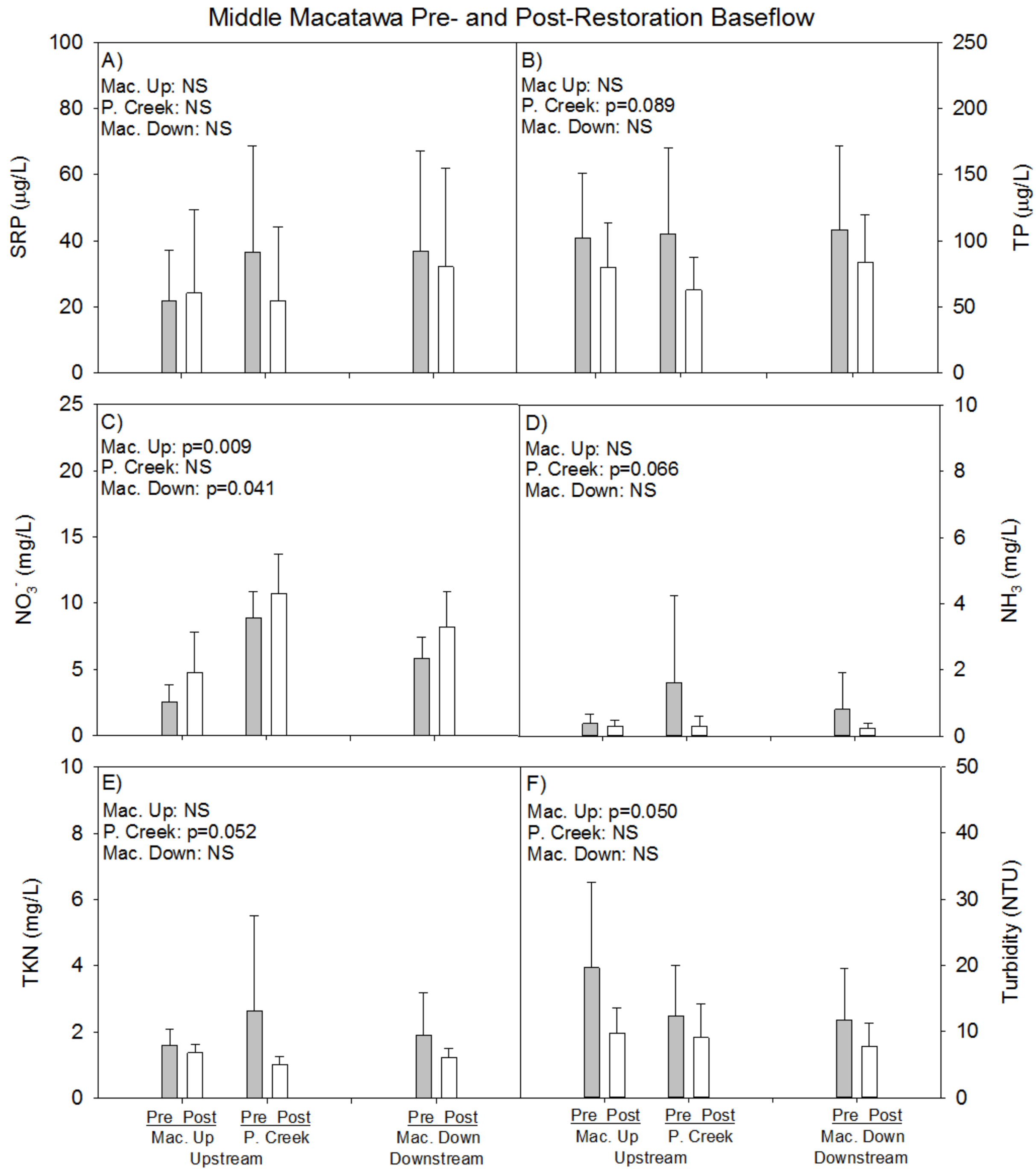

Figure 9. Middle Macatawa pre- and post-restoration water chemistry comparison at baseflow as of 2016 sampling year. Error bars represent 1 SD. Values in top left corner of each panel are p-value results from statistical analysis (Table 8).

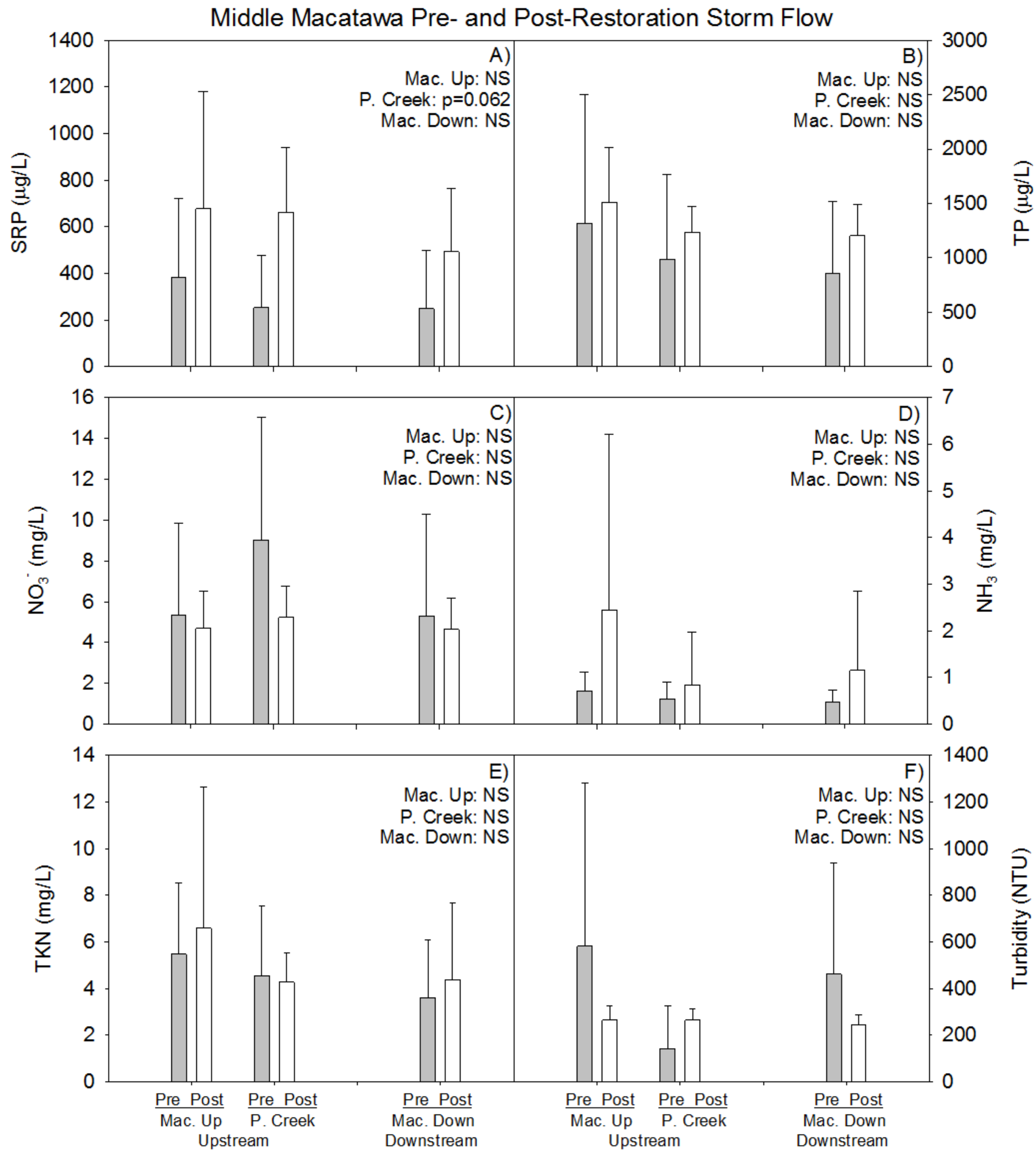

Figure 10. Middle Macatawa pre- and post-restoration water chemistry comparison at storm flow as of 2016 sampling year. Error bars represent 1 SD. Values in top right corner of each panel are p-value results from statistical analysis (Table 8).

3.2 Wetland Restoration: Haworth Property

3.2.1 Sampling Year 2016

Baseflow: Baseflow water quality parameters measured in the North Branch at the Haworth site were generally similar to baseflow observations at the Middle Macatawa property. DO concentrations were indicative of generally healthy conditions, averaging > 10 mg/L, but specific conductivity was high, while TDS and turbidity were < 0.6 g/L and ~7-8 NTU, respectively (Table 9).

Nutrient concentrations at baseflow were lower than those observed at the Middle Macatawa property, although absolute concentrations of P and nitrate were still high, and indicative of eutrophic conditions. SRP concentrations averaged 17 and 19 µg/L at the up and down sites (Fig. 11a), respectively, while mean TP concentrations were 54 µg/L at the up and down sites (Table 10, Fig. 11c), slightly greater than the TMDL target for the lake. The only even marginally significant difference between up- and downstream sites was for nitrate, which was marginally greater at the upstream site (Table 11, Fig. 12a).

Storm flow: Similar to the Macatawa site, there were no statistically significant differences in any of the water quality parameters (physical or chemical) during our measured storm events (Table 11), suggesting that the effect of runoff is overwhelming any localized impact of restoration to date. Storm runoff increased water temperatures by more than 2^{o}C compared to baseflow (Table 9), but diluted the levels of DO, specific conductivity, and TDS. In contrast, turbidity increased at both sites compared to baseflow, although not to the same degree observed at the Macatawa site (Table 9 vs. Table 5).

3.1.2 Pre- vs. Post-Restoration Comparison

Baseflow: A qualitative review of the mean water quality values during baseflow, based on the pre-restoration and post-restoration time periods, reveals generally similar patterns at both the up- and downstream sites (Tables 12, 13; Figs. 14, 15). Mean temperature, DO, specific conductivity, and TDS values were all slightly lower in the post-restoration period compared to the pre-restoration period (Table 12). In contrast, turbidity SRP, TP, and ammonia concentrations were slightly elevated following restoration (Tables 12, 13, Fig. 14), unlike the trend in the Middle Mac, where they declined following restoration; again, none of these contrasts were statistically different from one another (Table 14).

Storm flow: Water quality trends were more complex when comparing pre- vs. post-restoration periods during storm events. Both sites had lower temperature and turbidity but higher DO, conductivity, and TDS in the post-restoration period (Table 12). Mean SRP concentrations increased substantially in the post- vs. pre-restoration periods (Table 13, Fig. 15), and the difference was marginally significant ($p < 0.10$) for the North Down site (Table 14). TP also increased substantially in the post-restoration period at the North Down site (although not statistically significant; Table 14; Fig. 15), but actually increased at the North Up site (Tables 13, 14; Fig. 15). Both mean SRP and TP concentrations reached very high levels (Table 13) following storms in the post-restoration period. It is unclear if this may be related to construction activity, in which case these concentrations should decline over time. Mean ammonia concentrations also increased in the post-restoration period, but the change was not statistically significant (Tables 13, 14; Fig. 15).

To sum these results, out of 12 possible statistical tests, only 1 was even marginally statistically different—SRP during storm flow at the downstream site, with SRP greater post-restoration vs pre-restoration, which is the opposite of what we'd expect following restoration but is consistent with the results at the Macatawa Down site.

Table 9. Mean (1 SD) values of selected water quality parameters at the Haworth wetland restoration site for the 2016 sampling year. Data are divided into baseflow and storm flow conditions.

Flow	Site	n	Temp. (C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Base	North Up	10	10.85 (8.64)	10.66 (2.73)	807 (139)	0.525 (0.090)	7.0 (4.8)
	North Down	10	10.93 (9.02)	10.23 (2.72)	815 (78)	0.529 (0.050)	8.2 (8.1)
Storm	North Up	3	13.14 (9.47)	8.83 (3.19)	471 (28)	0.306 (0.018)	89.2 (29.2)
	North Down	3	13.27 (9.57)	8.70 (3.66)	499 (29)	0.324 (0.019)	102.0 (30.8)

Table 10. Table 6. Mean (1 SD) values of selected nutrient concentrations at the Haworth restoration site for the 2016 sampling year. Data are divided into baseflow and storm flow conditions.

Flow	Site	n	SRP (µg/L)	TP (µg/L)	NO_3^- (mg/L)	NH_3 (mg/L)	TKN (mg/L)
Base	North Up	10	19 (24)	54 (39)	2.05 (1.45)	0.09 (0.12)	0.82 (0.18)
	North Down	10	17 (18)	54 (38)	1.85 (1.32)	0.08 (0.12)	0.86 (0.22)
Storm	North Up	3	116 (42)	329 (70)	1.14 (0.77)	0.13 (0.03)	1.93 (0.23)
	North Down	3	224 (157)	480 (150)	0.91 (1.02)	0.27 (0.25)	2.27 (0.41)

Table 11. Statistical analysis results of 2016 sampling at Haworth sites at baseflow and storm flow. Parameter column indicates water quality parameter and transformation used to meet assumptions of normality and variance. All data were analyzed using either 2-tailed t-tests (t) or Wilcoxon signed-rank tests (W). Marginally significant differences (0.05 < p < 0.10) between sites are indicated with italic text and not significantly different data are in plain text.

		Test	Site	Notes
Base	SRP	W	0.195	NS
	log TP	t	0.980	NS
	NO_3^-	t	*0.100*	*up > down*
	log NH_3	t	0.416	NS
	TKN	t	0.436	NS
	Turbidity	t	0.737	NS
Storm	SRP	t	0.337	NS
	TP	t	0.339	NS
	log NO_3^-	t	0.829	NS
	NH_3	t	0.441	NS
	TKN	t	0.464	NS
	Turbidity	t	0.345	NS

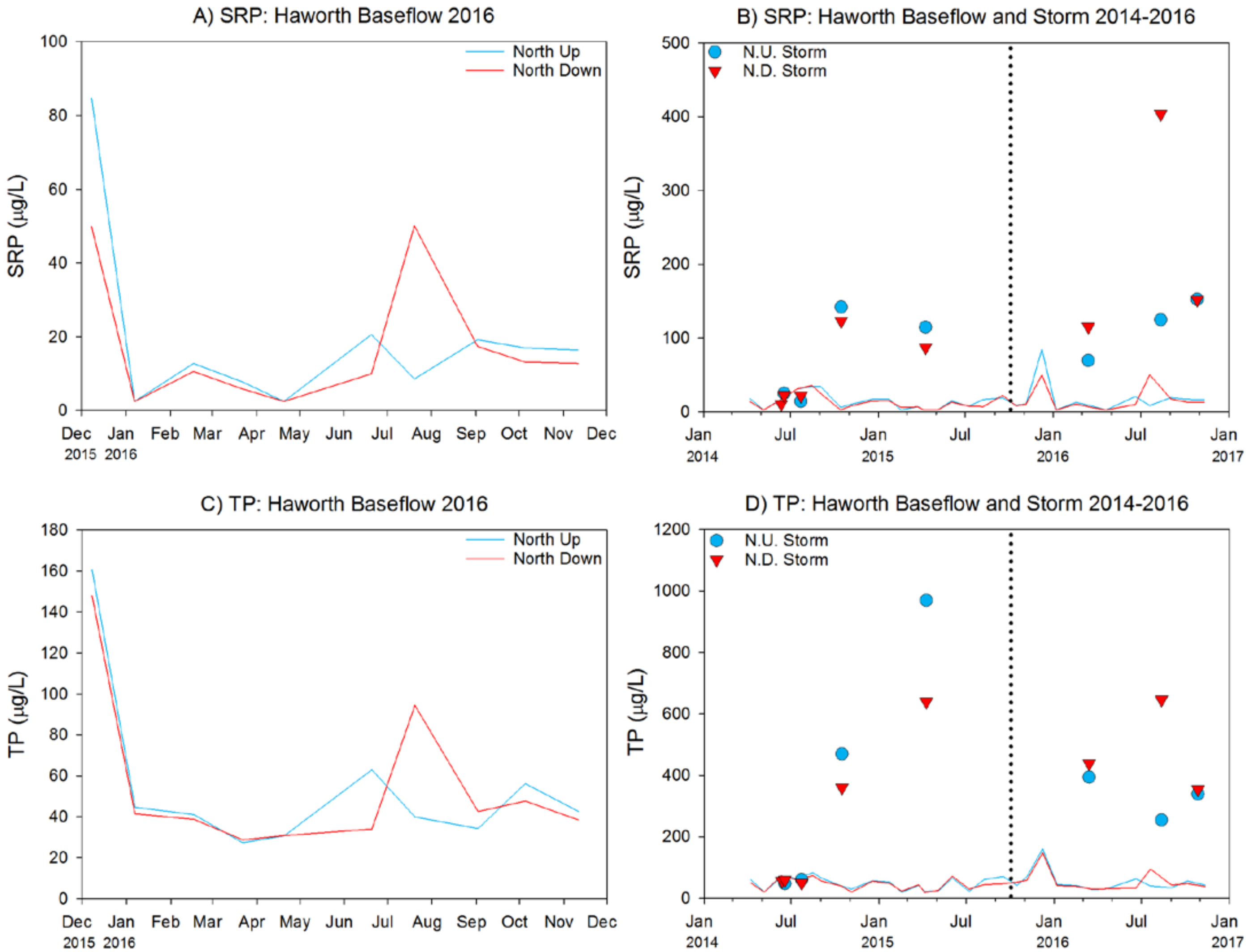

Figure 11. Soluble reactive phosphorus (SRP) (A, B) and total phosphorus (TP) (C, D) concentrations measured at Haworth wetland for 2016 (A, C) and total project history (B, D). Colored data lines in A and C magnify 2015 baseflow data shown in B and D, which allow us to include both baseflow and storm event concentrations in same graph; symbols represent storm events. Dotted line represents completion of wetland restoration. Note changes to scales of y-axes. Legend in A, C also applies to B, D.

