Bear Creek Hydrologic Reconnection and Habitat Enhancement Project

Post-Restoration Monitoring Report

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Michael C. Hassett

Alan D. Steinman

Grand Valley State University

Annis Water Resources Institute

Introduction

From March 2016 through November 2017, Grand Valley State University's Annis Water Resources Institute (AWRI) monitored Bear Creek and Bear Lake water quality in Muskegon, MI as part of the Hydrologic Reconnection and Habitat Enhancement Project in the Muskegon Lake Area of Concern (AOC). Prior to reconnection, phosphorus-rich sediments were dredged from two ponds, which were previously pumped dry and farmed for celery. These sediments were identified as a significant source of phosphorus to the overlying water column, based on a series of experimental studies (Smit and Steinman 2015; Steinman and Ogdahl 2016). If hydrologic reconnection of these ponds to adjacent Bear Creek occurred with the sediments still in place, there was concern that phosphorus would continue to be released into the water column and be transported downstream to Bear Lake and Muskegon Lake, which would threaten water quality and AOC delisting progress.

The purpose of this monitoring effort was to track water quality in the "to-be-restored" ponds, Bear Creek, Bear Lake before, during, and after restoration construction in order to (1) assess potential water quality impairment associated with restoration construction activities and (2) compare the area's water quality in "pre-restoration" and "post-restoration" periods of the project.

Methods

Field sampling sites and methodology were designed to be consistent with AWRI's past sediment and water quality monitoring at these waterbodies (cf. Steinman and Ogdahl 2015, 2016; Steinman and Hassett 2016). Sampling dates and locations are described in Tables 1, 2 and Fig. 1.

Bear Creek samples were collected in a downstream to upstream direction via kayak (Fig. 1). After the berm was removed, the order from start to finish was: downstream, west pond, east pond, upstream. Bear Lake surface water was collected by grab sampling and from the bottom with a horizontal Van Dorn water sampler. General water quality, including temperature, dissolved oxygen (DO), pH, specific conductance (SpCond), total dissolved solids (TDS), turbidity, and blue-green algae (BGA) concentrations were measured with an YSI 6600 sonde. A 250 mL sample of water was collected for total phosphorus (TP) analysis, from which a 20 mL subsample was collected and syringe-filtered through a 0.45 μm nylon membrane filter into scintillation vials for soluble reactive phosphorus (SRP) analysis. A separate 1 L amber bottle sample was collected for chlorophyll *a* (chl *a*) analysis (Steinman and Ogdahl 2016).

All samples were transported on ice to the lab. TP and SRP samples were refrigerated until measured on a SEAL AQ2 discrete auto-analyzer (USEPA 1993). P concentrations below the 5 μg/L detection limit (DL) were calculated as ½ the detection limit except for Dec. 2016 to May 2017, when TP and SRP analyses were performed by TRACE Analytical Laboratories, Inc. (Muskegon, MI) with DL of 10 μg/L. Chl *a* samples were vacuum-filtered on a GFF membrane and frozen until extracted and analyzed on a Shimadzu UV-1601 spectrophotometer (APHA 1992). The partly organic and partly inorganic portion of P bound to seston, or particulate P (part-P), was calculated as the difference between TP and SRP.

One sediment core sample per site was collected using a modified piston corer on June 27-28, 2017 for sediment characterization and sediment phosphorus isotherm analysis using methods consistent with pre-restoration sampling while using lower concentration isotherm P standards (Steinman and Ogdahl 2013). Sediment was extruded in the lab and the top 0-10 cm depth surface sample from each core was stored in plastic bags and refrigerated at 4°C until analysis. Sediments were homogenized by hand and subsampled for analysis of organic matter (OM), ash-free dry mass (AFDM), and P isotherm analysis. Sediment OM and AFDM were determined using gravimetric procedures (i.e., dry for 24 hours at 105˚C, weigh, ash at

550˚C for 4 hours, re-weigh; Steinman and Ogdahl 2016). The resultant ashed material was used for analysis of sediment TP on a Seal AQ2 Discrete Analyzer (U.S. EPA 1993).

Isotherm analysis indicates the capacity to which sediments can be a net source (release) or sink (retain) of P from the overlying water column. Sediment cores were subsampled in triplicate from the homogenized core section described above (modified from Mozaffari and Sims (1994) and Novak et al. (2004)). We added 20 mL of inorganic P solutions (KH_2PO_4 dissolved in 0.01 M KCl) as either 0, 25, 50, 100, 250, 500, 1000, or 5000 µg P/L to 50 mL centrifuge tubes containing 3 g of wet sediment. Centrifuge tubes were incubated for 24 hr on an orbital shaker table shaking at 250 RPM, then centrifuged for 20 min at 3600 RPM. The resulting supernatant was filtered through 0.45 µm filters before undergoing SRP analysis as described above.

P lost after the 24-hr equilibration is considered sorbed (S_1):

$$S_1 = (V/m)(C_0\text{-}C_{24})$$

where C_0 = the concentration of P added (µg/L); V = total volume (mL); C_{24} = solution P concentration after 24 hour equilibration (µg/L); and m = mass of dry sediment (g).