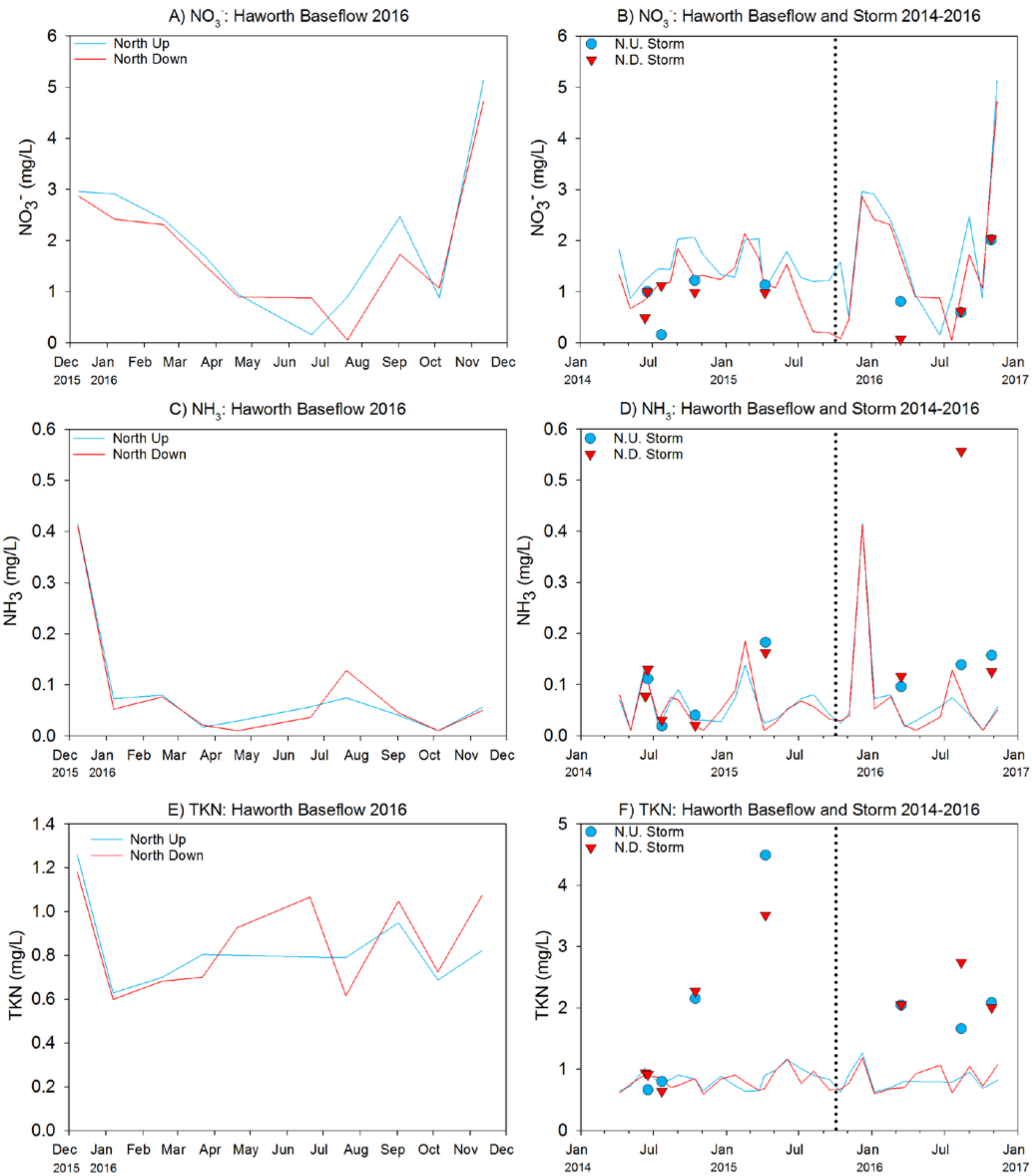

Figure 12. Nitrate (NO_3^-) (A, B), ammonia (NH_3) (C, D), and total Kjeldahl nitrogen (TKN) (E, F) concentrations measured at the Haworth wetland for 2016 (A, C, E) and total project history (B, D, E). Colored data lines in A, C, E magnify 2016 baseflow data shown in B, D, F, which allow us to include both baseflow and storm event concentrations in same graph; symbols represent storm events. Dotted line represents completion of wetland restoration. Note changes to scales of y-axes; and that y-axis scales are much lower than Middle Macatawa sites (Fig. 7). Legend in A, C, E also applies to B, D, F.

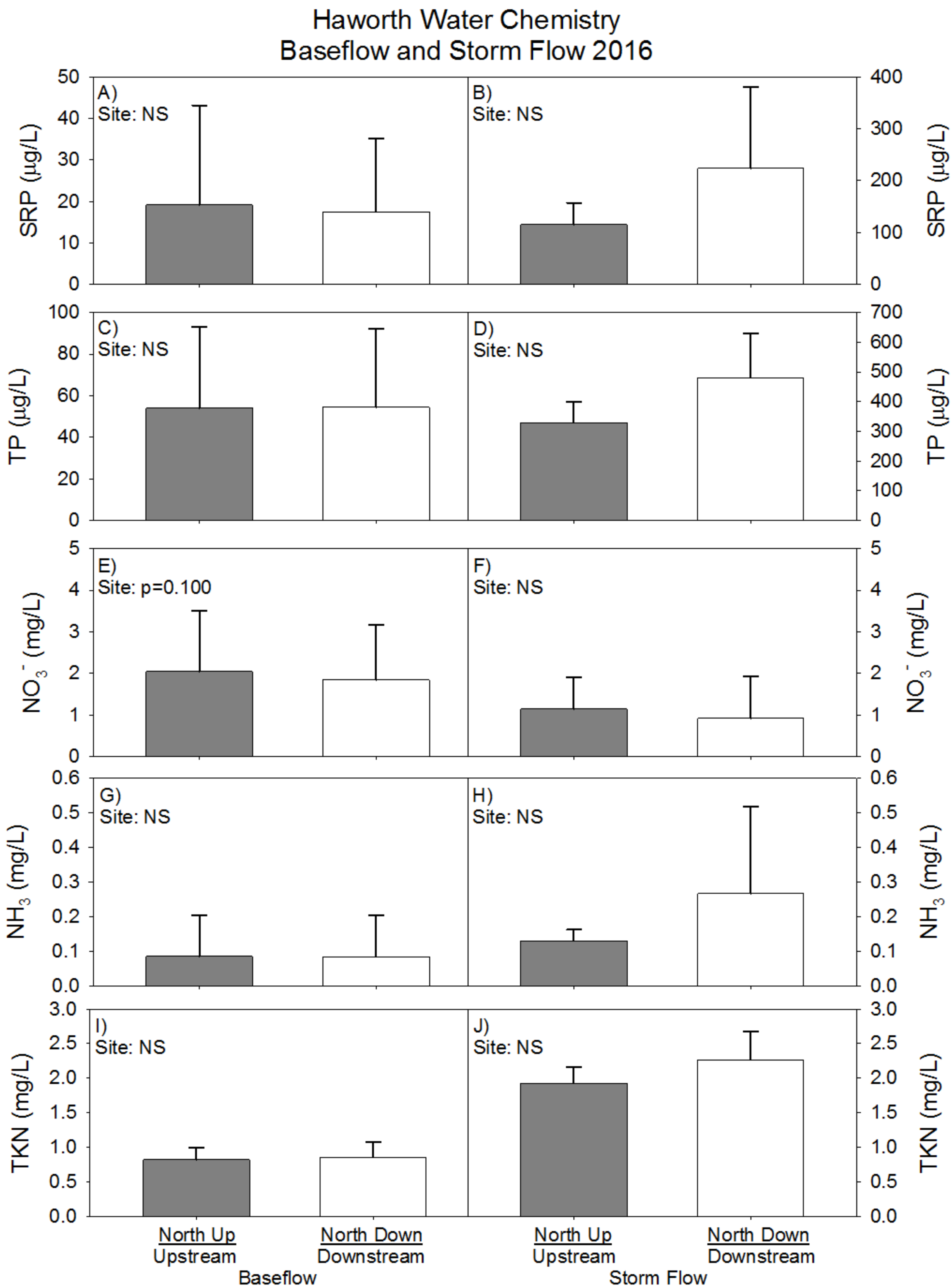

Figure 13. Mean (1 SD) water quality values at Haworth sites for 2016 sampling year at baseflow (A, C, E, G, I) and storm flow (B, D, F, H, J). Note that scales change in y-axes between flow regimes and water quality parameters.

Table 12. Mean (1 SD) values of selected water quality parameters at the Haworth wetland restoration site in pre- and post-restoration sampling periods. Grand Mean cells 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. 2016). Data are divided into baseflow and storm flow conditions.

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	12	10.96 (7.83)	10.07 (2.86)	829 (140)	0.539 (0.091)	6.4 (4.6)
	North Down	Pre	18	11.93 (6.96)	10.32 (3.36)	844 (194)	0.549 (0.126)	5.6 (3.0)
		Post	12	11.02 (8.18)	9.81 (2.80)	839 (105)	0.546 (0.068)	7.5 (7.5)
Storm	North Up	Pre	3	13.80 (5.92)	7.77 (2.29)	432 (283)	0.281 (0.184)	200.7 (223.6)
		Post	3	13.14 (9.47)	8.83 (3.19)	471 (28)	0.306 (0.018)	89.2 (29.2)
	North Down	Pre	3	13.80 (6.06)	7.84 (2.32)	478 (150)	0.310 (0.098)	143.6 (146.0)
		Post	3	13.27 (9.57)	8.70 (3.66)	499 (29)	0.324 (0.019)	102.0 (30.8)

Table 13. Mean (1 SD) values of selected nutrient concentrations at the Haworth restoration site in pre- and post-restoration sampling periods. Grand Mean cells 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. 2016). Data are divided into baseflow and storm flow conditions.

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	12	18 (22)	54 (36)	1.88 (1.39)	0.08 (0.11)	0.81 (0.17)
	North Down	Pre	18	13 (10)	44 (19)	1.17 (0.50)	0.06 (0.04)	0.80 (0.15)
		Post	12	16 (16)	55 (34)	1.58 (1.34)	0.08 (0.11)	0.84 (0.21)
Storm	North Up	Pre	4	74 (64)	387 (435)	0.88 (0.49)	0.09 (0.07)	2.03 (1.77)
		Post	3	116 (42)	329 (70)	1.14 (0.77)	0.13 (0.03)	1.93 (0.23)
	North Down	Pre	5	53 (49)	233 (263)	0.92 (0.24)	0.08 (0.06)	1.65 (1.22)
		Post	3	224 (157)	480 (150)	0.91 (1.02)	0.27 (0.25)	2.27 (0.41)

Table 14. Pre- and post-restoration statistical analyses of water quality at Haworth sites at baseflow (pre-, post- n = 10, 10) and storm flow (pre-, post- water chemistry n = 5, 3 and turbidity n = 3, 3). In order to remove potential bias of pre- vs. post-restoration samples collected from different time periods, baseflow tests incorporated an equal number of samples from identical months in pre- and post-restoration periods (Jan., Feb., Mar., Apr., Jun., Jul., Sep., Oct., Nov., Dec.). Storm flow tests incorporated all possible sampled storm events. All tests performed are either paired t-tests (baseflow) or unpaired t-tests (storm flow). Parameter indicates water quality metric. Transformation column indicates pre- and post- data that were transformed to meet test assumptions. Significant differences ($p < 0.05$) are indicated with bold text, marginally significant differences are indicated with italics, and not significantly different data are in plain text.

		North Up			North Down		
Flow	Parameter	Transform	p-value	Notes	Transform	p-value	Notes
Base	SRP	sqrt	0.218	NS	sqrt	0.244	NS
	TP	sqrt	0.296	NS	-	0.251	NS
	NO_3^-	-	0.353	NS	-	0.105	NS
	NH_3	1/sqrt	0.857	NS	log	0.677	NS
	TKN	-	0.946	NS	-	0.434	NS
	Turbidity	-	0.787	NS	-	0.218	NS
Storm	SRP	-	0.378	NS	-	*0.057*	*post > pre*
	TP	-	0.834	NS	-	0.195	NS
	NO_3^-	-	0.599	NS	-	0.994	NS
	NH_3	-	0.404	NS	-	0.156	NS
	TKN	-	0.931	NS	-	0.444	NS
	Turbidity	-	0.440	NS	-	0.654	NS

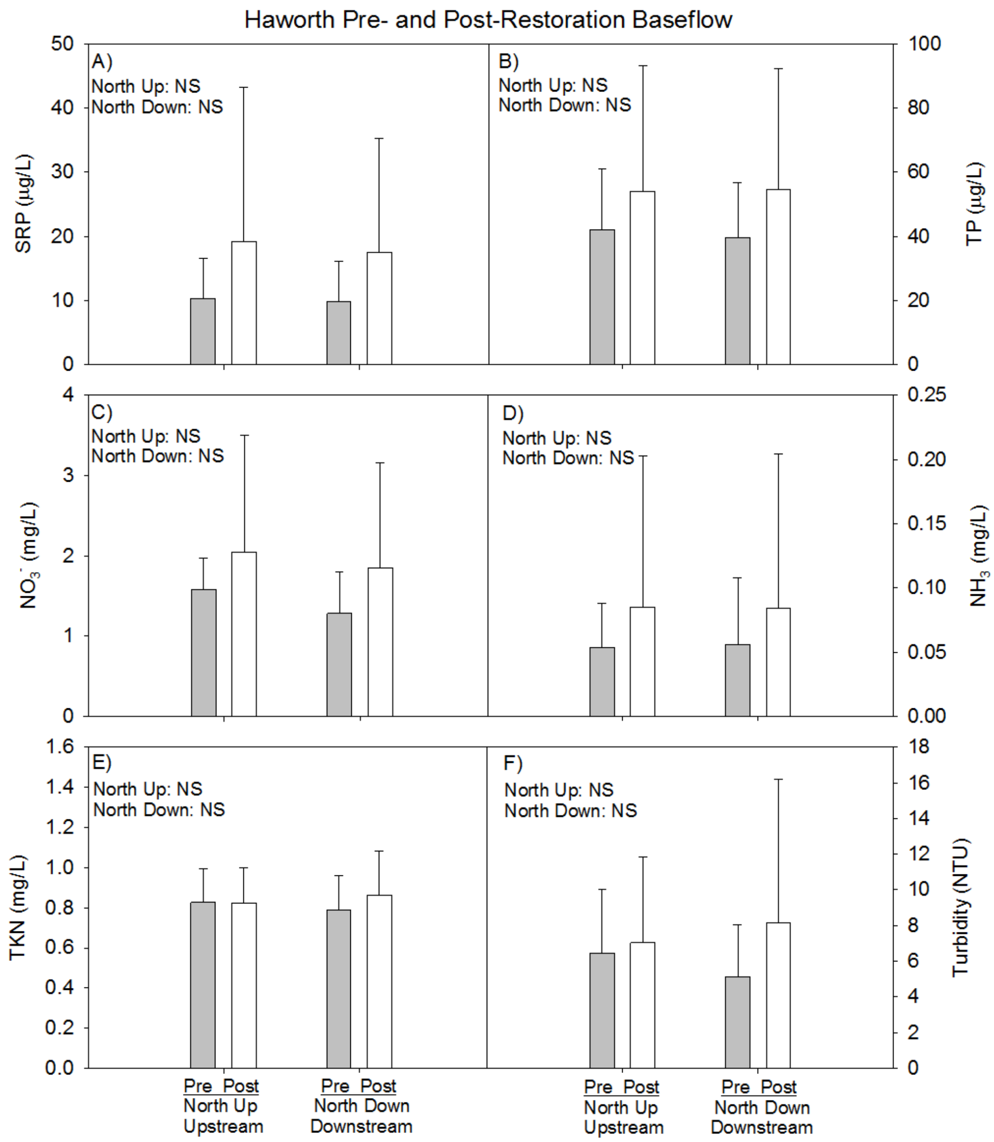

Figure 14. Haworth pre- and post-restoration water chemistry comparison at baseflow as of 2016 sampling year. Error bars represent 1 SD. Values in top left corner of each panel are p-value results from t-tests analyzing difference between restoration periods (Table 14).

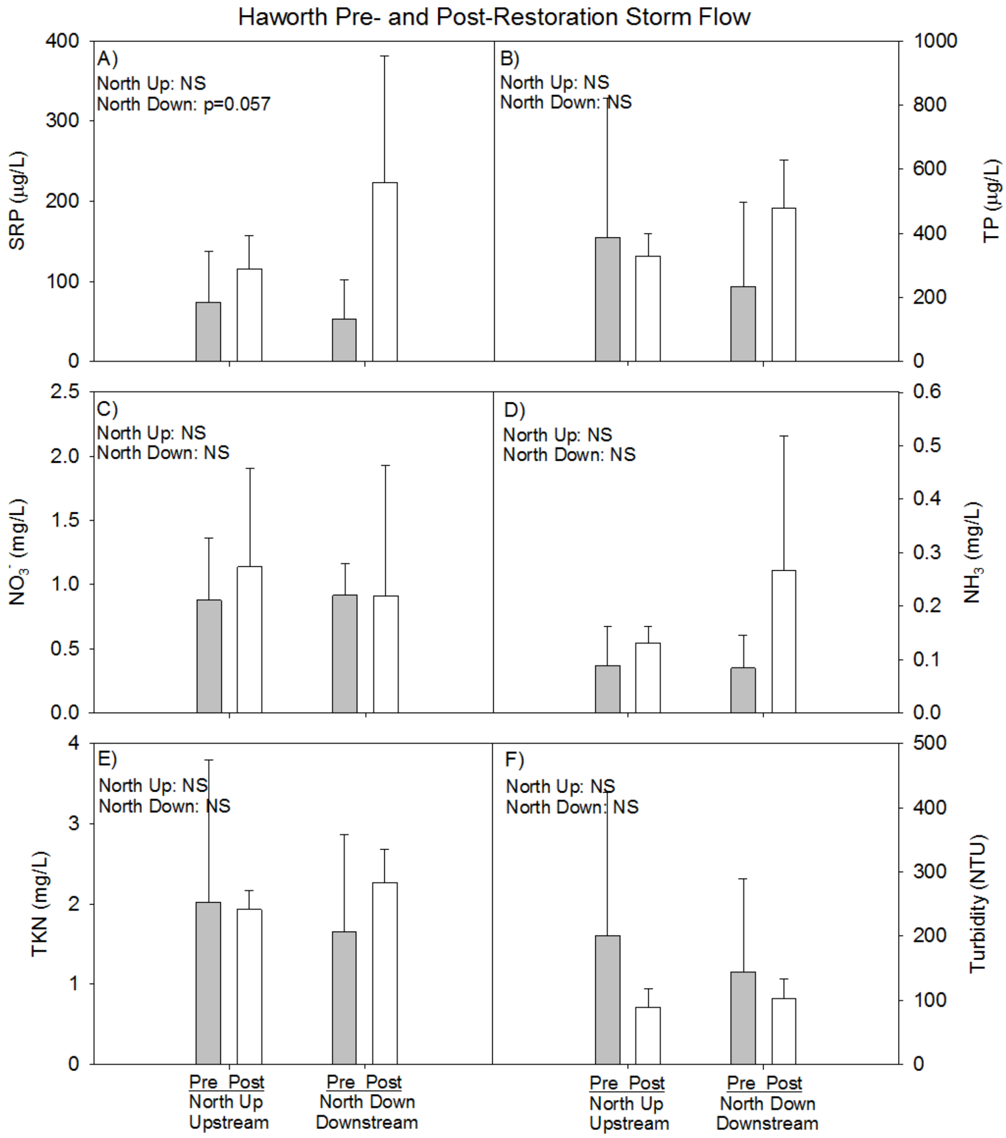

Figure 15. Haworth pre- and post-restoration water chemistry comparison at storm flow as of 2016 sampling year. Error bars represent 1 SD. Values in top left corner of each panel are p-value results from t-tests analyzing difference between restoration periods (Table 14).