Native sorbed P (S_0) is estimated using the least squares fit of the plot of S_1 vs. C_{24} at low P concentrations (i.e., during linear relationship):

$$S_1 = S_0 + bC_{24}$$

The constant (y-intercept) is considered as the initial sediment P present in the adsorbed phase. The values for S_0 and S_1 are added to obtain the corrected P sorption (S):

$$S = S_1 + S_0$$

The equilibrium P concentration (EPC) of the sediments, defined as the solution P concentration at which $S_1 = 0$, is calculated from the equation:

$$EPC = S_0/b$$

The P sorption isotherm is constructed by plotting the mean quantity of P sorbed (mg/kg) against the mean P equilibrium concentration (mg/L) using the linear version of a Langmuir equation:

$$c/(x/m) = (1/S_{max})c + 1/(k)(S_{max})$$

where x/m (mg/kg) is the quantity of P sorbed by the sediment, S_{max} (mg/kg) is the P sorption maxima, k (L/mg) is a sorption constant relative to P binding energy, and c (mg/L) is the P equilibrium concentration.

Modified Hesslein in-site porewater samplers (peepers) were deployed in the west and east ponds on August 31, 2017 and retrieved two weeks later on September 14, 2017. Duplicate sets of peepers were deployed per pond at each of two locations within each pond (Fig. 1). Peepers were prepared in the laboratory consistent with methods and deployed at sites previously described during pre-restoration monitoring (Steinman and Ogdahl 2013).

Statistical Analysis

Data were analyzed to characterize water quality (e.g., TP, SRP, chl *a*, turbidity) differences between (1) upstream and downstream sites; and (2) pre-restoration and post-restoration ponds using either two-tailed paired t-tests (normally-distributed data) or Wilcoxon signed-rank tests (non-normally distributed data).

In pre- and post-restoration comparisons, 2 July 2014 and 30 July 2014 water quality and chemistry values were first averaged together to create mean July 2014 values and were then compared to 13 July 2017 values. Statistical significance was set with $\alpha = 0.05$ and testing was performed in SigmaPlot v.13.0 (Systat Software, Inc.).

Table 1. Dates and locations of field sampling events for water quality monitoring in Bear Creek, Bear Lake, and the ponds in 2016-2017. Additional samples for sediment phosphorus (P) isotherms and passive sediment porewater "peeper" samplers were collected from all Bear Creek and pond sites, but not from Bear Lake. Samples were not taken on 12 Dec 2016 due to ice issues; samples on this day were collected from the pond shoreline location nearest to pond sites after breaking through ice layer and removing ice chunks with a cup on a stick.

Sampling Period	**Date**	**Bear Creek Upstream**	**Bear Creek Downstream**	**Bear Lake**	**West Pond**	**East Pond**	**Sampling Notes**
Pre-Restoration	Mar. 10, 2016	X	X	X	X	X	
Construction	Apr. 4, 2016	X	X				
	May 12, 2016	X	X				
	Jul. 19, 2016	X	X	X			
Ponds Refilled	Dec. 7, 2016	X	X		X	X	
	Dec. 12, 2016	X	X		X	X	soft ice cover
	Feb. 22, 2017	X	X		X	X	
	Mar. 2, 2017	X	X	X	X	X	
Post-Restoration	Apr. 13, 2017	X	X	X	X	X	berm removal
	May 11, 2017	X	X		X	X	
	Jun. 15, 2017	X	X		X	X	
	Jun. 27-28, 2017						isotherm coring
	Jul. 13, 2017	X	X	X	X	X	
	Aug. 10, 2017	X	X		X	X	
	Aug. 31, 2017						peepers deployed
	Sep. 14, 2017	X	X		X	X	peepers retrieved
	Oct. 12, 2017	X	X	X	X	X	
	Nov. 14, 2017	X	X		X	X	