3.3 Lake Macatawa: Long-Term Monitoring

3.3.1 Sampling Year 2016

The water column in Lake Macatawa was reasonably well-mixed during all three sampling seasons. Temperatures did not change very much with depth on any date, although there was a slight gradient in fall, where bottom temperatures were ~2.5°C cooler than at surface (Table 15). Bottom water DO was reduced to ~1/2 of surface water concentrations in summer and fall; although mean DO concentrations never were < 4 mg/L, some individual sites did have low concentrations during the summer sampling campaign. Sites 1, 2, and 4 DO concentrations were 1.08, 2.59, and 0.72, respectively (data not shown). Low DO also occurred at sites 1 and 4 in summer 2014 and 2015, which are the two deepest Lake Macatawa sites that were sampled (~7m and 9.5m, respectively). This suggests that hypoxic conditions can set up in the deeper portions of Lake Macatawa, at least for certain periods of the summer. This is important because hypoxia not only reduces habitat quality for desirable invertebrate and fish communities, it also can lead to the release of phosphorus from the sediments (internal loading; Steinman et al. 2004, Steinman and Ogdahl 2012).

Lake-wide means of specific conductivity were < 600 µS/cm and declined through the sampling year, consistent with TDS values (Table 15). Lake-wide mean turbidity values were ≤ 15 NTU at the surface but were 2-5× greater at the bottom, presumably due to turbulence that stirred up flocculent sediments (Table 15).

Surface SRP concentrations remained < 10 µg/L at all sites in 2016 (Table 16, Fig. 16a). Caution should be exercised when looking at SRP values, as SRP is the bioavailable form of P, so low SRP concentrations may simply be due to it being taken up by the algae, and now most of it is in the form of particulate P. In that sense, total P gives a better indication of lake trophic status. Mean surface TP ranged from 56-103 µg/L (Table 16), and concentrations declined as one moved westward in the lake regardless of season (Fig. 16c), presumably due to the settling out of particles and dilution from high quality Lake Michigan water advecting into the western end of Lake Macatawa. Nonetheless, these TP concentrations still exceed the 50 µg/L interim TMDL target for Lake Macatawa. Despite occasional spikes in bottom water SRP and TP (e.g., spring site 1 and summer site 4; Fig. 16b,d), overall there was no evidence of systemic internal P loading in Lake Macatawa, which if present, would be indicated by very high concentrations of SRP and/or TP (> 400 µg/L) in bottom waters, as we have measured in Mona Lake (Muskegon County, MI; Steinman et al. 2009).

Mean surface chlorophyll concentrations peaked in summer (Table 16), and were lowest at the site closest to Lake Michigan (Fig. 16e). Concentrations exceeded the 22 µg/L hypereutrophic threshold commonly used by MDEQ in its assessments of Lake Macatawa (Holden 2014), with one very high (202 µg/L) measurement at site in summer, during bloom conditions (Fig. 16e). Secchi depths became shallower through the year, indicating less clear waters in fall than spring; transparency was low, in general, near or less than 1 m (Table 16), indicating eutrophic to hypereutrophic conditions (Fuller and Minnerick 2008).

3.3.2 Pre- vs. Post Restoration Comparison

A qualitative assessment of lake conditions reveals no consistent evidence that lake condition has improved yet (Table 17, Fig. 17). Of course, 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 (Carpenter 2005, Sharpley et al. 2013).

One metric worth noting is chlorophyll *a*. The concentrations in 2016 exceeded 2015 measurements in all depths and seasons, with a maximum of 204 µg/L at site 1 near the mouth of the Macatawa River (Table 16; Figs. 16e,17e). Averaging all sites and depths per year shows average 2016 chlorophyll *a* increased 20 µg/L (63%); however, 2016 values are comparable and within range of previous Project Clarity chlorophyll a measurements in summer 2013 (Fig. 17e). Chlorophyll concentrations are highly dynamic in lakes, as blooms can be easily disrupted by storm conditions; hence, time of sampling can heavily influence these numbers. As a consequence, we are recommending a citizen science initiative in Lake Macatawa, where shoreline residents conduct weekly assessments of lake color, using a standardized color spectrum. We will then use those data to help “fill in the gaps” in our more rigorous, but less frequent, chlorophyll *a* sampling.

Table 15. Lake-wide means (1 SD) of select general water quality parameters recorded during 2016 monitoring year. Within 2016, n is the number of lake sites composing the seasonal mean at each depth.

Season	Depth	n	Temp. (C)	DO (mg/L)	SpCond (µS/cm)	TDS (g/L)	Turbidity (NTU)
Spring	Top	5	11.62 (0.43)	11.61 (0.63)	575 (78)	0.374 (0.050)	13.0 (3.1)
	Middle	5	11.28 (0.42)	11.04 (0.76)	580 (81)	0.377 (0.053)	15.8 (7.1)
	Bottom	5	11.03 (0.51)	9.57 (0.88)	579 (83)	0.376 (0.054)	38.0 (23.4)
Summer	Top	5	27.34 (0.64)	12.06 (0.56)	505 (71)	0.328 (0.046)	15.2 (2.1)
	Middle	5	26.98 (0.80)	8.47 (3.15)	500 (84)	0.325 (0.055)	11.0 (3.9)
	Bottom	5	25.99 (1.45)	4.30 (4.55)	497 (67)	0.323 (0.043)	28.6 (20.9)
Fall	Top	5	17.40 (0.31)	9.08 (1.11)	489 (70)	0.318 (0.046)	9.9 (1.9)
	Middle	5	16.74 (1.01)	6.62 (2.12)	490 (86)	0.319 (0.056)	13.7 (8.4)
	Bottom	5	14.91 (2.32)	5.20 (2.32)	426 (68)	0.277 (0.044)	46.4 (26.6)

Table 16. Lake-wide means (1 SD) of phosphorus concentrations, chlorophyll *a*, and Secchi depths measured during 2016 monitoring year. Within 2016, n is the number of lake sites composing the seasonal mean at each depth.

Season	Depth	n	SRP (µg/L)	TP (µg/L)	Chl (µg/L)	Secchi depth (m)
Spring	Top	5	8 (8)	103 (57)	34.18 (6.99)	1.1 (0.2)
	Bottom	5	5 (1)	68 (17)	25.62 (6.75)	
Summer	Top	5	5 (3)	56 (28)	111.17 (57.25)	0.7 (0.1)
	Bottom	5	13 (18)	71 (45)	28.11 (27.12)	
Fall	Top	5	6 (4)	87 (30)	60.52 (21.67)	0.5 (0.1)
	Bottom	5	7 (2)	65 (21)	51.24 (22.97)	

Table 17. Lake-wide grand means (1 SD) of phosphorus concentrations, chlorophyll *a*, and Secchi depths measured during multi-year project history. Grand mean cells have two rows per cell: data in the top row represent pre-restoration sampling (Spring 2014 – Fall 2015) and data in bottom row represent post-restoration sampling (Spring 2016 – Fall 2016). For Grand Mean, n is the number of years each season was sampled in pre- or post-restoration periods.

Season	Depth	Period	n	SRP (µg/L)	TP (µg/L)	Chl (µg/L)	Turbidity (NTU)	Secchi depth (m)
Spring	Top	Pre	2	3 (0)	66 (4)	25.42 (4.36)	9.0 (6.2)	0.6 (0.1)
		Post	1	8 (ND)	103 (ND)	34.18 (ND)	13.0 (ND)	1.1 (0.2)
	Bottom	Pre	2	3 (1)	98 (30)	23.64 (2.82)	16.9 (3.0)	
		Post	1	5 (ND)	68 (ND)	25.62 (ND)	38.0 (ND)	
Summer	Top	Pre	3	6 (3)	110 (66)	67.31 (39.36)	16.2 (6.6)	0.4 (0.1)
		Post	1	5 (ND)	56 (ND)	111.17 (ND)	15.2 (ND)	0.7 (0.1)
	Bottom	Pre	3	17 (18)	107 (49)	31.65 (13.49)	22.1 (10.7)	
		Post	1	13 (ND)	71 (ND)	28.11 (ND)	28.6 (ND)	
Fall	Top	Pre	3	10 (12)	134 (23)	62.92 (42.82)	25.5 (3.9)	0.4 (0.1)
		Post	1	6 (ND)	87 (ND)	60.52 (ND)	9.9 (ND)	0.5 (0.1)
	Bottom	Pre	3	11 (13)	158 (19)	60.81 (35.29)	30.7 (2.8)	
		Post	1	7 (ND)	65 (ND)	51.24 (ND)	46.4 (ND)	

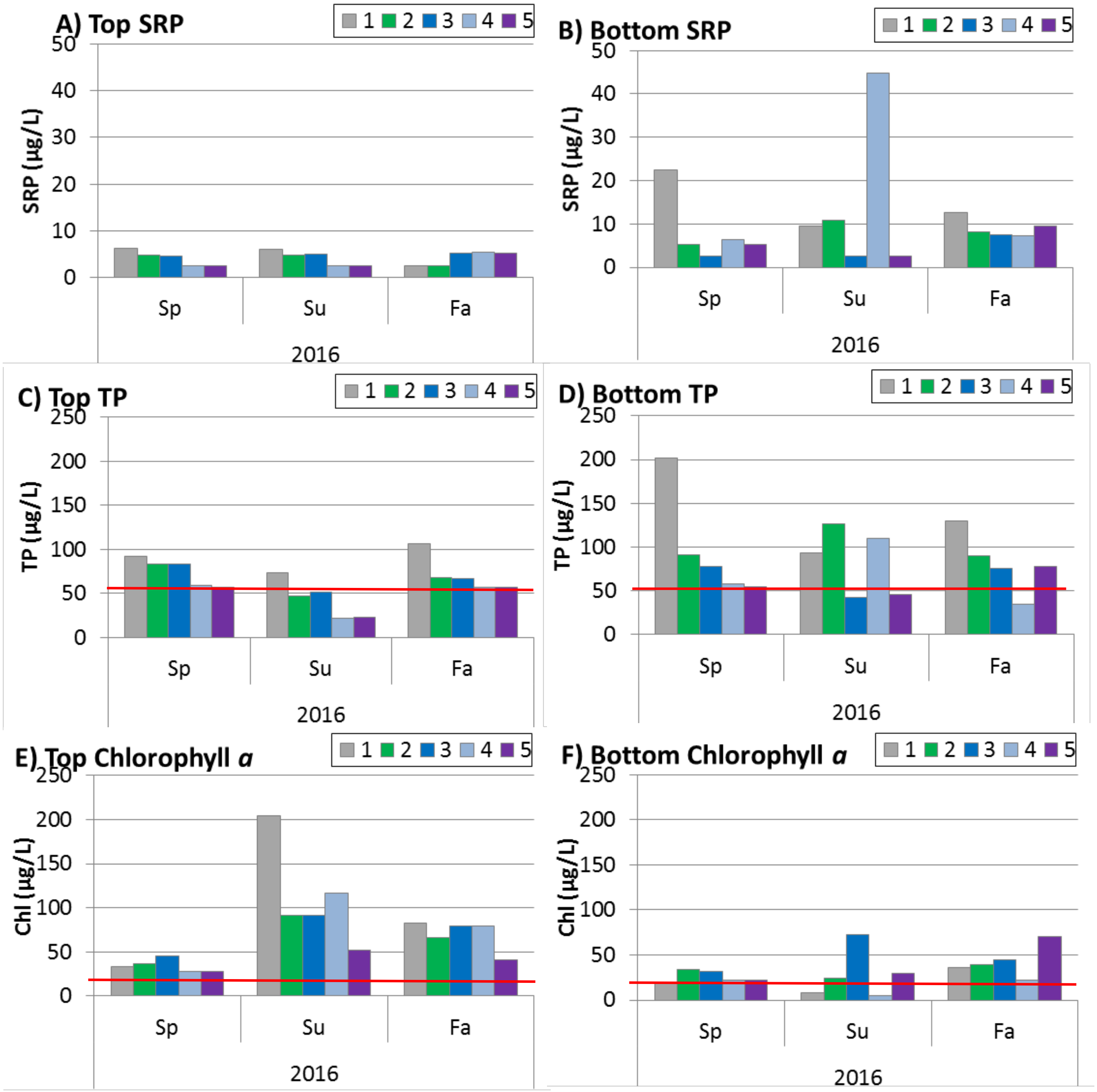

Figure 16. Soluble reactive phosphorus [SRP]: A, B; total phosphorus [TP]: C, D) and chlorophyll *a* (E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during in 2016. The red horizontal line on the TP figures (C, D) indicates the interim TMDL goal of 50 µg/L (Walterhouse 1999). The red horizontal line on the chlorophyll figures (E, F) indicates the hypereutrophic boundary of 22 µg/L used by MDEQ for assessing chlorophyll in Lake Macatawa (Holden 2014). Note scales change on y-axes.

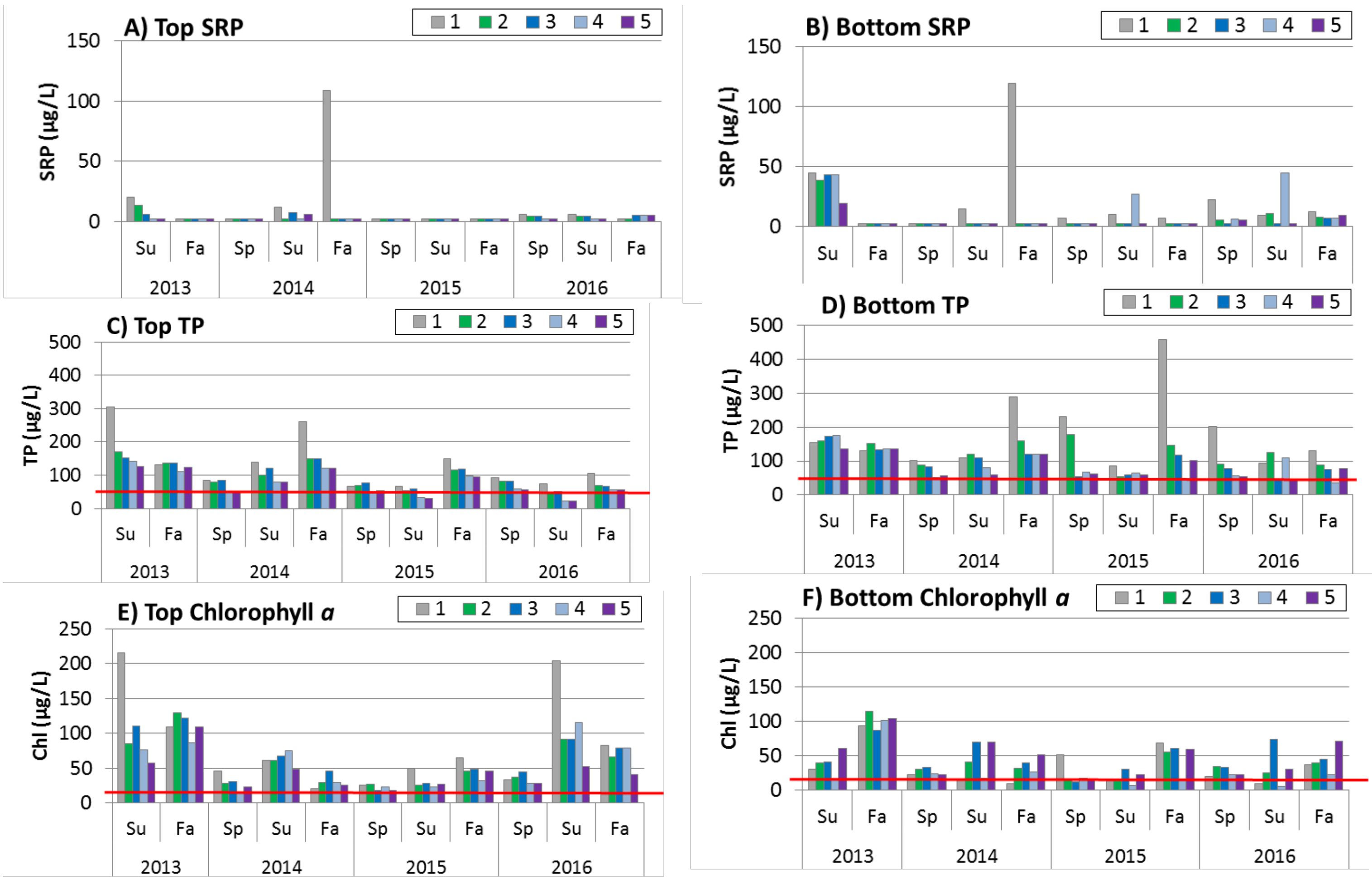

Figure 17. Soluble reactive phosphorus [SRP]: A, B; total phosphorus [TP]: C, D) and chlorophyll *a* (E, F) concentrations measured at the 5 monitoring stations in Lake Macatawa during 2013 through 2016. The red horizontal line on the TP figures (C, D) indicates the interim TMDL goal of 50 µg/L (Walterhouse 1999). The red horizontal line on the chlorophyll figures (E, F) indicates the hypereutrophic boundary of 22 µg/L used by MDEQ for assessing chlorophyll in Lake Macatawa (Holden 2014). 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. 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 fertilizer into the Maumee River, and eventually Lake Erie, triggering massive harmful algal blooms (Michalak et al. 2013). Hence, years with anomalously good or bad lake condition may be driven largely by the precipitation.

In Lake Macatawa, the relationship between lake TP and precipitation has not been clear-cut. Between 1972 and 2016, the relationship between precipitation and TP concentration in the lake was not statistically significant (Fig. 18; $R^2 = 0.122$; $p > 0.10$). 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., 2008). Interestingly, the relationship between TP and precipitation is much stronger since 2013, and is marginally significant ($R^2 = 0.836$; $p = 0.085$). However, this relation is based on only 4 data points, so it should be viewed cautiously.