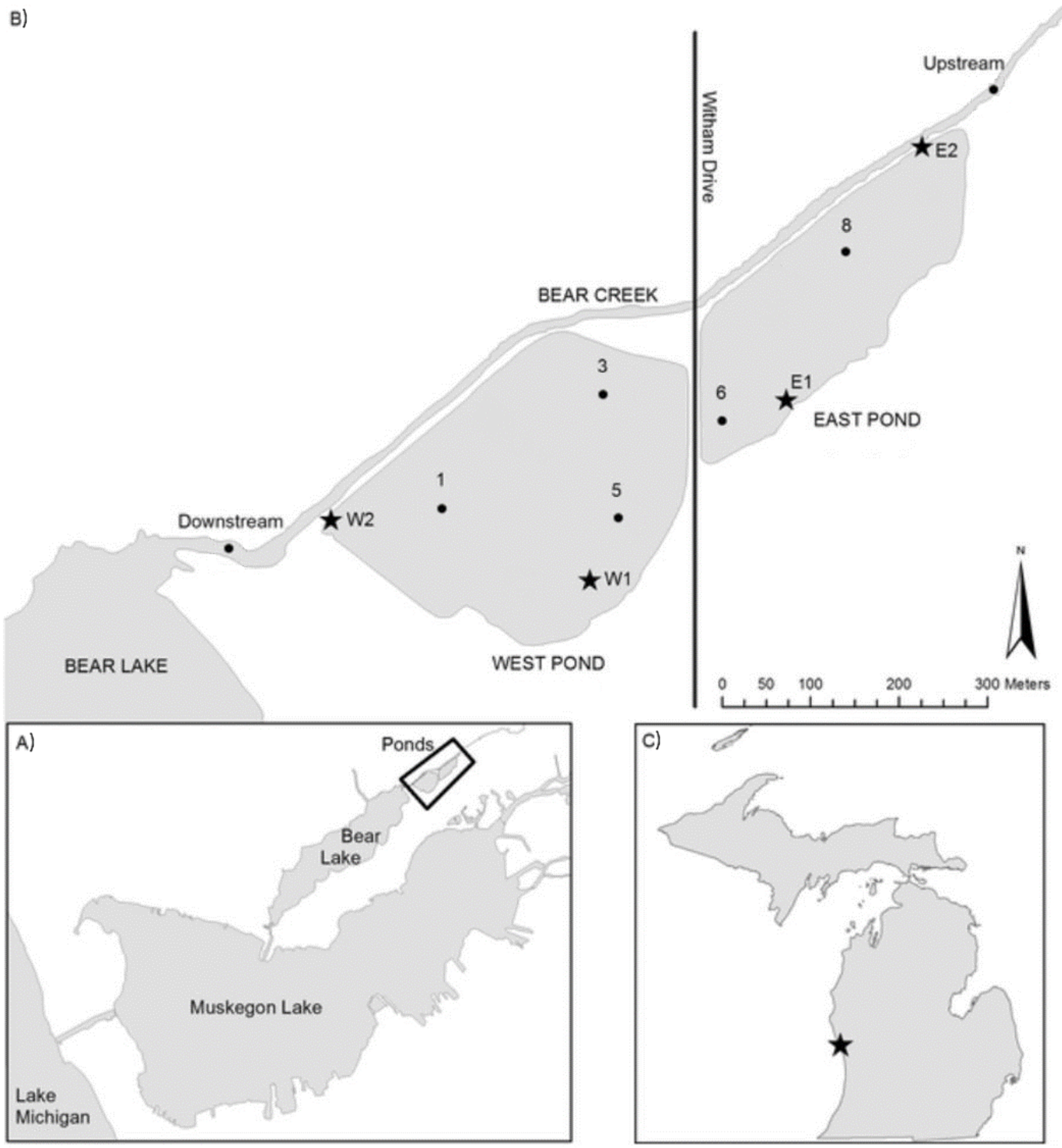

Figure 1. A) location of restoration area (outlined in thick black lines) within the Muskegon Lake Area of Concern; B) blow up of restoration site, including the two ponds that were dredged, Bear Creek, and sampling locations for water quality and sediment isotherms (dots) and sediment porewater (stars); and C) location of Muskegon (star) in map of Michigan. Note that this map uses outlines from pre-restoration satellite imagery; the earthen berm that previously separated the ponds from Bear Creek has been removed.

Table 2. Sampling coordinates

Site	Latitude	Longitude
Bear Lake	43.2637	-86.2702
Bear Creek Downstream	43.2652	-86.2684
West 1	43.2656	-86.2653
West 3	43.2668	-86.2630
West 5	43.2655	-86.2629
East 6	43.2665	-86.2614
East 8	43.2682	-86.2597
Bear Creek Upstream	43.2699	-86.2578

Results

*Assessment of **Bear Creek** Water Quality Impairment*

Following dredging, TP increased throughout the year until peaking in summer at all sites (Fig. 2A), with concentrations generally hovering between 20 and 40 µg/L. SRP concentrations generally were below 10 µg/L (Fig. 2B). Temperature and turbidity also showed temporal increases from winter through summer (Fig. 3A, D) but the other parameters were relatively stable throughout the year, with the exception of DO, which showed a mid-summer drop (Fig. 3B).

Few statistically significant differences were found when comparing upstream and downstream monthly physical and chemical water quality parameters. TP concentrations were generally higher downstream than upstream (Fig. 2A), although the difference was not statistically significant (Table 3). In contrast, SRP had a marginally greater upstream concentration than downstream (Table 3), although the absolute concentration difference (8 vs 6 µg/L) is so small that it likely had limited significance at the ecosystem scale.

DO, pH, SpCond, ORP, TDS, turbidity, and BGA values were not significantly different between post-restoration (April-November, 2017) creek sites (Table 3). Mean water temperature was significantly higher by ~5°C at the downstream site (Fig. 3A, Table 3), which may be related to backflow from warmer Bear Lake given the high water levels in 2017. Chl *a* also was significantly greater at the downstream site during post-restoration (Fig. 2C, Table 3), which again may be related to algal-rich backflow from Bear Lake; however, upstream vs downstream chl *a* concentrations were not significantly different during the pre-restoration period, which coincided with lower water levels (Steinman and Ogdahl 2016).