Overall precipitation in 2016 was within the range that has been measured over the past 11 years (i.e., blue triangles generally fall within the gray bars) (Fig. 19). There was not a consistent relationship between precipitation and total phosphorus at the Middle Macatawa downstream site in 2016 (i.e., the blue and red triangles only rarely co-locate, and during high precipitation months they are usually far apart (e.g., June, September, December). We view these data as appropriate for screening purposes only, as the TP concentrations are single sampling events, which may miss pulses of high P concentrations after storm events.

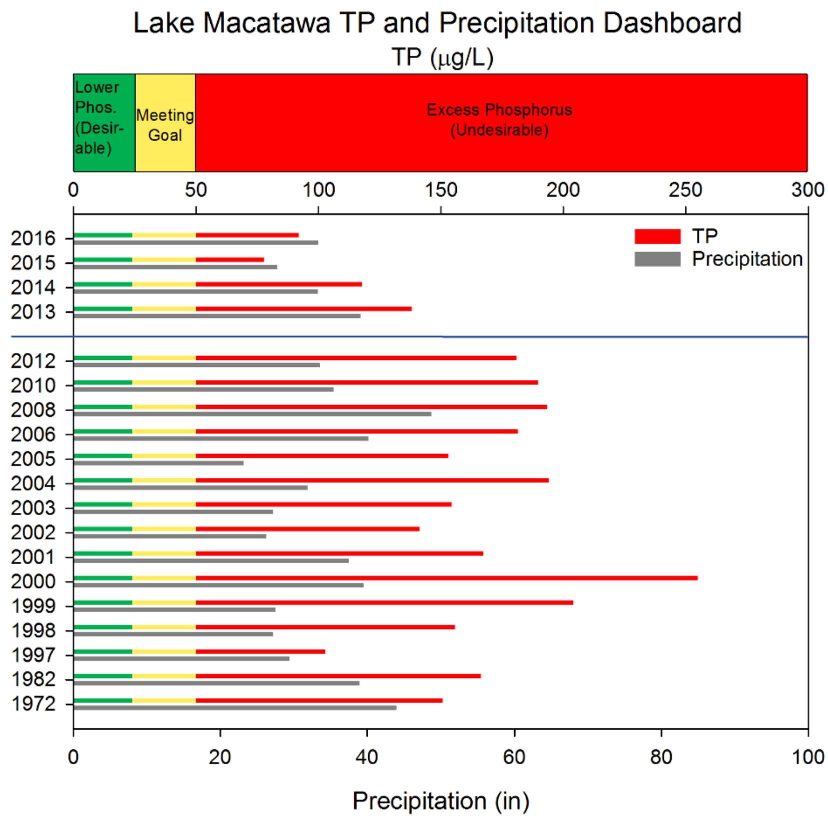

Figure 18. Lake Macatawa TP and precipitation dashboard summary. TP bars average data from top depths at sites 1, 2, and 4 to represent a continuum of water moving through Lake Macatawa in the east, central, and west basins, respectively. Yellow and red portions of the TP axis indicate averages meeting or exceeding the interim 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 (1982-2012; S. Holden, personal communication), and AWRI (since 2013). Precipitation data sources include the National Climatic Data Center (2005-2016; NOAA) and Weather Underground (1972-2004; The Weather Company).

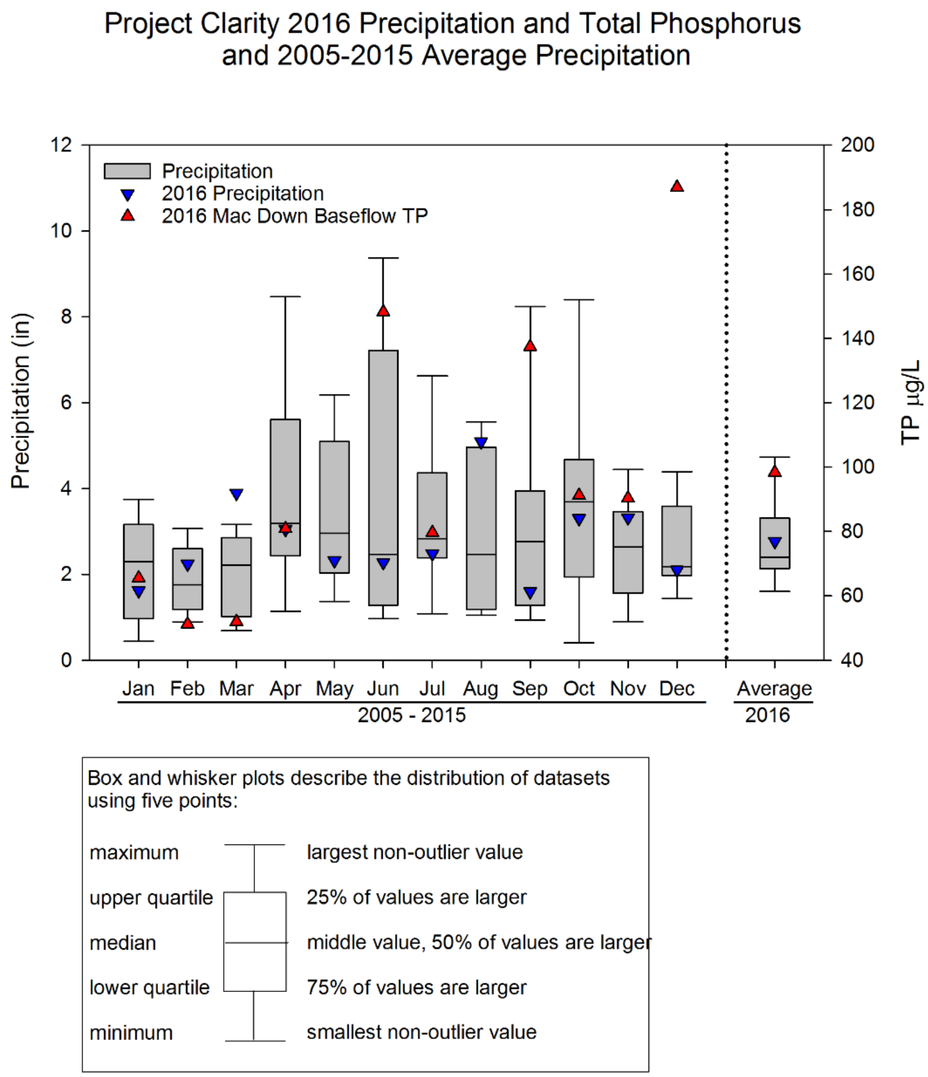

Figure 19. Box and whisker plot showing precipitation data for each month between 2005 and 2015 (gray bars), cumulative precipitation for each month in 2016 (blue triangles), and TP concentration from the Middle Macatawa downstream sampling point for each month we sampled baseflow in 2016 (red triangles; no baseflow samples were taken in May and August). The far right box and whisker show the average 2016 precipitation and TP data. Precipitation data are from the National Climatic Data Center (2005-2016; NOAA).

4. Additional Studies

AWRI also is engaged in a number of research projects to help inform management decisions for Project Clarity. Appendix A contains the report covering our high-resolution terrestrial Lidar study measuring bank erosion in the Macatawa Watershed, while Appendix B contains the report on Year 3 of fish monitoring in Lake Macatawa. The three student research projects are briefly described below.

4.1 Tile Drains as a Source of Phosphorus

Delilah Clement successfully defended her Master of Science degree at AWRI in May, 2016. Her research examined the phosphorus concentrations in tile drain effluent, and their effect on algal growth in laboratory bioassays. Her research was recently published (Clement and Steinman 2017). The key findings from her research include: 1) SRP and TP concentrations in the tile drain effluent were greatest during the non-growing season, a finding recently corroborated (Van Esbroeck et al. 2016); 2) overall SRP and TP concentrations in the tile drain runoff could get as high as 450 and 560 µg/L, respectively; and 3) SRP, the most bioavailable form of phosphorus, accounted for 60% of the total phosphorus. The key management recommendation is to focus on P retention in winter and spring, when runoff concentrations are highest.

4.2 Two-Stage Ditches as Phosphorus Retention Devices

This study is being conducted by Emily Kindervater as part of her Master of Science degree at AWRI. The work is focused on how effective two-stage ditches are at retaining phosphorus compared to traditional, trapezoidal-shaped ditches. For this project, Emily: 1) monitored water quality monthly, including TP, SRP, and turbidity, 2) conducted spring and fall sediment analyses to determine general sediment P content variability, most abundant fraction, and the equilibrium P concentration (EPC), 3) sampled benthic periphyton monthly for analysis of community structure and P content, and 4) conducted an end-of-growing-season aboveground vegetation survey for ground cover estimation and P content. Sediment TP content varied between 95 and 950 mg/kg dry sediment and tended to be lower in the two-stage reach. In both spring and fall, the major fraction of P was the Al-bound fraction in one ditch system and both Al-bound and Ca-bound fractions in the other system. EPC values suggest that in the spring, the sediment in one ditch system was retaining phosphorus but in the two-stage and reference of the other system, there was both potential retention and release at certain sites. During the fall, in both systems, the reference site had potential release of P while the two-stage was retaining P. Periphyton and vegetation analyses are currently being finalized. This work will be completed in 2017.

4.3 Summer Undergraduate Intern Project

Muhidin Abdimalik was an undergraduate summer intern from the University of Missouri-St. Louis, who worked in the Steinman lab in 2015. Muhidin examined the role of light and nutrients in controlling the growth of attached vs. floating algae in Lake Macatawa. We conducted this experiment using the dock of the Koster family in Pine Bay (Fig. 20). Attached algal growth was co-limited by both nitrogen and phosphorus, while floating algae were limited by phosphorus. Light was not a limiting resource, perhaps because the arrays were deployed in relatively shallow water. Implications from this study indicate that both phosphorus and nitrogen need to be managed in the watershed. The experiment resulted in a publication (Steinman et al. 2016).

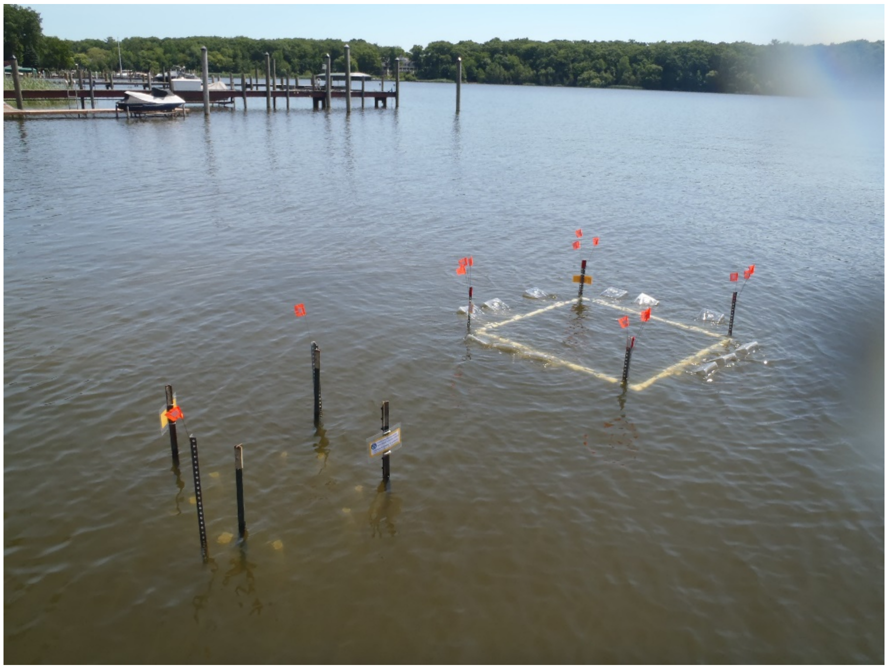

Figure 20. Experimental arrays in Pine Bay to examine competition between attached vs. floating algae for nutrients and light.

5. Summary

The results of the 2016 monitoring effort were consistent with prior findings for Lake Macatawa and its watershed, indicating that water quality is still severely impaired in this system (Holden 2014; Hassett et al. 2016). This is the first full year of post-restoration monitoring at the Middle Macatawa and Haworth sites, so our focus was on assessing both 2016 conditions and comparing pre- vs. post-restoration water quality conditions at these restoration sites and in Lake Macatawa.

Water quality has not improved in 2016 in Lake Macatawa and its watershed. Phosphorus concentrations are too high throughout the system, far in excess of the TMDL target, and water transparency, while anecdotally improved in 2016, actually was quite poor based on our discrete measurements. Occasional hypoxic conditions during the summer at the deeper lake sites also suggest degraded conditions and bear watching in the future.

We did not observe any water quality benefits in 2016 from the restoration activities. This is not particularly surprising, for 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 environmental 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 are a concern, especially in the Peter's Creek sub-basin; we identified this problem last year, but concentrations continue to be extremely high, in some cases above human health thresholds. The finding that growth of at least some algae in Lake Macatawa are co-limited by nitrogen (Steinman et al. 2016) indicates that nutrient management should focus on both nitrogen and phosphorus (cf. Conley et al. 2009).

Agricultural BMPs are being implemented in the Macatawa watershed, and are clearly needed to reduce P, N, and sediment loading; tile drain effluent appears to be an additional source of P (and maybe N) that has not received adequate attention in the past but is now being recognized as a factor contributing to toxic algal blooms in the western basin of Lake Erie (Lam et al. 2016, Van Esbroeck et al. 2016).

Our 2016 results underscore the dire need for remediation in the Macatawa watershed. The magnitude of nutrient reduction that is necessary to satisfy the phosphorus TMDL and result in a healthy Lake Macatawa will require long-term and sustainable dedication, coordination, and cooperation among stakeholders and professionals. The successful execution of Project Clarity is a major step toward realizing the goals for Lake Macatawa. Continued monitoring as part of the project will document progress along the way.

6. Acknowledgements

Funding was provided through Project Clarity funds; our thanks to Travis Williams and Dan Callam of ODC for all of their help and knowledge of the area. We gratefully acknowledge the field and lab support provided by Mary Ogdahl, Delilah Clement, Emily Kindervater, Nicole Hahn, Brittany Jacobs, Travis Williams, Dan Callam, Ben Heerspink, Joey Broderik, and Andy Taehen. Brian Scull preformed P and N analysis in the laboratory.

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Appendix A. Using High-Resolution Terrestrial Lidar to Measure Bank Erosion (Thompson and McNair)

Appendix B. Long-Term Fish Monitoring of Lake Macatawa: Results from Year 3 (Ruetz and Ellens)

Using High-Resolution Terrestrial Lidar to Measure Bank Erosion

Kurt Thompson and James N. McNair, Annis Water Resources Institute

Introduction and Overview

Bank erosion is a significant contributor to sediment loads in many streams in the northern U.S. It accounts for 31 to 44% of the suspended sediment load of the Blue Earth River in Minnesota (Sekely et al. 2002), an average of 45% of the suspended sediment load of streams throughout Iowa (Odgaard 1984), and up to 79% of mean annual sediment loads measured in 29 experimental catchments scattered across Pennsylvania (Evans et al. 2003). It is thought to be the dominant source of stream sediment loads in most lowland catchments (Kiesel et al. 2009) and tends to be particularly important in catchments that are highly urbanized, or that are primarily agricultural but with significant densities of grazing animals or an admixture of urbanized areas. All of these patterns suggest that bank erosion probably is an important source of suspended sediment in streams flowing into Lake Macatawa.

Despite the potential importance of bank erosion as a contributor to sediment loads in streams, most models used by watershed managers to estimate annual sediment loads from catchments fail to account for it. Traditional field survey methods, such as installing erosion pins or using electronic total-station survey instruments to characterize changes in stream bank topography, are labor- and time-intensive, which limits the interest of watershed managers in employing these techniques across multiple catchments within a given watershed. In addition, erosion pins are invasive in the sense that they must be driven into the stream bank and therefore are likely to alter the erosion process by weakening the soil and creating artificial eddies that modify the scouring process during high-flow events.

In this pilot project, we applied a relatively new technology called a *terrestrial laser scanner* (TLS) to the problem of detecting and quantifying bank erosion in the Lake Macatawa watershed. The project was designed to capture a temporal sequence of high-resolution 3D digital scans from six individual stream banks within three sub-catchments of the Macatawa watershed over the course of a year. Lidar-based measurement has been determined to have numerous advantages over commonly-used survey methods such as erosion pins and total-station transects, including non-invasiveness, greater accuracy, greater simplicity, and reduced field effort. The sites selected for the project were in three separate but adjacent sub-catchments of the watershed and were located (1) on the Macatawa River near the USGS flow gauge, (2) on the Black River in Poppen Woods, and (3) on Peter's Creek (Fig. 1). Two banks were scanned at each site.

The study sites were selected based on an initial investigation of multiple locations within the watershed because of (a) the apparent degree of bank erosion at each site (ranging from low to extreme), (b) the accessibility of the locations throughout the year-long project, (c) the sparseness of existing vegetation on the bank slopes at the time of the initial lidar survey (dense vegetation cover prevents accurate scanning of the bank's soil surface), and (d) other field work that was being done concurrently by AWRI for Project Clarity at two of the sites (USGS and Poppen Woods), reducing cost, travel time, and number of field personnel.

Figure 1. Lidar stream-bank sites in the Lake Macatawa watershed.

As noted above, the TLS's main advantage is its unique ability to easily acquire high-resolution digital 3D point data, creating a digital "snapshot" of the physical characteristics of the banks at a particular moment in time with millimeter accuracy in all dimensions. The current generation of TLS devices have been developed for ease of use and are lightweight and battery powered, can attach directly to standard survey tripods, are controlled by an integrated touch-screen computer interface, and come with multiple, automated sensors for precise leveling and orientation. Once a series of 3D digital lidar scans are captured and are registered to one another using lidar processing software, other tools can be used to detect and quantify even very slight physical changes in the surface of the banks over time.

Methods

Lidar data were collected from the six stream banks during three time periods: April 2015 (spring), December 2015 (late fall/early winter), and April 2016 (spring). All lidar scans were performed under base-flow conditions. The first scan (April 2015) served as a baseline for comparison with the two subsequent scans. Changes in stream-bank surfaces between the first and third scans reflect changes over an entire year. Changes between the first and second scans make it possible to determine how much of the annual change occurred before versus after the winter-spring transition. We focus on the first and third scans in this report, since these cover the longest period of time and include a complete seasonal cycle.

The TLS used in this project was a Trimble TX5 laser scanner, which collects lidar data at a continuous rate of 488,000 points per second, automatically saving the 3D data to 64-GB secure digital (SD) memory cards for easy transfer to desktop computers for processing with Trimble RealWorks software. The typical setup time for the TX5 at the target bank site was approximately 10 minutes, which included installing the TX5 on the survey tripod and leveling and orienting the device using an integrated dual-axis compensator (inclinometer), altimeter, and electronic compass. Once the TX5 was leveled, a preliminary 5- to 7-minute preview scan was run to determine parameters of the target bank so scanning could be restricted to the selected area. The high resolution scan took about 20 to 25 minutes to complete at each site. The digital scan files saved on the SD cards were approximately 1 to 2 GB in size, containing about 13 to 15 million 3D (x, y, z) points. A 70-megapixel digital image of the target bank site was also automatically collected by the TX5 at the end of the scan and saved to the SD card.

During the first lidar field survey in April 2015, a hand-held laser rangefinder was employed at the TX5 setup position on the bank opposite the target bank (at approximately the mid-point of the target bank) to measure the distance from the position of the TX5 to the proposed boundaries of the target bank scan. The total distance from the scanner to the target bank was intentionally limited to 20 meters or less to eliminate ranging noise (0.5 mm at 90% reflectivity and 1.1 mm at 10% reflectivity at 25 meters). The potential ranging noise introduced to the lidar scans depends on the ambient light conditions at the time of the actual survey and increases with the distance the laser light has to travel between the scanner and the target. The TX5 was rated to capture scans at distances of up to 120 m, so restricting the project scan distance to 20 meters or less, regardless of ambient light conditions, minimizes the scan noise.

Figure 2. Trimble TX5 terrestrial laser scanner.

At each of the target bank sites, two 4-ft long iron rebar stakes with aluminum and steel survey caps were driven into the ground at the boundary edges to delineate the scan capture area with an unobstructed sight line back to the TX5 setup position. Another iron stake and survey cap was driven into the ground at the TX5 setup site, so that the TX5 would be set up precisely in the same location for all the remaining project scans. The target bank boundary stakes allowed for the temporary placement of two magnetic spheres as laser targets (Fig. 3a, b). These target spheres were included in every lidar scan so they could be used by the Trimble RealWorks software in processing the lidar scans from each bank to assist in accurately registering scans from the three collection times to each other.

Lidar scans were collected for all three time periods at each of the six stream banks. The digital files were then transferred to a computer to be opened in Trimble RealWorks software for registration. An example of a raw lidar scan and the remarkable detail that the TX5 captures is shown in Fig. 4. The 70-megapixel full-color image that was captured directly after the collection of the lidar scan is shown in Fig. 5.

Using the Trimble RealWorks software, the April 2015 and the April 2016 lidar scans where imported into a project file as individual raw scans. Each of these scans was then re-sampled to form individual 3D point clouds of the (x, y, z) data (Figs. 6, 7). Once the raw scans were converted to point clouds, the scans were registered to one another using the automatic target registration module. The April 2015 scan was selected first, and the registration module was

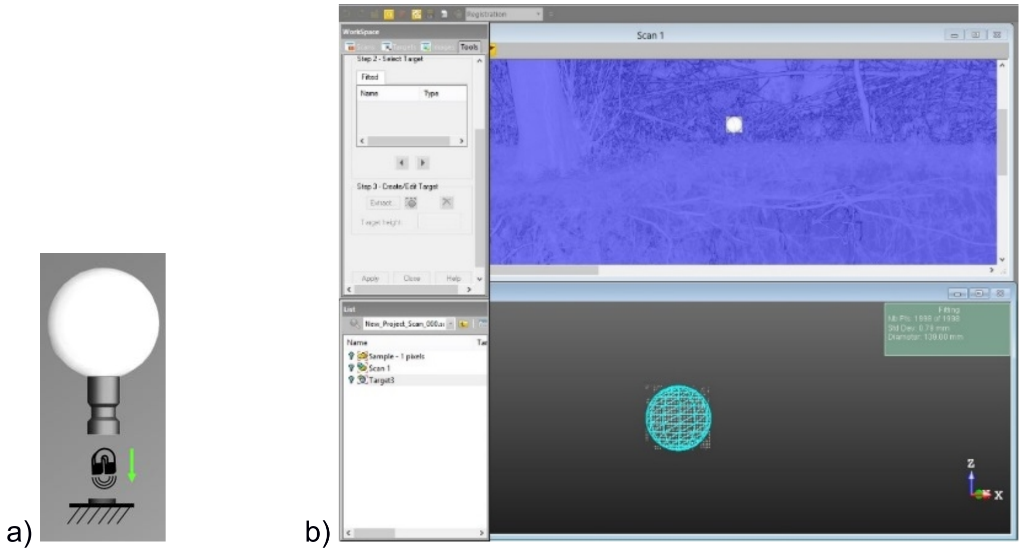

Figure 3. Magnetic sphere shown (a) schematically and (b) as a registered 3D target in the lidar software.

Figure 4. A raw lidar scan taken on April 2015 at the USGS upstream bank site.

Figure 5. A high-resolution color image of the USGS upstream bank site taken immediately after the lidar scan shown in Fig. 4.

activated and set to search for the (two) 139-mm target spheres digitally embedded in the scan. The registration module correctly detected the two target spheres within the scan, and these 3D objects were stored as assigned targets, uniquely identifying them as registration controls in the April 2015 scan. This process was repeated for the April 2016 scan. The four target spheres (two from April 2015 and two from April 2016) were then matched to their positional counterpart in each scan; specifically, the number 1 target sphere in the April 2015 scan was matched to the number 1 target sphere by position in the April 2016 scan, and this procedure was repeated for the number 2 target sphere in both scans.

The registration module required that each scan have at least three known positional elements (3D objects) within the data to register the point clouds to one other. The first two objects for each scan were the two 139-mm target spheres, while the third object was the TX5 instrument's physical origin position (leveled and oriented), which was exactly the same in both scans. Having met the minimum criteria for positional objects within both scans, the registration module was able to register the April 2015 and April 2016 scans and point clouds together (Fig. 8).

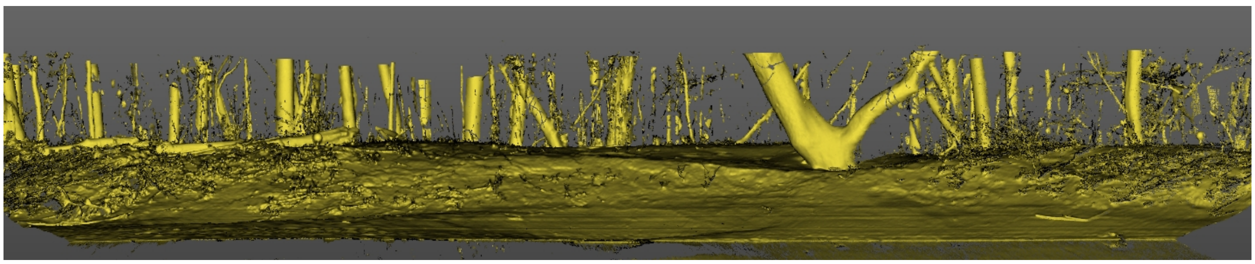

Figure 6. Lidar scan of the Peter's Creek downstream bank site in April 2015, in shades of yellow.

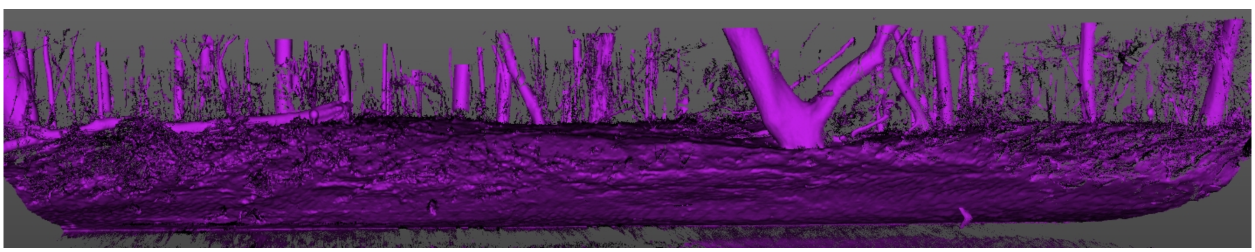

Figure 7. Lidar scan of the Peter's Creek downstream bank site in April 2016, in shades of magenta.

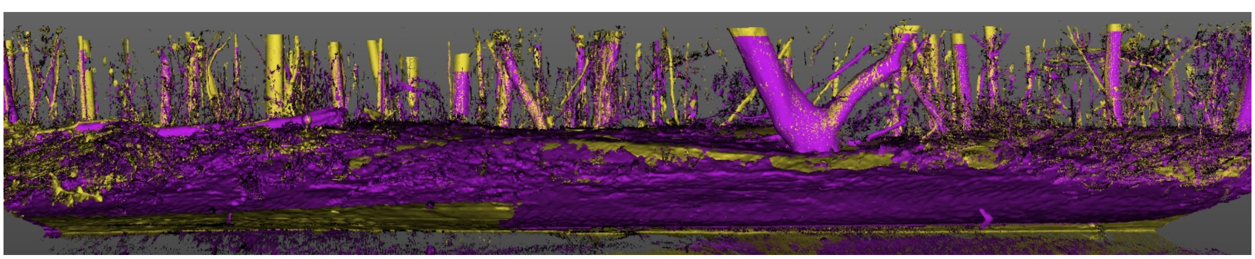

Figure 8. Overlay of registered lidar scans of the Peter's Creek downstream bank site in April 2015 and April 2016. The color that is visible at each point on the bank indicates whether the bank surface there was closer to the laser scanner in April 2015 (yellow) or in April 2016 (magenta), which in turn indicates whether net erosion (yellow visible) or deposition (magenta visible) occurred. The residual measurement error was 1.12 mm, so points with little or no change (e.g., tree trunks) may be colored incorrectly.

A report (Fig. 9) was generated after registration was completed to document the residual error in distance measurements, based on the known target locations. The target-based registration process was applied to all six pairs of scans from April 2015 and April 2016.

After all scans were registered together, a segmentation module was used to remove vegetation around the targeted bank area for each April 2015 and April 2016 point cloud. An example showing the result of this process is displayed in Fig. 10. After segmentation was completed, the measurement module was used to determine the physical characteristics of the "clean" targeted bank areas in preparation for comparing the (x, y, z) surface of each bank in April 2015 and April 2016 and calculated the volume of change due to erosion and deposition.

To quantify the erosional and depositional changes at each of the six stream bank locations, the registered pairs of point clouds for the April 2015 and April 2016 time periods were analyzed together using a 3D volume-comparison module called Volume Calculation. The module was run on all 3 pairs of point clouds, with April 2015 as the beginning (reference) surface and April 2016 as the comparison surface.

Registration Report (Target-Based)
Report by station

User Name: AWRI

Date: Wed Dec 07 10:14:56 2016
Project Name: ProjectPetersCreekDS

Length Measurement Units: Millimeters
Coordinate System: X, Y, Z

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2 STATION(S) - Mean Distance: 1.12 Max Distance: 1.12
2 TARGET(S) - Mean Distance: 1.12 Max Distance: 1.12

21idds.1_Scan_sub001.1 - 3 Scanned Objects - Mean Distance: 1.12

Object Name	Corresponding Target	Scan Per Target	Residual Error	Delta X	Delta Y	Delta Z	Fitting Error	Distance to Scanner
21idds.1_Scan_sub001.1	--	--	--	--	--	--	--	0.00 mm
Target1	001	2	1.12 mm	-0.04 mm	-1.12 mm	0.10 mm	0.77 mm	16069.46 mm
Target2	002	2	1.12 mm	0.04 mm	1.12 mm	-0.10 mm	0.90 mm	20976.99 mm

Scan021sub.1 - 3 Scanned Objects - Mean Distance: 1.12

Object Name	Corresponding Target	Scan Per Target	Residual Error	Delta X	Delta Y	Delta Z	Fitting Error	Distance to Scanner
Scan021sub.1	--	--	--	--	--	--	--	0.00 mm
Target3	001	2	1.12 mm	0.04 mm	1.12 mm	-0.10 mm	0.92 mm	16041.12 mm
Target4	002	2	1.12 mm	-0.04 mm	-1.12 mm	0.10 mm	0.97 mm	20987.01 mm

Figure 9. Report for target-based registration of scans and point clouds from the Peter's Creek downstream bank for April 2015 and April 2016 (residual error = 1.12 mm).

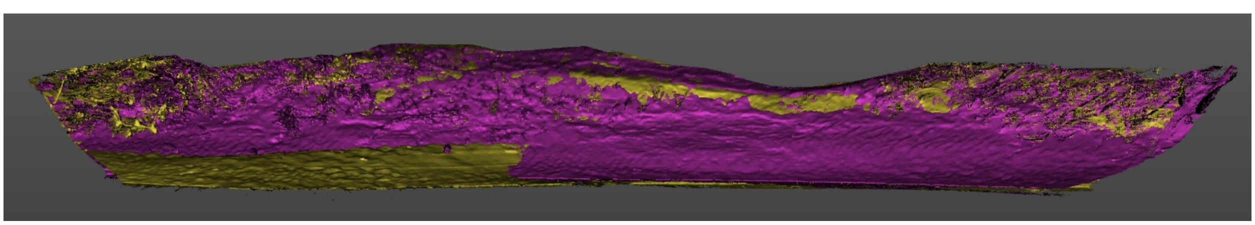

Figure 10. Overlay of registered lidar scans of the Peter's Creek downstream bank for April 2015 and April 2016 with extraneous vegetation segmented out. Color interpretation is the same as in Fig. 8.

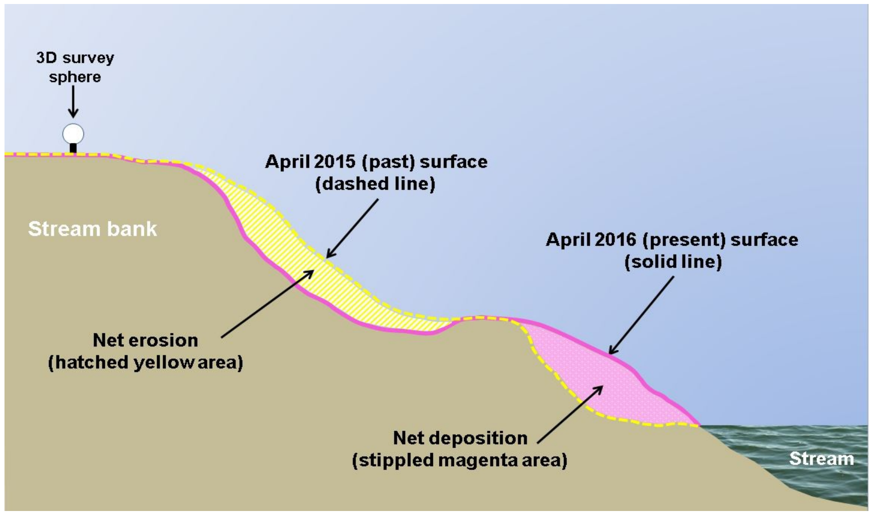

Figure 11. Schematic representation of the method used by the Volume Calculation module to compute separate volumes of soil deposition and soil erosion for different portions of the same stream bank. Portions of the bank where the surface was higher or closer to the lidar scanner in April 2016 than in April 2015 (shown in magenta) are assumed to have been filled with deposited soil; portions of the bank where the surface was lower or farther from the scanner in April 2016 (shown in yellow) are assumed to have been cut out by erosion.

The Volume Calculation module estimates volumes of eroded and deposited sediment as follows. Each scan defines an (x, y, z) surface in 3-dimensional space. After the scans acquired on different dates at a given bank are registered, horizontal and vertical distances on these surfaces share the same origin and therefore can be compared. Portions of the bank surface that were higher or closer to the lidar scanner in April 2016 than in April 2015 ("fill" locations) were assumed to have incurred soil deposition, while portions that were lower or farther from the scanner ("cut" locations) were assumed to have incurred erosion (see Fig. 11). The Volume Calculation module determines the volumes of these depositional and erosional portions of each bank by calculating volumes of the "gaps" between the bank surfaces for the two dates being compared. Volumes of deposited soil are given a positive sign, while volumes of eroded soil are given a negative sign. The difference between the volumes of deposited and eroded sediment for a given bank is the net change in soil volume between the two dates. If the net change is positive, the bank showed overall net deposition; if the net change is negative, the bank showed overall net erosion.

Results and Discussion

The physical characteristics of the segmented banks are summarized in Table 1, along with the residual error for each pair of registered scans. The majority of the registered pairs had very low residual errors (< 2.5 mm). The USGS upstream site, however, had an error of 13.85 mm, nearly seven times the size of the closest residual error of 2.08 mm for the USGS downstream site. We believe that the survey stake for the target sphere at the downstream end of the USGS upstream site was physically levered upward about 10 mm from its original position by the root ball of a tree that fell into the Macatawa River a few feet from the stake. The large residual error reported for this scan is due specifically to this target sphere. Careful examination of other non-moving objects such as tree trunks and large branches indicated that the overall residual error for the upstream bank at the USGS site was indistinguishable from the overall residual error in the other scans. We recommend that in the future, multiple targets (more than 2) should be used for registering scans so that any anomalous targets can be deleted prior to registration.

Results of the volume-change analysis are shown in Table 2. A portion of each bank showed sediment gain (positive volume between the 2015 and 2016 surfaces) and the rest showed sediment loss (negative volume between surfaces). These gains and losses are reported separately in Table 2. The difference between the gains and losses for each bank is the net total change in sediment volume between April 2015 and April 2016. Negative values of the net total change indicate net erosion from the bank, while positive values indicate net deposition.

The results in Table 2 show that both banks at the USGS and Poppen Woods sites exhibited net erosion, and that erosion was especially prevalent for the upstream bank at the USGS site (net loss of 10.49 m^3 of sediment). The upstream bank at the Peter’s Creek site showed net deposition, while the downstream site showed essentially no net change.

The results of this pilot project confirm the utility of high-resolution terrestrial lidar as a method for measuring stream bank erosion. The spatial resolution of this technique vastly surpasses that of the traditional alternatives (e.g., erosion pins, total-station transects), as does its ease of use. The main issue with this relatively new technology at the present time is the high purchase price. This issue makes it necessary to rent rather than purchase the instrument and software. While this, too, is relatively expensive (roughly $500 per day), several sites can be scanned in a single day and only a small number of scan dates per year (as few as one) are required for most purposes. We therefore believe that this promising technology is cost-effective with adequate planning.