We also compared the TP and SRP data from this current study (2017) with pre-restoration TP and SRP data (2014) over the same period in each year (April-November) to provide additional context to the post-restoration findings (Fig. 4). TP concentrations were variable over this period, with a few spikes immediately after pond re-fill, likely due to resuspended sediments (Fig. 4A). SRP concentrations were relatively low throughout the 3-yr sampling period; there was a tendency for SRP concentrations to be greater at the downstream site prior to restoration, whereas this trend reversed in the post-restoration phase (Table 3, Fig. 4B).

Assessment of ***Bear Lake*** *Water Quality Impairment*

TP concentrations generally exceeded the 30 µg/L threshold in Bear Lake, peaking in July with concentrations ~60 µg/L (Fig. 2A). SRP concentrations were always less than 10 µg/L, and often were below those in Bear Creek (Fig. 2B), likely due to high algal demand in the lake of this bioavailable form of P. Particulate-P, the calculated fraction of P that is not readily available for biological uptake, was not significantly different between post-restoration creek sites (Table 3). Chl *a* followed TP trends with high values in summer and fall; Bear Lake chl *a* concentrations were ~2-4× higher than Bear Creek downstream samples collected at the same time (Fig. 2C). Water temperature and DO at the lake (and Creek) sites followed seasonal trends as expected (Fig. 3A, B).

pH remained relatively consistent across seasons, barring a noticeable one-time spike in the Bear Lake site at both depths in April 2017 during berm removal (Fig. 3C). The highest post-restoration turbidity values were observed during the period of berm removal (Table 1, Fig. 3D), and were observed at both downstream Bear Creek and in Bear Lake. TDS and specific conductance in creek and pond sites both increased slightly throughout the year after berm removal, although maximum conductance values remained well below 600 µS/cm (Fig. 3E, F). Human-induced aquatic ecosystem impairment has been associated with specific conductance values exceeding 600 µS/cm (Uzarski et al. 2005, Steinman et al. 2011).