Table 1. Physical characteristics of the April 2015 and April 2016 banks after target sphere registration and segmentation to remove extraneous vegetation.

Bank Location	USGS		Poppen Woods		Peter’s Creek	
	Up	Down	Up	Down	Up	Down
Bank erosion condition	Extreme	Moderate	Extreme	Low	Extreme	Moderate
Bank height, m	2.87	2.06	2.15	1.54	1.34	1.53
Bank length, m	26.07	23.58	19.82	19.70	20.31	19.46
Average bank slope, degree	58.51	36.65	49.73	34.22	44.59	22.67
Registration residual error, mm	13.85	2.08	0.71	1.26	0.88	1.12

Table 2. Volume comparison of 3D point cloud surfaces from April 2015 to April 2016 (in m^3) for all six project bank locations. Numbers shown represent the calculated volume between the bank surfaces for the two scan times. Positive volumes apply to areas of each bank that experienced deposition, while negative volumes apply to areas that experienced erosion. The difference between the two (net total change) is the net change in volume of soil for each bank, which can be positive (net deposition) or negative (net erosion).

Bank Location	USGS		Poppen Woods		Peter's Creek	
	Up	Down	Up	Down	Up	Down
Bank erosion condition	Extreme	Moderate	Extreme	Low	Moderate	Moderate
Positive volume (gain), m^3	1.05	2.20	1.50	2.26	1.93	3.81
Negative volume (loss), m^3	11.54	4.55	4.54	4.20	1.91	1.06
Net total change, m^3	-10.49	-2.35	-3.04	-1.94	0.02	2.75

Additional studies will be required to realize the full potential of this technology as a method for estimating the contribution of bank erosion to catchment-scale sediment loads. Future work should focus on two key tasks: (1) developing a GIS-based method for scaling up site-specific measurements of bank erosion and deposition to entire catchments and (2) developing a method for estimating the annual catchment-scale sediment yield (i.e., eroded sediment that actually exits the catchment) resulting from net bank erosion measured at the site scale. Accomplishing these two tasks will make it feasible to calculate estimates of annual catchment-scale sediment loads derived from bank erosion that correspond to readily available estimates of loads derived from field erosion. This will make it possible to objectively identify the relative contributions of these two major sources of sediment, which is necessary in order to appropriately prioritize management efforts to reduce total sediments load exported to Lake Macatawa.

Acknowledgements

Many current and former AWRI staff and students helped us to accomplish the goals of this project: Mary Ogdahl, Maggie Oudsema, Michael Hassett, Delilah Clement, Emily Kindervater, Nicole Hahn, Brittany Jacobs, and NSF-REU QUEST student Eli Jacobson. We would also like to thank Travis Williams, executive director of the Outdoor Discovery Center Macatawa Greenway (ODCMG) for funding this project and Dan Callum, the Greenway manager, for his valuable support in helping to select our stream bank sites and in soliciting stakeholder cooperation for our field collection efforts. Thanks also to Mark TenHove from Michigan Surveyors Supply for providing the Trimble TLS equipment and software and for his expert technical assistance and service to us in delivering and setting up the instrument, and in analyzing the lidar data. We would also like to thank Dr. Alan Steinman, AWRI Director, for his thoughtful comments on this report.

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Long-Term Fish Monitoring of Lake Macatawa: Results from Year 3

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16 January 2017

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Introduction

This study was initiated to provide critical information on littoral fish populations that will be used to evaluate the performance of watershed restoration activities that are part of Project Clarity. 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 third 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 Ruetz et al. 2007; 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 (Figure 2).

Fish sampling.—At each study site, we sampled fish via fyke netting and boat electrofishing. Fyke nets were set on 6 September 2016 during daylight hours (i.e., between 0900 and 1300) and fished for about 25.7 h (range = 22.9-29.2 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 8 September 2016. 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 also measured water quality variables (i.e., temperature, dissolved oxygen, specific conductivity, total dissolved solids, turbidity, pH, oxidation-reduction potential, and chlorophyll *a*) in the middle of the water column using a YSI 6600 multi-parameter data sonde. We made one measurement at each fyke net (n = 12) 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). We also visually estimated the percent macrophyte cover for the length of each electrofishing transect during fish sampling.

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 85 cm (Table 2). Water temperature was similar (at about 24 °C) when we conducted fyke netting and boat electrofishing (Tables 2 and 3). At fyke nets, mean % cover of macrophytes was zero at sites #1 and #3, whereas mean % cover of macrophytes was 13% and 8% at sites #2 and #4, respectively. Conversely, we visually estimated macrophyte cover at electrofishing transects to be 5% at site #1, 35% at site #2, 85% at site #3, and 90% at site #4, which was greater than our estimates at fyke nets. The visual estimates of % macrophyte cover for electrofishing is over a greater area at each site than estimates for fyke netting, which accounts for the differences. For instance, we observed extensive macrophyte beds at site #3 that were in deeper water than we were able to fish fyke nets but were part of the electrofishing transect. The % macrophyte cover in 2016 was higher than the two previous years, especially when macrophyte cover was assessed during boat electrofishing transects (Figure 3). 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. Moreover, 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 natural fish communities in Lake Macatawa. The presence of macrophyte beds in the vicinity of our fish sampling sites were likely related to the lower turbidity we observed in the lake in 2016 compared with previous years (Figure 4B); however, the low turbidity in 2016 was likely the result of natural inter-annual variation in the system.

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 that 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, to a lesser degree, specific conductivity were lower in 2016 than in the previous two years (Figure 4). In fact, turbidity was lowest at every site in 2016 (when compared to the previous two years; Figure 4B), whereas specific conductivity showed a clear decrease at only site #1 (Figure 4A), which is closest to the mouth of the Macatawa River (Figure 1). As expected, we found a negative correlation between % macrophyte cover and turbidity (Figure 5), although we caution that this relationship is based on observations at only four sites during a single year in autumn.

We captured 1,648 fish comprising 24 species in Lake Macatawa during the 2016 sampling surveys (Table 4). Although we captured fewer fish species in 2016 than in previous years (2014: 28 species; 2015: 30 species), we captured more individuals in 2016 (2014: 1,127 fish; 2015: 537 fish). The most abundant fishes in the combined catch of both gears (fyke netting and boat electrofishing during 2016) were gizzard shad (28%), yellow perch (23%), bluegill (11%), white perch (9%), largemouth bass (8%), and pumpkinseed (7%), which composed 86% of the total catch (Figure 6A). Three of the 24 species captured during 2016 were non-native to the Great Lakes basin (Bailey et al. 2004)—alewife (<1%), white perch (9%), and round goby (1%)—which composed 10% of the total catch (Table 4). For the first time during this study, we captured a native logperch (Bailey et al. 2004), which is a small benthic species that is often displaced by the invasive round goby (e.g., Balshine et al. 2005, Bergstrom and Mensinger 2009).

We captured about 1.5 times as many fish in fyke netting as boat electrofishing (Table 4), but the number of fish species captured in fyke netting (22 species) was similar to boat electrofishing (21 species). Three fish species were captured only by fyke netting (i.e., alewife, green sunfish, and bluntnose minnow), whereas two species were captured only by boat electrofishing (i.e., logperch and walleye). However, the difference in catch between the two gears was less pronounced in 2016 compared with the previous two years. Nevertheless, using both sampling gears likely provide a better characterization of the littoral fish assemblage of Lake Macatawa than either gear by itself, which is consistent with findings in Muskegon Lake where small-bodied fishes were better represented in fyke netting and large-bodied fishes were better represented in nighttime boat electrofishing (Ruetz et al. 2007).

In fyke netting, gizzard shad (37%), bluegill (16%), yellow perch (13%), white perch (8%), and pumpkinseed (8%) were the most abundant fishes captured, which composed 81% of the total fish captured (Figure 6B). Although gizzard shad was the most abundant species in the catch at sites #1 and #3, bluegill was most common at site #2 and pumpkinseed was most common at site #4 (Table 5). The next most abundant species in the catch at each site were white perch and bluegill at sites #3, yellow perch and spotfin shiner at site #2, bluegill and yellow perch at site #1, and yellow perch at site #4 (Table 5). There also was variation in total catch among the sites, with more fish captured at sites #1 and #3 than sites #2 and #4 (Table 5; Figure 7A). Compared with the previous two fyke netting surveys, the most abundant species in the catch varied among years (Figure 8) as did the patterns in total catch among sites (Figure 7A). 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 fewer round goby and more yellow perch in 2016 than the previous two years (Figure 8). The relative abundance of gizzard shad in 2016 was intermediate compared with the other two years (Figure 8). However, as we continue our monitoring of Lake Macatawa, we will be better able to assess how dynamic these spatial patterns among sites are over time and whether the observed patterns are associated with other environmental variables.

In boat electrofishing, the most abundant fishes captured were yellow perch (37%), largemouth bass (17%), gizzard shad (15%), white perch (10%), pumpkinseed (7%), bluegill (4%), and brook silverside (2%), which composed 92% of the total catch (Figure 6C). Yellow perch was most abundant in the catch at sites #4 and #3, and largemouth bass was most abundant in the catch at sites #2 and #1 (Table 6). The next most abundant species in the catch was gizzard shad at sites #3, #4, and #1, whereas yellow perch and white perch were nearly equally abundant in the catch at site #2 (Table 6). Total catch also varied among sites. In 2016, total catch at sites #2, #3, and #4 were among the highest during this study, whereas catch at site #1 was among the lowest (Figure 7B). Thus, there was not a positive association in total catch across sites between the two sampling gears in 2016 (Figure 7). Compared with the two previous boat electrofishing surveys, the most abundant species in the catch varied among years (Figure 9), although the pattern was weaker than what was observed for fyke netting (Figure 8). The main difference in the littoral fish assemblage among annual electrofishing surveys was that gizzard shad and largemouth bass were more common and spottail shiner was less common in 2016 compared with the two previous years (Figure 9).

In conclusion, the observations reported here are the third 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 three years of fish monitoring, we observed differences in total catch (Figure 7) and fish species composition of the catch among years (Figures 8 and 9). Water clarity was higher (i.e., lower turbidity; Figure 4B) and macrophytes were more common at our sampling sites in 2016 than in previous years (Figure 3). These environmental conditions were likely, in part, responsible for the higher total catch of fish in 2016. Nevertheless, not too much weight should be attributed to differences among only three sampling years. Once we accumulate several years 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. Maggie Oudsema was instrumental in coordinating logistics, site selection, and conducting field work. Emily Kindervater assisted with boat electrofishing. Andrya Whitten was a coauthor on previous reports, and this report is an update of those.

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Table 1. Locations (latitude and longitude) for each 2016 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. The coordinates at the end of transect at site #3 were not recorded.

			Electrofishing			
	Fyke netting		Start		End	
Site	Lat (°)	Long (°)	Lat (°)	Long (°)	Lat (°)	Long (°)
1	42.79586	86.12163	42.79548	86.12354	42.79600	86.12086
2	42.78896	86.14401	42.78809	86.14471	42.78959	86.14384
3	42.78642	86.17484	42.78544	86.17400	.	.
4	42.77993	86.19643	42.77910	86.19769	42.77985	86.19606

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 6 September 2016 with a YSI sonde.

Site	Depth (cm)	Water Temperature (°C)	Dissolved Oxygen (mg/L)	% Dissolved Oxygen	Specific Conductivity (uS/cm)	Total Dissolved Solids (g/L)	Turbidity (NTU)	pH	Oxidation Reduction Potential	Chlorophyll *a* (ug/L)
1	91±2	23.96±0.02	9.01±0.04	107.1±0.5	543±1	0.353±0.000	17.9±0.5	7.93±0.01	398±1	56.1±3.7
2	89±6	24.26±0.02	8.92±0.16	106.6±1.9	492±0	0.320±0.000	15.9±2.8	8.24±0.03	381±1	46.3±2.8
3	82±4	24.41±0.01	9.98±0.10	119.6±1.2	449±1	0.292±0.000	8.3±1.8	8.70±0.01	366±3	34.8±2.0
4	79±7	24.00±0.11	10.58±0.08	125.8±0.8	426±1	0.277±0.000	6.6±1.2	8.75±0.01	378±3	24.0±0.8

Table 3. Water quality variables at fish sampling sites in Lake Macatawa. Measurements were made during nighttime boat electrofishing on 8 September 2016 with a YSI sonde.

Site	Water Temperature (°C)	Dissolved Oxygen (mg/L)	% Dissolved Oxygen	Specific Conductivity (uS/cm)	Total Dissolved Solids (g/L)	Turbidity (NTU)	pH	Oxidation Reduction Potential (mV)	Chlorophyll *a* (ug/L)
1	24.40	8.16	97.80	542	0.352	16.4	7.89	413	41.4
2	24.52	9.16	110.00	489	0.318	11.2	8.24	374	69.8
3	24.23	9.82	117.30	424	0.276	8.9	8.93	352	21.3
4	22.77	8.36	97.20	429	0.279	5.9	8.41	381	25.5

Table 4. Number and mean total length (TL; ranges reported parenthetically) of fish captured by fyke netting (*n* = 12 nets) on 7 September 2016 and boat electrofishing (*n* = 4 transects) on 8 September 2016 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*	1	1	7.9	0	--
bowfin	*Amia calva*	6	3	48.9 (43.6-54.8)	3	46.7 (43.2-50.0)
freshwater drum	*Aplodinotus grunniens*	15	7	10.5 (9.5-12.3)	8	17.9 (10.7-39.5)
white sucker	*Catostomus commersoni*	16	5	39.9 (33.9-45.1)	11	35.6 (24.2-43.6)
common carp	*Cyprinus carpio*	10	3	66.1 (64.2-69.6)	7	57.3 (37.4-68.2)
spotfin shiner	*Cyprinella spiloptera*	67	61	8.0 (5.5-10.1)	6	7.9 (7.0-8.6)
gizzard shad	*Dorosoma cepedianum*	462	359	9.6 (5.1-17.2)	103	12.3 (8.0-17.6)
banded killifish	*Fundulus diaphanus*	4	3	8.4 (7.0-10.7)	1	6.5
channel catfish	*Ictalurus punctatus*	7	6	34.2 (7.2-57.8)	1	51.0
brook silverside	*Labidesthes sicculus*	26	11	7.2 (6.4-7.8)	15	7.1 (4.6-8.0)
green sunfish	*Lepomis cyanellus*	1	1	6.0	0	--
pumpkinseed	*Lepomis gibbosus*	122	75	9.5 (5.4-17.8)	47	9.2 (5.6-17.7)
bluegill	*Lepomis macrochirus*	183	156	6.8 (2.5-20.8)	27	9.0 (4.3-18.7)
hybrid sunfish	*Lepomis* sp.[1]	8	8	16.4 (14.5-18.8)	0	
largemouth bass	*Micropterus salmoides*	137	22	11.0 (6.1-25.4)	115	16.5 (5.3-41.1)
white perch	*Morone americana*	141	78	9.3 (7.3-10.8)	63	9.9 (6.7-22.5)
round goby	*Neogobius melanostomus*	18	15	6.5 (3.8-9.7)	3	9.8 (8.7-11.2)
emerald shiner	*Notropis atherinoides*	4	3	8.9 (8.3-9.6)	1	8.9
golden shiner	*Notemigonus crysoleucas*	12	11	9.3 (7.7-10.8)	1	7.2
spottail shiner	*Notropis hudsonius*	18	11	8.5 (6.8-10.7)	7	9.6 (8.0-12.4)
yellow perch	*Perca falvescens*	374	129	12.5 (5.6-24.0)	245	10.1 (7.7-25.9)
logperch	*Percina caprodes*	1	0	--	1	12.2
bluntnose minnow	*Pimephales notatus*	2	2	8.0 (7.0-8.9)	0	--
black crappie	*Pomoxis nigromaculatus*	12	9	9.8 (7.1-20.2)	3	7.6 (6.2-9.6)
walleye	*Sander vitreus*	1	0	--	1	35.5
	Total	**1648**	**979**		**669**	

[1]The hybrid sunfish was likey a cross between a pumpkinseed and green sunfish. We did not include this taxon in our counts when we report species richness.

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 7 September 2016. 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*	1	7.9	0	--	0	--	0	--
bowfin	*Amia calva*	1	43.6	0	--	2	51.5 (48.2-54.8)	0	--
freshwater drum	*Aplodinotus grunniens*	2	10.4 (10.3-10.6)	1	12.3	3	10.0 (9.5-10.9)	1	10.3
white sucker	*Catostomus commersoni*	1	33.9	2	40.4 (38.0-42.7)	1	40.0	1	45.1
common carp	*Cyprinus carpio*	0	--	0	--	2	66.9 (64.2-69.6)	1	64.5
spotfin shiner	*Cyprinella spiloptera*	19	7.4 (5.5-9.8)	32	8.1 (6.6-10.1)	6	8.8 (6.1-10.1)	4	9.2 (8.5-9.8)
gizzard shad	*Dorosoma cepedianum*	279	9.2 (5.1-14.3)	6	12.4 (10.9-15.2)	68	10.8 (7.8-14.5)	6	13.9 (11.0-17.2)
banded killifish	*Fundulus diaphanus*	0	--	0	--	3	8.4 (7.0-10.7)	0	--
channel catfish	*Ictalurus punctatus*	2	23.6 (7.2-40.1)	0	--	2	26.0 (18.6-33.4)	2	53.0 (48.1-57.8)
brook silverside	*Labidesthes sicculus*	1	7.5	7	7.5 (6.9-7.8)	2	6.5 (6.4-6.5)	1	6.4
green sunfish	*Lepomis cyanellus*	0	--	0	--	0	--	1	6.0
pumpkinseed	*Lepomis gibbosus*	11	9.0 (6.2-15.9)	13	14.4 (7.6-17.7)	23	7.4 (5.5-13.2)	28	9.1 (5.4-17.8)
hybrid sunfish	*Lepomis* sp.[1]	0	--	0	--	0	--	8	16.4 (14.5-18.8)
bluegill	*Lepomis macrochirus*	37	6.2 (2.6-16.4)	49	6.9 (3.5-18.8)	53	6.4 (4.2-14.7)	17	8.5 (2.5-20.8)
largemouth bass	*Micropterus salmoides*	4	14.4 (6.6-25.4)	8	10.1 (8.2-12.7)	3	11.8 (11.1-13.0)	7	9.7 (6.1-15.7)
white perch	*Morone americana*	3	8.9 (7.8-10.0)	3	10.0 (9.2-10.6)	60	9.4 (7.4-10.8)	12	8.9 (7.3-10.1)
round goby	*Neogobius melanostomus*	1	5.7	1	3.8	8	6.4 (5.5-8.4)	5	7.3 (6.4-9.1)
emerald shiner	*Notropis atherinoides*	0	--	2	9.2 (8.9-9.6)	1	8.3	0	--
golden shiner	*Notemigonus crysoleucas*	5	8.9 (7.7-10.8)	5	9.6 (8.1-10.7)	1	10.0	0	--
spottail shiner	*Notropis hudsonius*	0	--	0	--	11	8.5 (6.8-10.7)	0	--
yellow perch	*Perca falvescens*	26	12.6 (9.2-22.9)	35	17.2 (9.7-21.1)	46	9.8 (6.4-20.1)	22	10.8 (5.6-24.0)
bluntnose minnow	*Pimephales notatus*	1	7.0	0	--	1	8.9	0	--
black crappie	*Pomoxis nigromaculatus*	3	4.3 (7.1-20.2)	1	11.9	1	8.5	4	8.2 (7.4-8.7)
	Total	**397**		**165**		**297**		**120**	

[1]The hybrid sunfish was likey a cross between a pumpkinseed and green sunfish.

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 8 September 2016. 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	--	1	43.2	2	48.8 (47.7-50.0)
freshwater drum	*Aplodinotus grunniens*	3	26.3 (19.4-39.5)	3	13.5 (10.7-18.8)	2	11.9 (11.1-12.7)	0	--
white sucker	*Catostomus commersoni*	3	38.3 (34.9-42.6)	2	26.7 (24.2-29.2)	3	37.0 (30.5 -43.6)	3	37.6 (28.5-42.2)
common carp	*Cyprinus carpio*	2	59.1 (50.5-67.6)	1	37.4	4	61.4 (52.6-68.2)	0	--
spotfin shiner	*Cyprinella spiloptera*	0	--	6	7.9 (7.0-8.6)	0	--	0	--
gizzard shad	*Dorosoma cepedianum*	8	10.5 (8.0-14.7)	13	11.7 (9.7-15.0)	45	12.1 (8.2-15.8)	37	13.1 (10.6-17.6)
banded killifish	*Fundulus diaphanus*	0	--	1	6.8	0	--	0	--
channel catfish	*Ictalurus punctatus*	0	--	1	51.0	0	--	0	--
brook silverside	*Labidesthes sicculus*	0	--	8	7.2 (4.6-8.0)	1	6.5	6	7.1 (6.7-7.5)
pumpkinseed	*Lepomis gibbosus*	4	12.4 (7.7-17.0)	15	10.7 (7.5-17.0)	3	9.8 (7.7-13.5)	25	7.8 (5.6-17.7)
bluegill	*Lepomis macrochirus*	0	--	23	9.4 (4.3-18.7)	0	--	4	6.4 (5.5-7.1)
largemouth bass	*Micropterus salmoides*	10	18.6 (12.7-25.6)	53	20.0 (9.7-41.1)	31	13.6 (9.4-25.1)	21	11.1 (5.3-15.5)
white perch	*Morone americana*	3	17.0 (9.2-22.5)	45	9.7 (7.9-11.9)	8	9.6 (7.7-10.5)	7	8.1 (6.7-9.9)
round goby	*Neogobius melanostomus*	0	--	1	11.2	1	8.7	1	9.6
emerald shiner	*Notropis atherinoides*	1	8.9	0	--	0	--	0	--
golden shiner	*Notemigonus crysoleucas*	0	--	1	7.2	0	--	0	--
spottail shiner	*Notropis hudsonius*	0	--	1	11.5	2	8.4 (8.2-8.5)	4	9.7 (8.0-12.4)
yellow perch	*Perca falvescens*	5	9.8 (8.7-10.5)	47	11.4 (8.0-25.9)	65	9.6 (8.1-20.0)	128	9.8 (7.7-22.6)
logperch	*Percina caprodes*	0	--	0	--	1	12.2	0	--
black crappie	*Pomoxis nigromaculatus*	0	--	1	9.6	0	--	2	6.6 (6.2-7.1)
walleye	*Sander vitreus*	0	--	1	35.5	0	--	0	--
	Total	**39**		**223**		**167**		**240**	

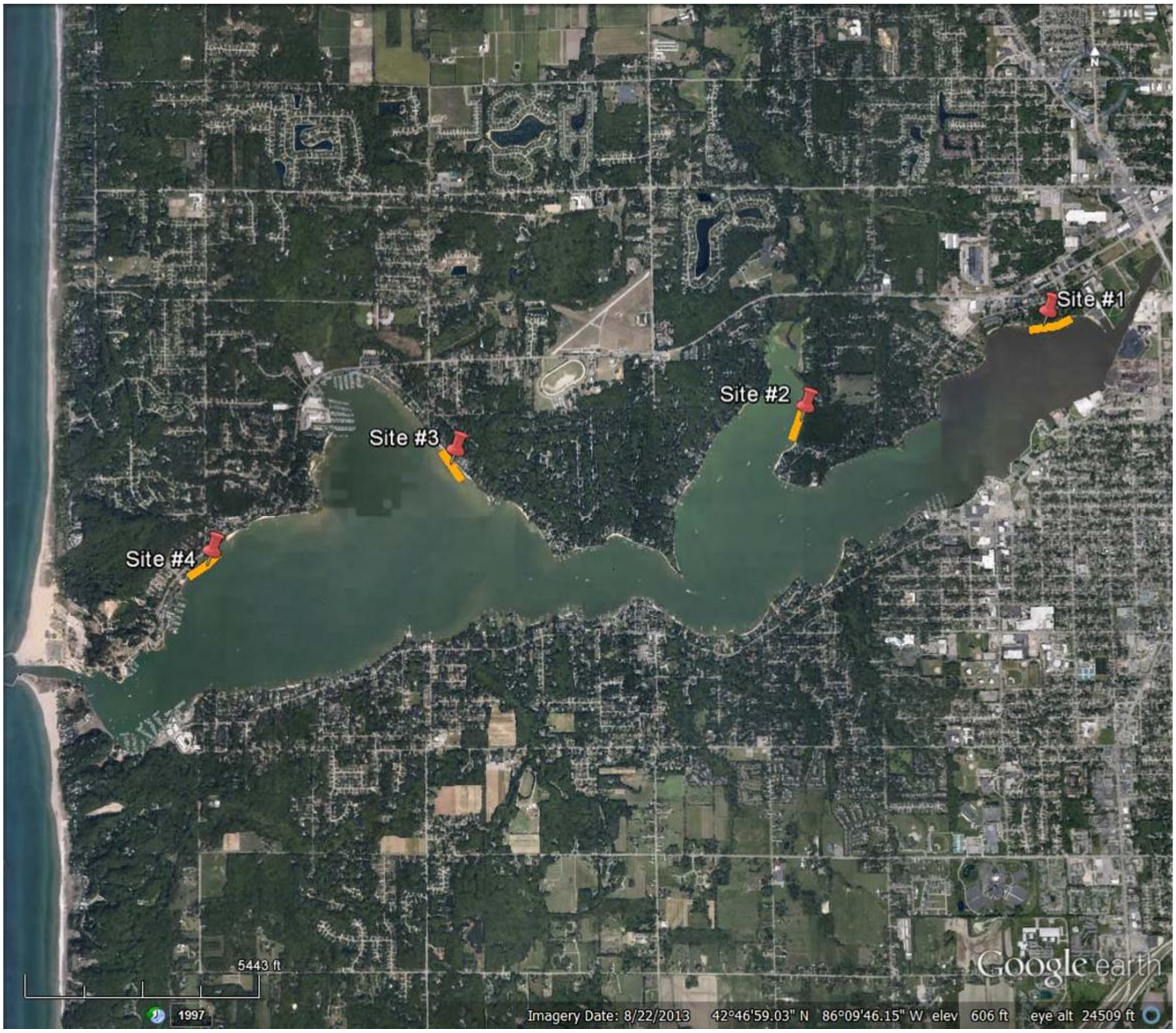

Figure 1. Map of Lake Macatawa (Ottawa County, Michigan) showing fish sampling sites. The orange transects depict approximately where boat electrofishing was conducted at each site. Site #1 is closest to the Macatawa River and site #4 is closest to Lake Michigan.

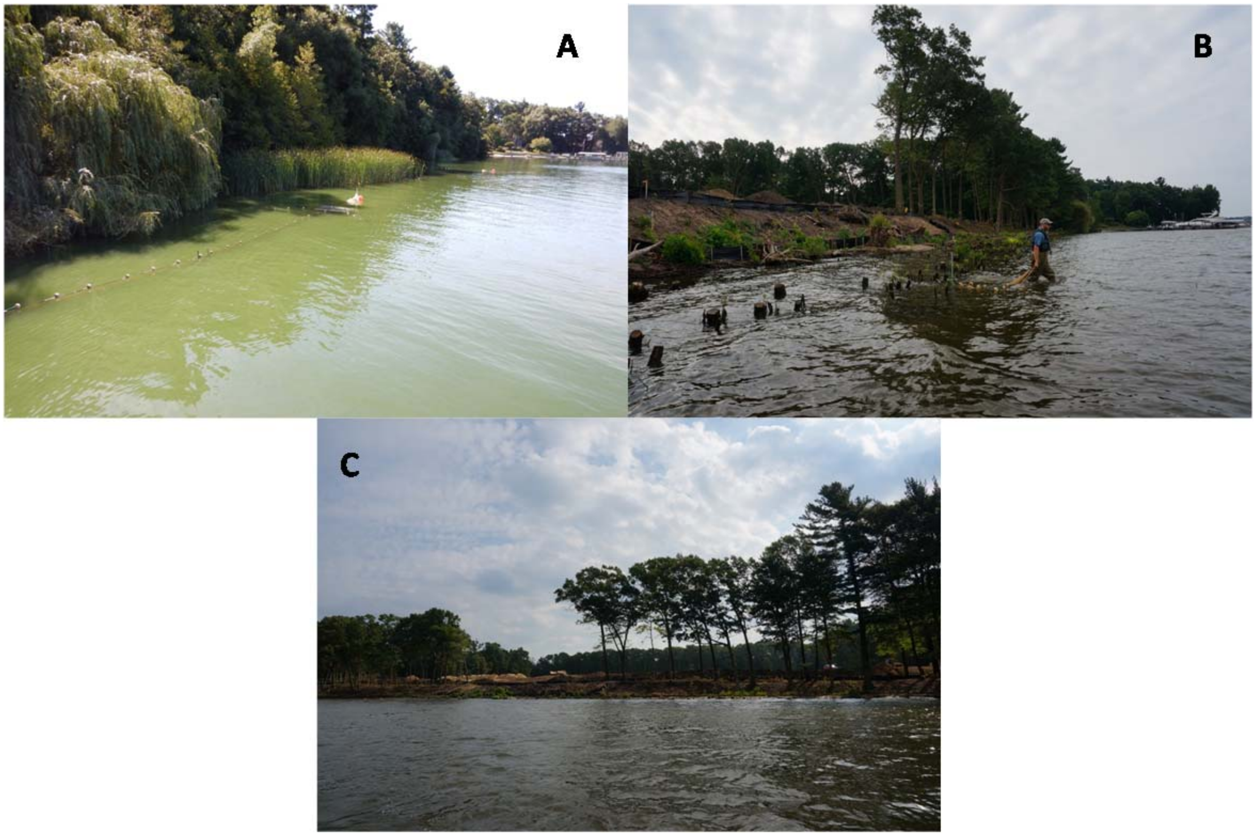

Figure 2. Photographs of riparian area at site #2 in (A) 2014 and (B and C) 2016 showing change in raparian area. Note that pictures A and B were taken with the photographer looking in a southernly direction. The riparian area looked similar in 2014 and 2015 (not shown).

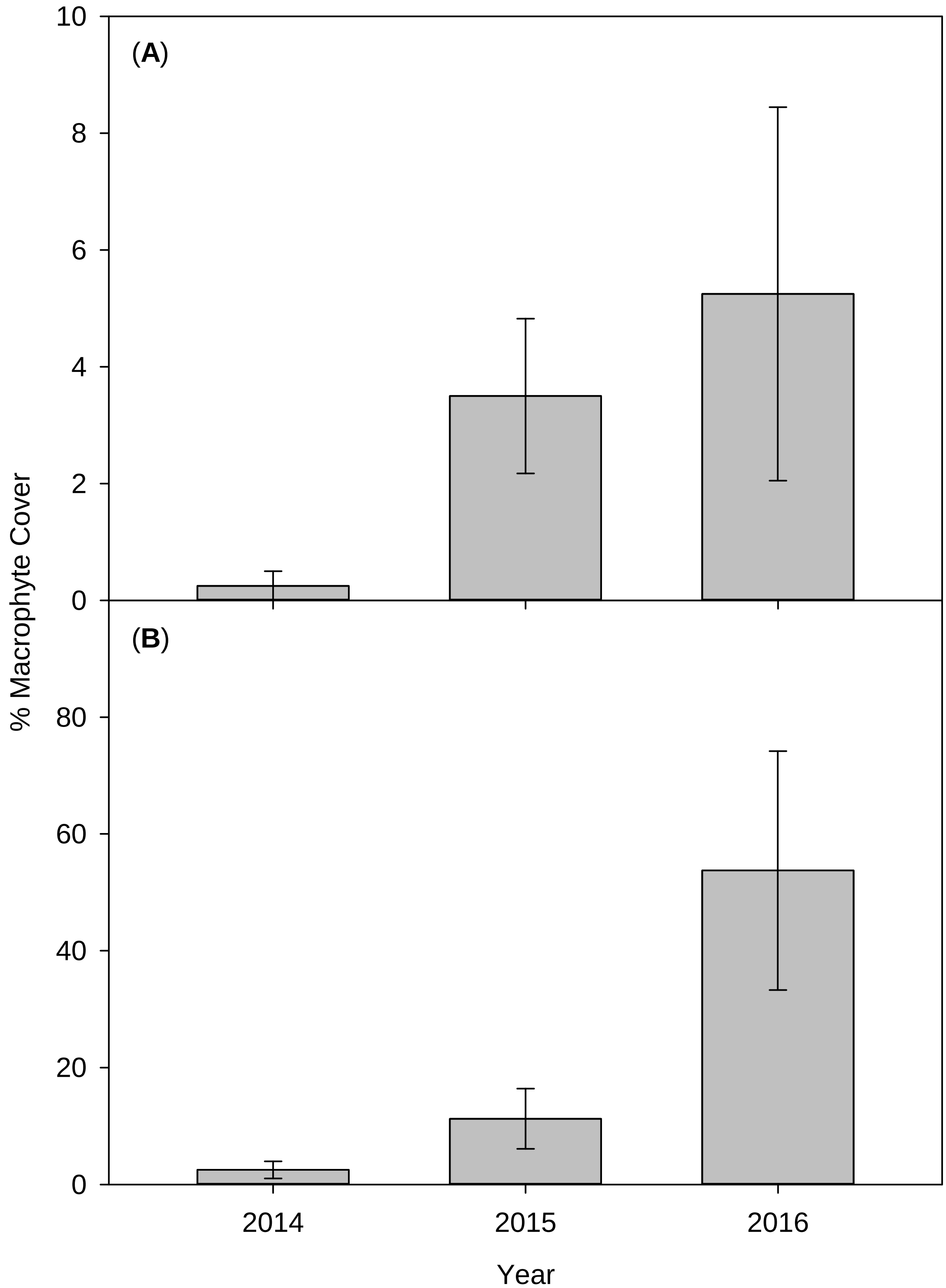

Figure 3. Mean (±1 standard error) % macrophyte cover visually estimated at (A) fyke net locations and (B) boat electrofishing transects in Lake Macatawa (*n* = 4 sites per year). Note that the *y*-axis varies by an order of magnitude between the two panels. The area where macrophyte cover is assessed during fyke netting is much less compared with a boat electrofishing transect.

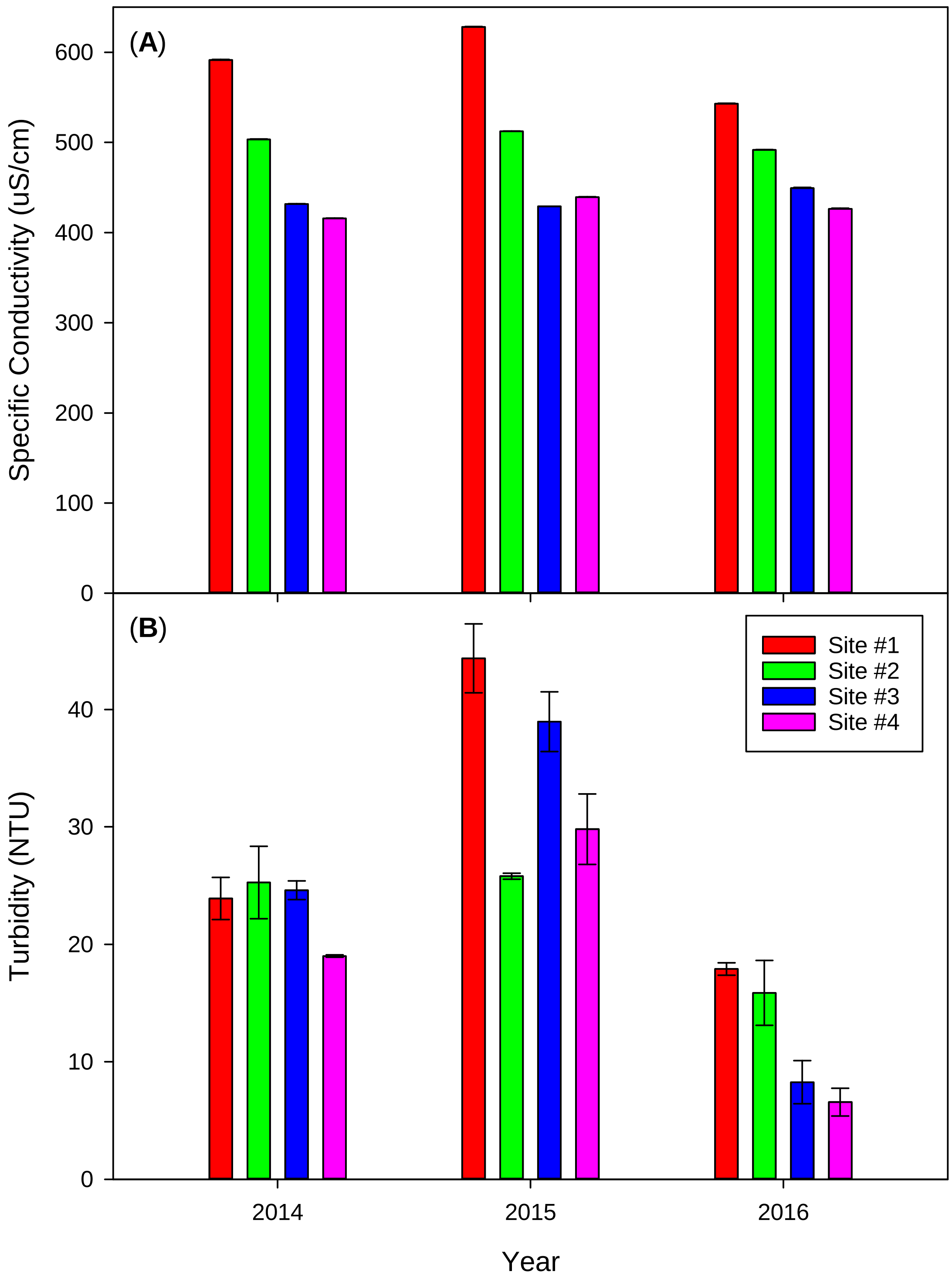

Figure 4. Mean (A) specific conductivity and (B) turbidity measured during fyke netting in Lake Macatawa. Error bars represent ±1 standard error (*n* = 3 nets per site), although they may be too small to be visible for some means.