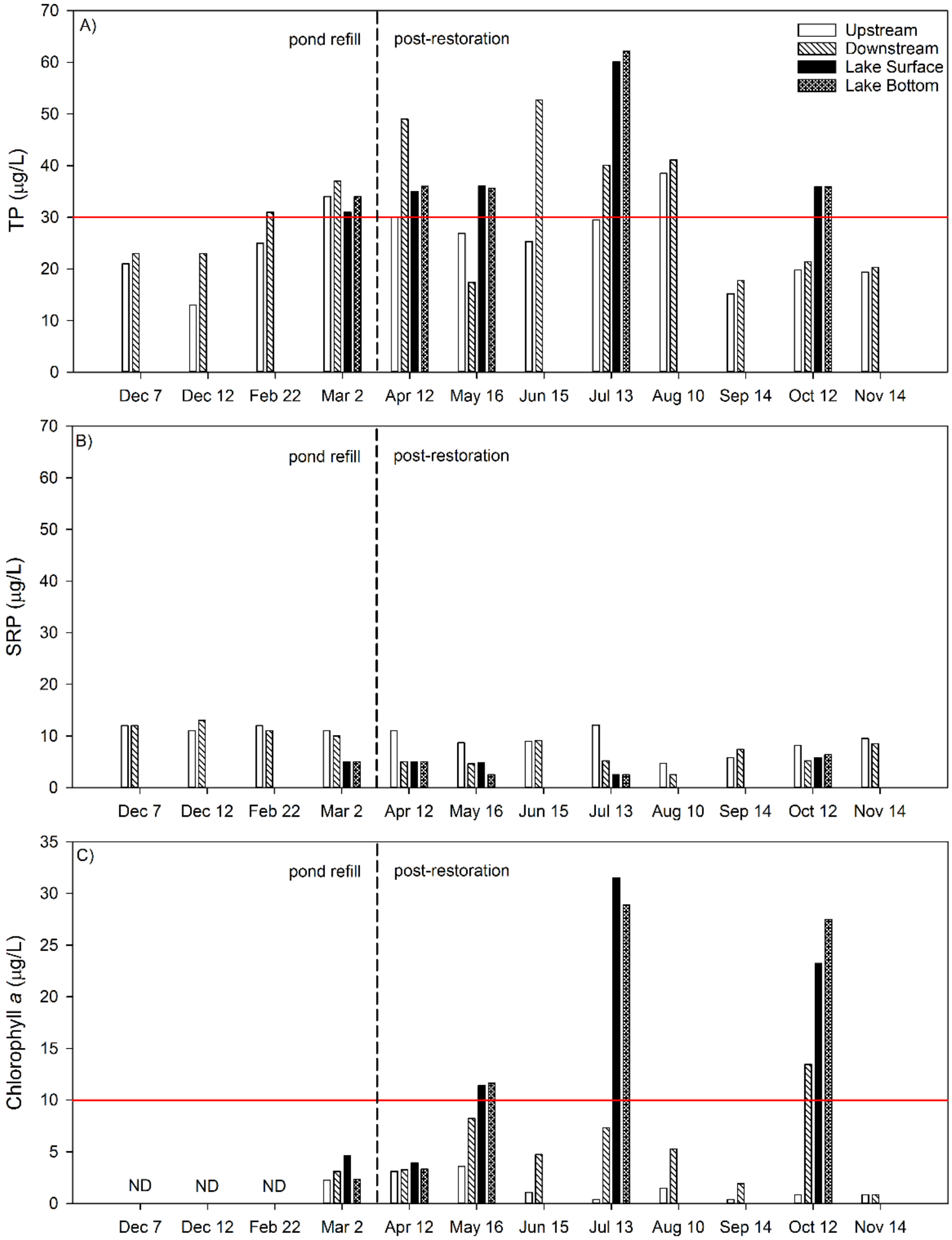

Figure 2. Post-dredging (December 2016 through November 2017) TP, SRP, and chl *a* concentrations at Bear Creek and Bear Lake sites. Bear Lake sites post-dredging were sampled only in March-May, July, and October 2017. ND = no data, as chlorophyll was not sampled during winter 2016-2017. Red reference lines at 30 and 10 µg/L represent the TP target goal set by the Bear Lake TMDL (MDEQ 2008) and chl *a* restoration goal for Muskegon Lake AOC, respectively.

West and East Pond Post-Restoration Assessments: Water Quality

TP concentrations were generally high (60-90 µg/L) during pond refill in December 2016, with one site (East 8) close to 300 µg/L (Fig. 5A). TP increased immediately after refilling, suggesting the high concentrations were associated with sediments that were mobilized and resuspended during refilling. The overall pattern of SRP concentration was similar to TP, although absolute concentrations were much lower (Fig. 5B). Chl *a* was not sampled during winter 2016-2017, but post-restoration seasonal chl *a* peaks were observed in March, June, and October reaching ~18-33 µg/L (Fig. 5C).

Water temperature and DO followed expected seasonal trends (Fig. 6A, B). pH remained relatively consistent through the year (Fig. 6C). Turbidity spiked upon refilling, and was consistent with a greater amount of TDS upon refilling (Fig. 6D, E); turbidity quickly declined after refilling ended, with the disturbed sediments appearing to have settled in February before increasing again in the ice-free spring-fall sampling year (Fig. 6D). TDS and specific conductance showed synchronous variation over time (Fig. 6E, F).

We analyzed each of the three west pond sites separately (Table 4). At all sites, post-restoration values of TP, SRP, specific conductance, and TDS were significantly lower than pre-restoration conditions (Table 4). Notably, TP and SRP concentrations means decreased by 10-100 fold (Fig. 7A, B), a clear indication of dredging's beneficial impact on P concentration. Particulate-P was significantly lower post-restoration at all three west pond sites, decreasing by one order of magnitude each time (Table 4). Turbidity results varied by site but absolute differences were very small, even at sites with statistically significant differences (Table 4). BGA significantly decreased at West 1 and 5 sites, but showed no significant change at West 3 (Table 4). Chl *a*, temperature, DO, pH, and ORP showed no significant effects of restoration (Table 4).

Comparison of pre- and post-restoration conditions within the east pond generated results similar to those of the west pond. TP, chl, pH, conductance, TDS, and BGA all significantly decreased in post-restoration compared to pre-restoration conditions (Table 5). In contrast, SRP showed no significant change at East 6 and increased significantly by 2 µg/L in post-restoration at East 8 (Table 4, Fig. 8B). Particulate-P was significantly lower at both sites and decreased by an order of magnitude compared to pre-restoration (Table 5). The east pond had been partially dredged in the past, and consequently had much lower pre-restoration SRP concentrations than the west pond (~4 vs. ~700 µg/L, respectively; Tables 4, 5); hence, further reductions of SRP in the east pond were not expected. Turbidity showed no significant differences due to restoration even though mean turbidity decreased overall (Table 5).

West and East Pond Post-Restoration Assessments: Sediment

Sediment TP and percent organic matter values declined dramatically at all pond sites except East 6 (Table 6), consistent with the goals of dredging. The anomalous result at East 6 may be a result of sediment addition, perhaps for road stabilization, which eroded downhill and added TP and OM.

Equilibrium phosphorus concentrations (EPC_0) in surface sediments decreased substantially at all 3 sites in the west pond after dredging, while east pond EPC_0 values changed very little (Table 6, Fig. 9). A comparison of EPC_0 values to overlying water column SRP concentrations revealed that EPC_0 exceeded SRP at most pond sites (Fig. 9), indicating that most of the observed pond sites would still serve as a source of P to the water column. However, the amount of P released would likely be much less compared to pre-restoration because of reduced concentration gradients between the sediment and water column. The only post-restoration site not currently serving as a source of P is the downstream Bear Creek site, which was also the site with the highest percentage of sediment organic matter and anecdotally may have been one of few vegetated sites (Table 6, Fig. 9). Bear Creek sites have no P isotherm pre-restoration data for comparison, but all post-restoration pond site mean EPC_0 values are less than or approximately equal to the upstream Bear Creek site mean (Table 6, Fig. 9).