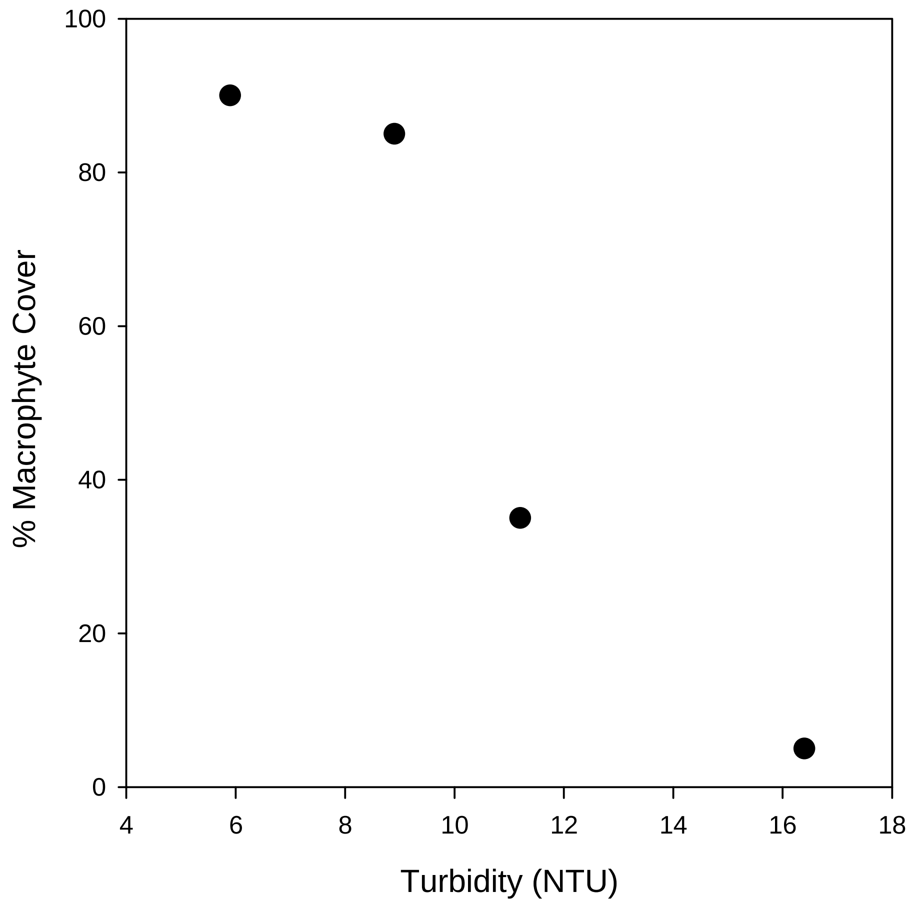

Figure 5. A significant negative correlation was detected between % macrophyte cover and turbidity (r = -0.95, P = 0.049). Variables were measured during nighttime boat electrofishing surveys in Lake Macatawa during 2016 (Table 3). Each point represents a single fish sampling site.

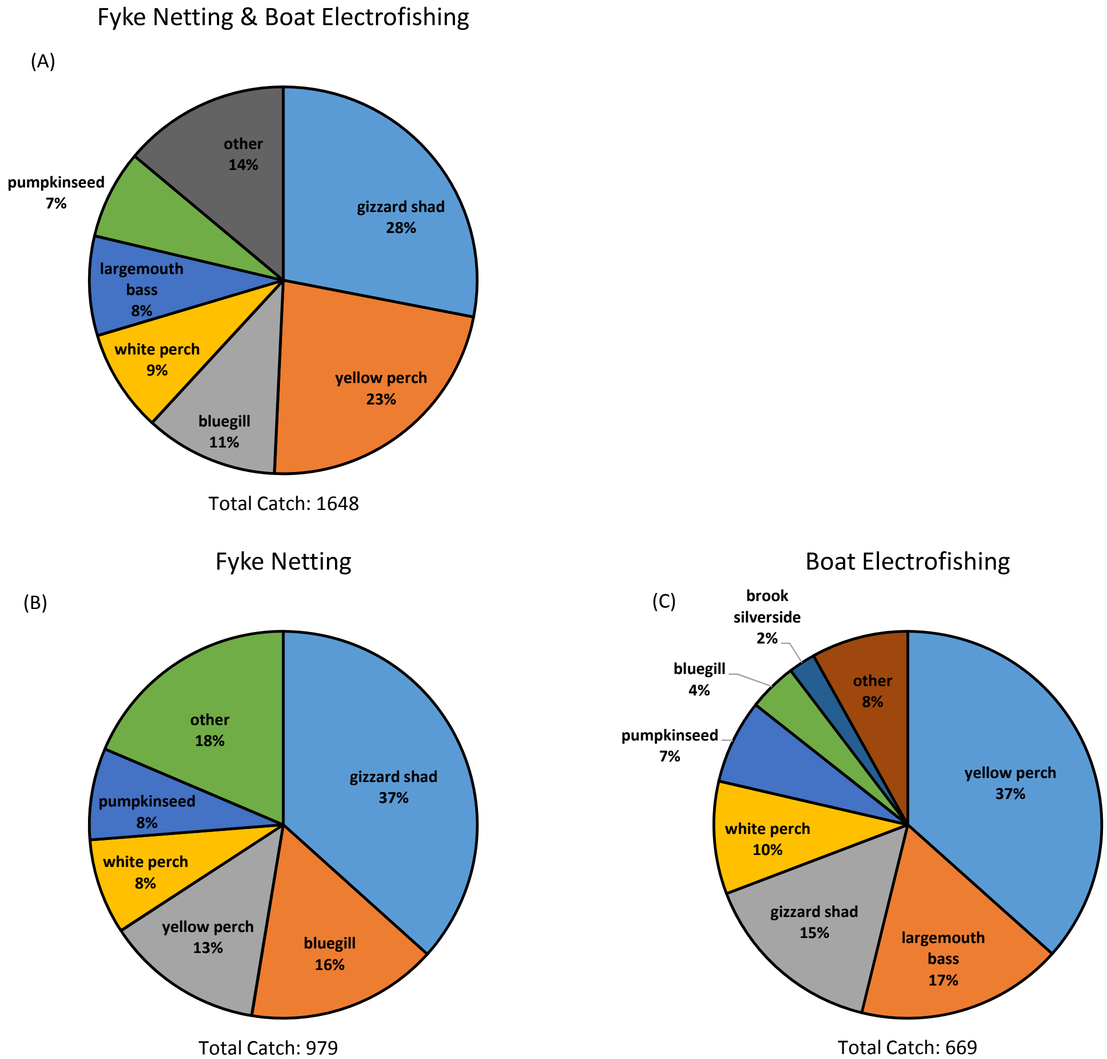

Figure 6. Fish species captured in littoral habitats of Lake Macatawa by (A) fyke netting and boat electrofishing (i.e., combined catch), (B) fyke netting (*n* = 12 nets), and (C) boat electrofishing (*n* = 4 transects) during September 2016. Catch data, including the species pooled in the “other” category, are reported in Table 4.

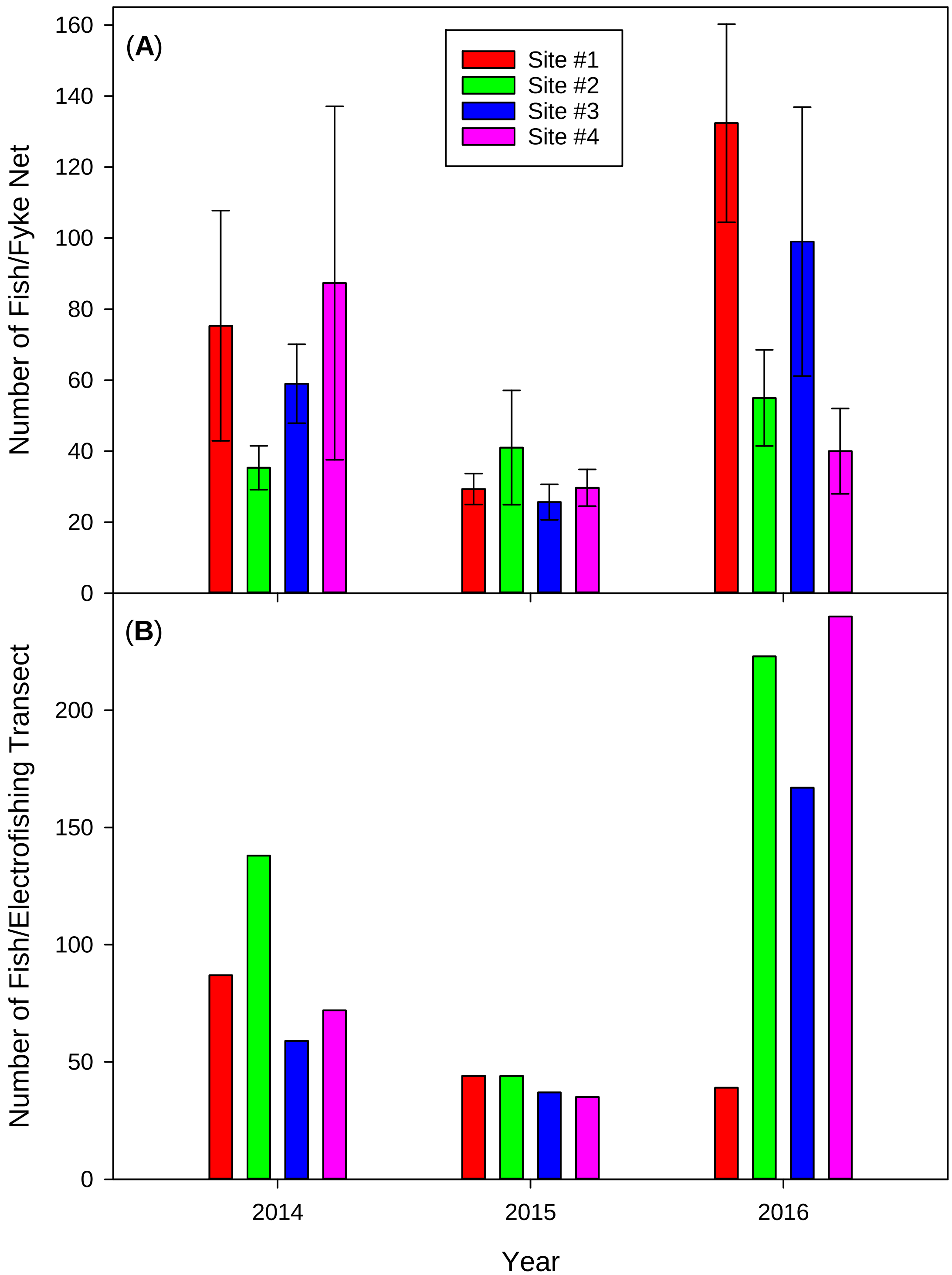

Figure 7. (A) Mean number (±1 standard error) of fish captured in fyke nets (*n* = 3 nets per site) and (B) number of fish captured during a boat electrofishing transect (*n* = 1 transect per site) in Lake Macatawa.

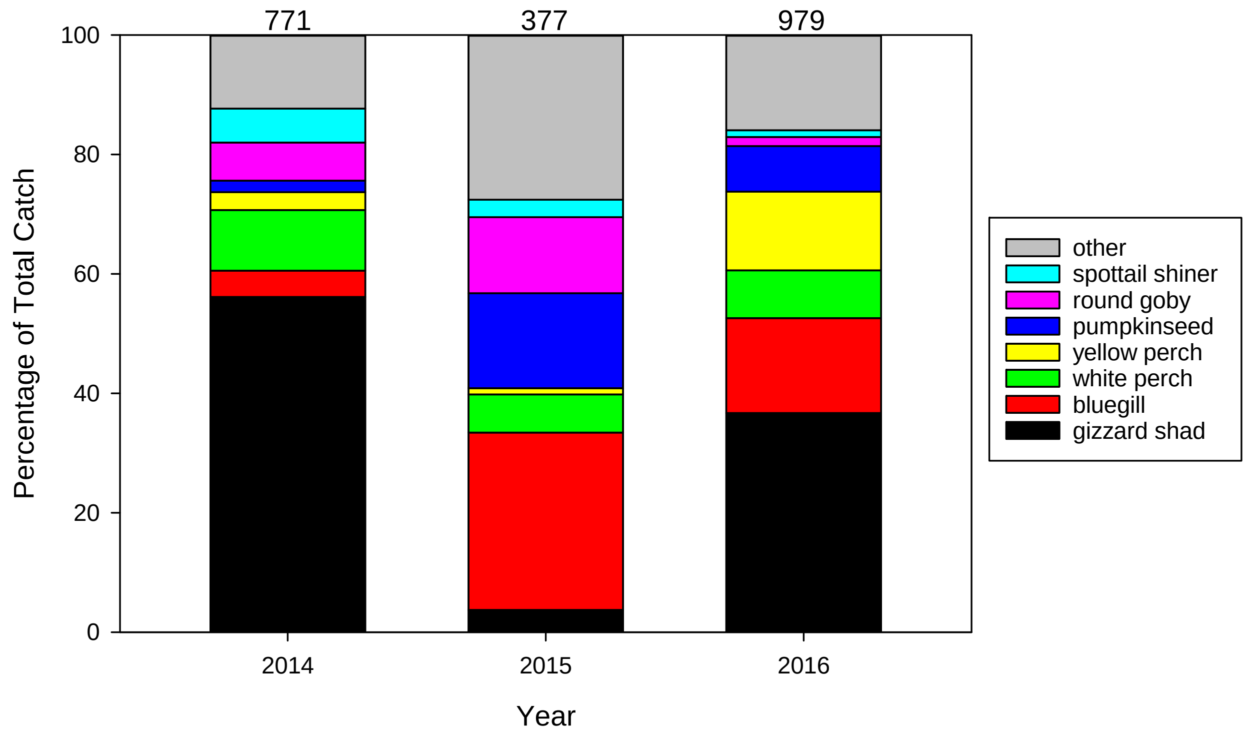

Figure 8. Fish species composition (pooled across sites) in fyke netting surveys for each sampling year. Note that the number of fish captured differed among years, which is reported at the top of each bar.

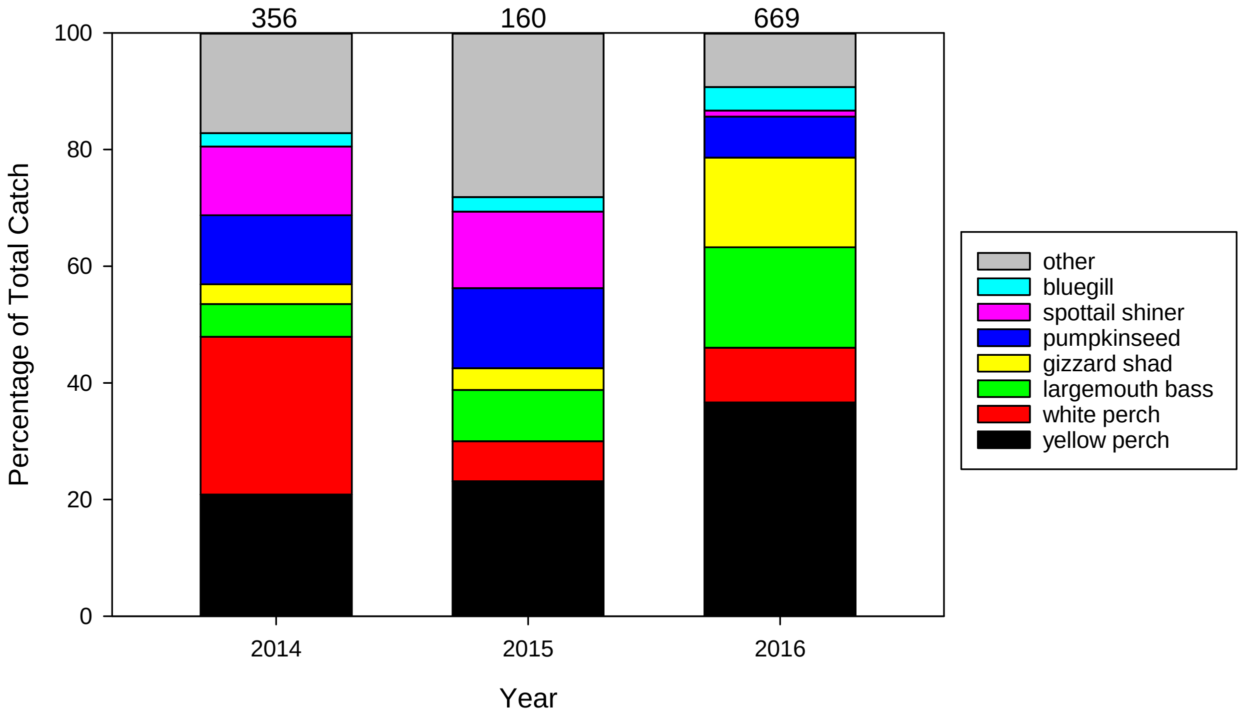

Figure 9. Fish species composition (pooled across sites) in boat electrofishing surveys for each sampling year. Note that the number of fish captured differed among years, which is reported at the top of each bar.