SRP concentrations in sediment porewater were lower after dredging in the west pond but not in the east pond (Fig. 10). Porewater SRP at the west pond sites decreased significantly at both near-surface and near-bottom depths after dredging (Table 7), whereas dredging had no significant effect in the east pond at either depth (Table 8).

Table 3. Post-restoration (April – November, 2017; n = 7 except turbidity where n=5) upstream vs. downstream mean (±SD) water quality values. Statistical analyses used paired t-tests (t) or Wilcoxon signed rank test (r). Statistically significant results (p<0.05) are indicated with bold text and marginally significant results (p<0.10) are indicated with italic text. Chl *a* = chlorophyll *a*; DO = dissolved oxygen; SpCond = specific conductance; ORP = oxidation-reduction potential; TDS = total dissolved solids; BGA = blue-green algae.

Parameter (Units)	Upstream	Downstream	p-value	Test
TP (µg/L)	25 (8)	30 (14)	0.276	t
SRP (µg/L)	8 (2)	6 (2)	*0.083*	*t*
Part-P (µg/L)	17 (8)	24 (14)	0.131	t
Chl *a* (µg/L)	1.2 (1.1)	6.0 (4.2)	**0.023**	**t**
Temperature (°C)	13.7 (4.2)	18.5 (7.2)	**0.007**	**t**
DO (mg/L)	9.5 (1.3)	8.6 (2.0)	0.133	t
DO (%)	91 (5)	91 (18)	0.991	t
pH	7.9 (0.2)	8.0 (0.4)	0.396	t
SpCond (µS/cm)	400 (28)	399 (33)	0.866	t
ORP (mV)	417 (44)	414 (41)	0.317	t
TDS (g/L)	0.260 (0.018)	0.259 (0.021)	0.852	t
Turbidity (NTU)	5 (3)	5 (2)	0.621	t
BGA (cells/mL)	247 (598)	392 (951)	0.109	r

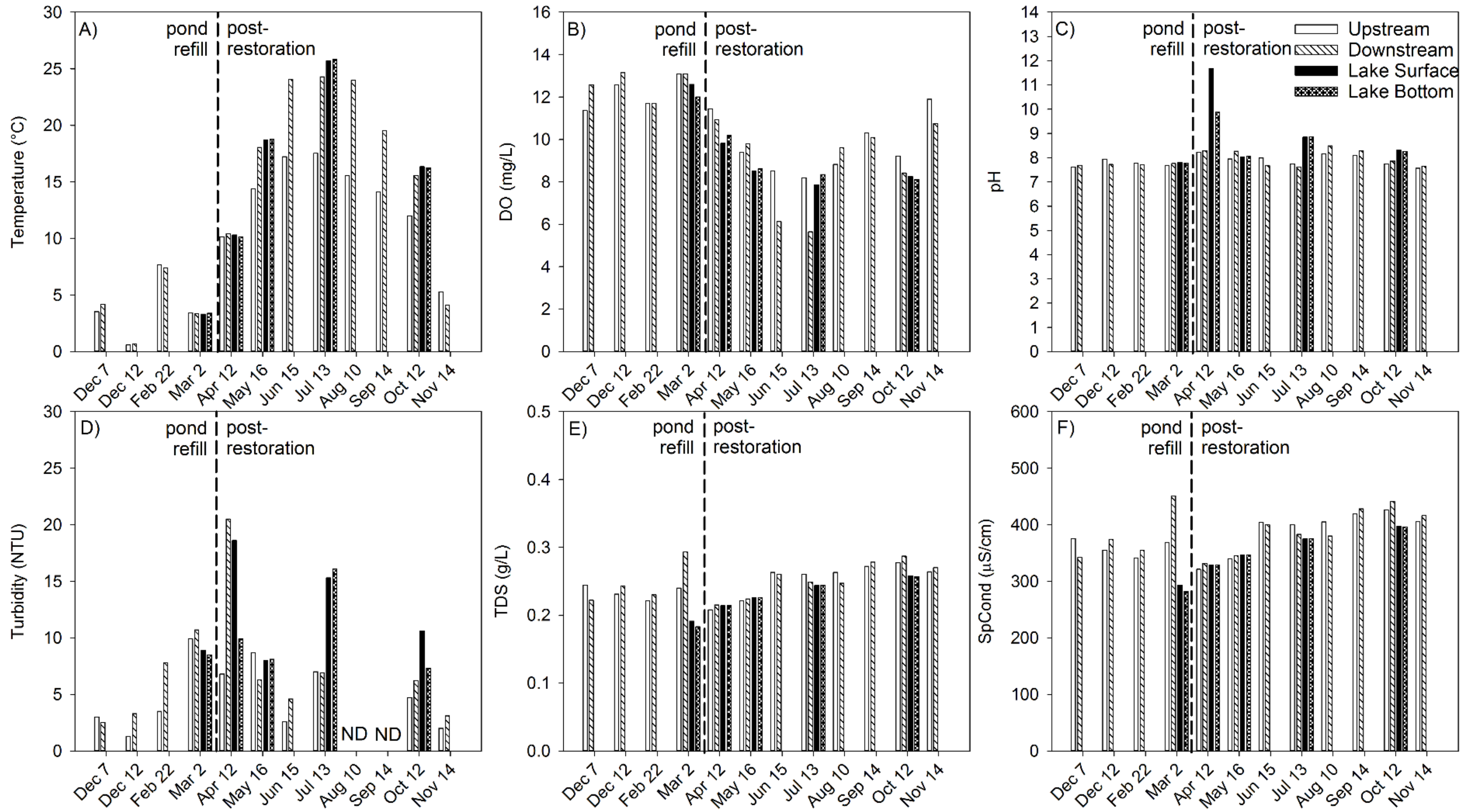

Figure 3. Temperature, dissolved oxygen (DO), pH, turbidity, total dissolved solids (TDS), and specific conductance (SpCond) of Bear Creek upstream & downstream and Bear Lake near-surface and near-bottom sites during pond refill (Dec. 2016 – Mar. 2017), berm removal (Apr. 2017), and post-filling (May – Nov. 2017) periods. Bear Lake sites post-restoration were sampled only in Mar.-May, Jul., and Oct. 2017. ND = no data (due to turbidity sensor error in August and September).

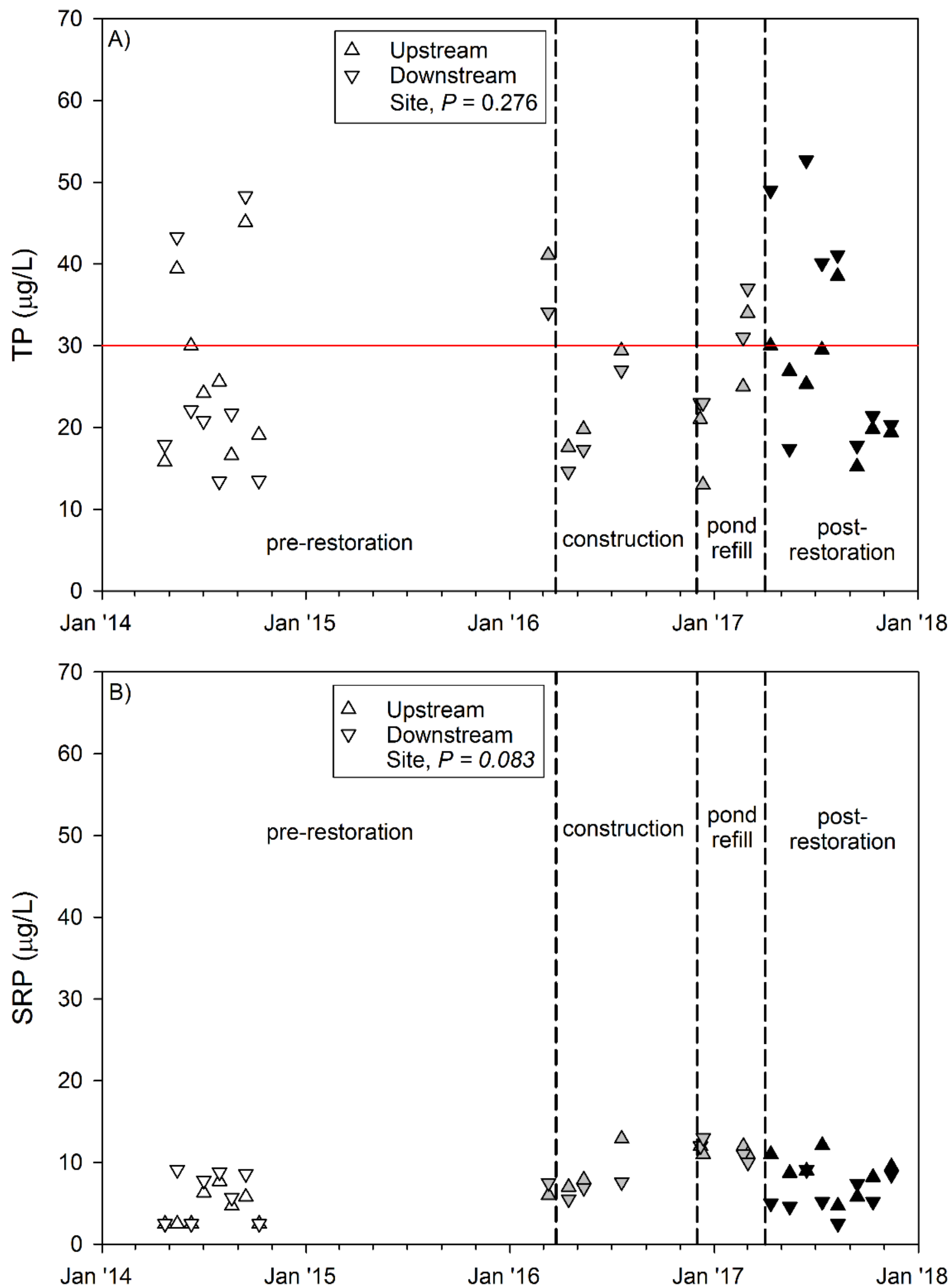

Figure 4. Bear Creek TP (A) and SRP (B) site concentrations over project period. P-values in the inserted boxes are based on only the post-restoration data (black symbols), comparing monthly upstream vs. downstream paired t-tests. Pre-restoration (open and one set of grey symbols), construction (grey symbols), and pond refill (grey symbols) samples are not included in this statistical analysis. Red reference line at 30 µg/L represents TP target goal set by the Bear Lake TMDL (MDEQ 2008).

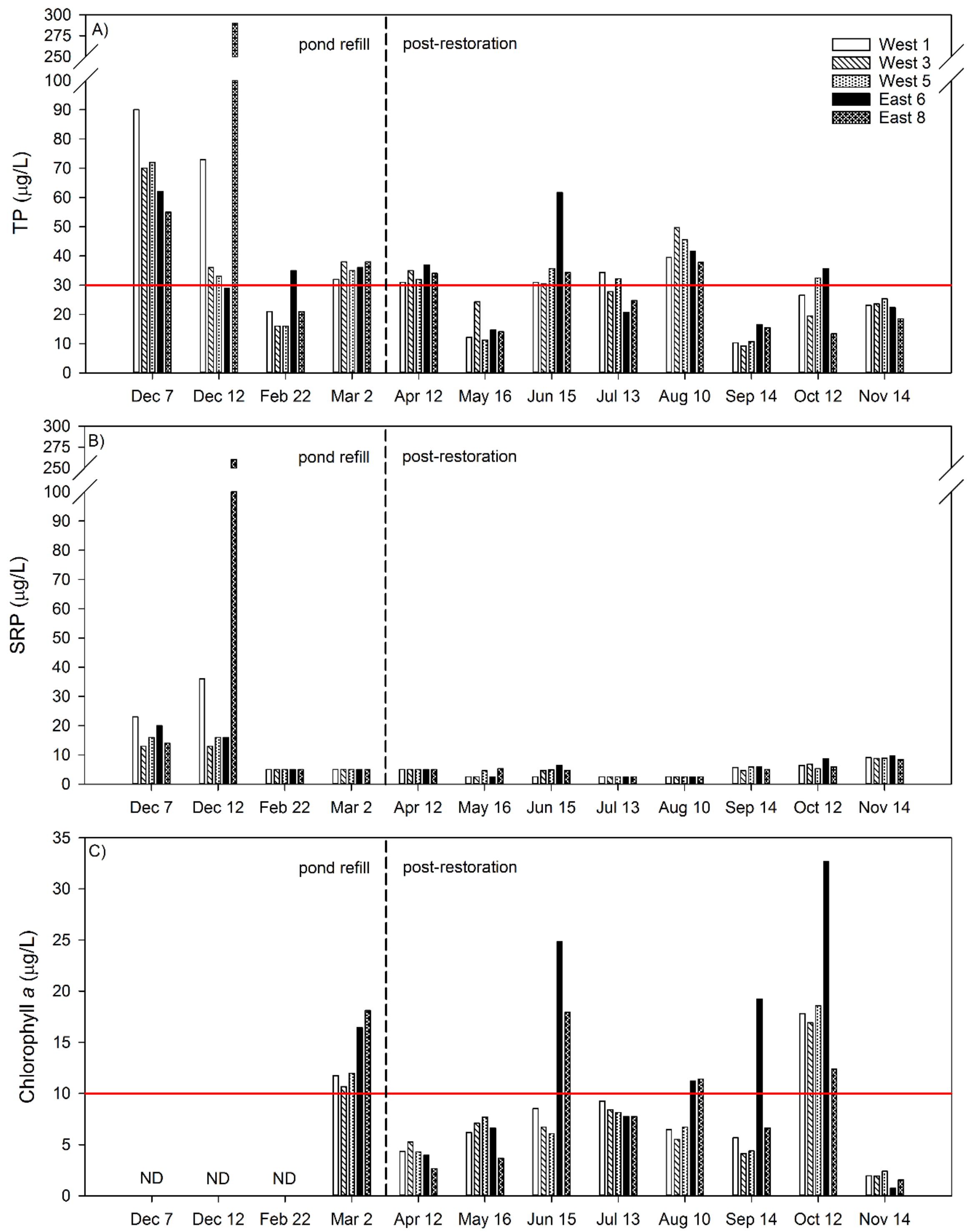

Figure 5. December 2016 through November 2017 TP (A), SRP (B), and chlorophyll (C) site concentrations at West and East ponds. Note that y-axis scales differ among panels and that y-axes in panels A and B are broken and that axis scales before and after the breaks are not identical. ND = no data, as chlorophyll was not sampled during winter 2016-2017. Red reference lines at 30 and 10 µg/L represent TP target goal set by the Bear Lake TMDL (MDEQ 2008) and chl restoration goal for Muskegon Lake AOC, respectively.

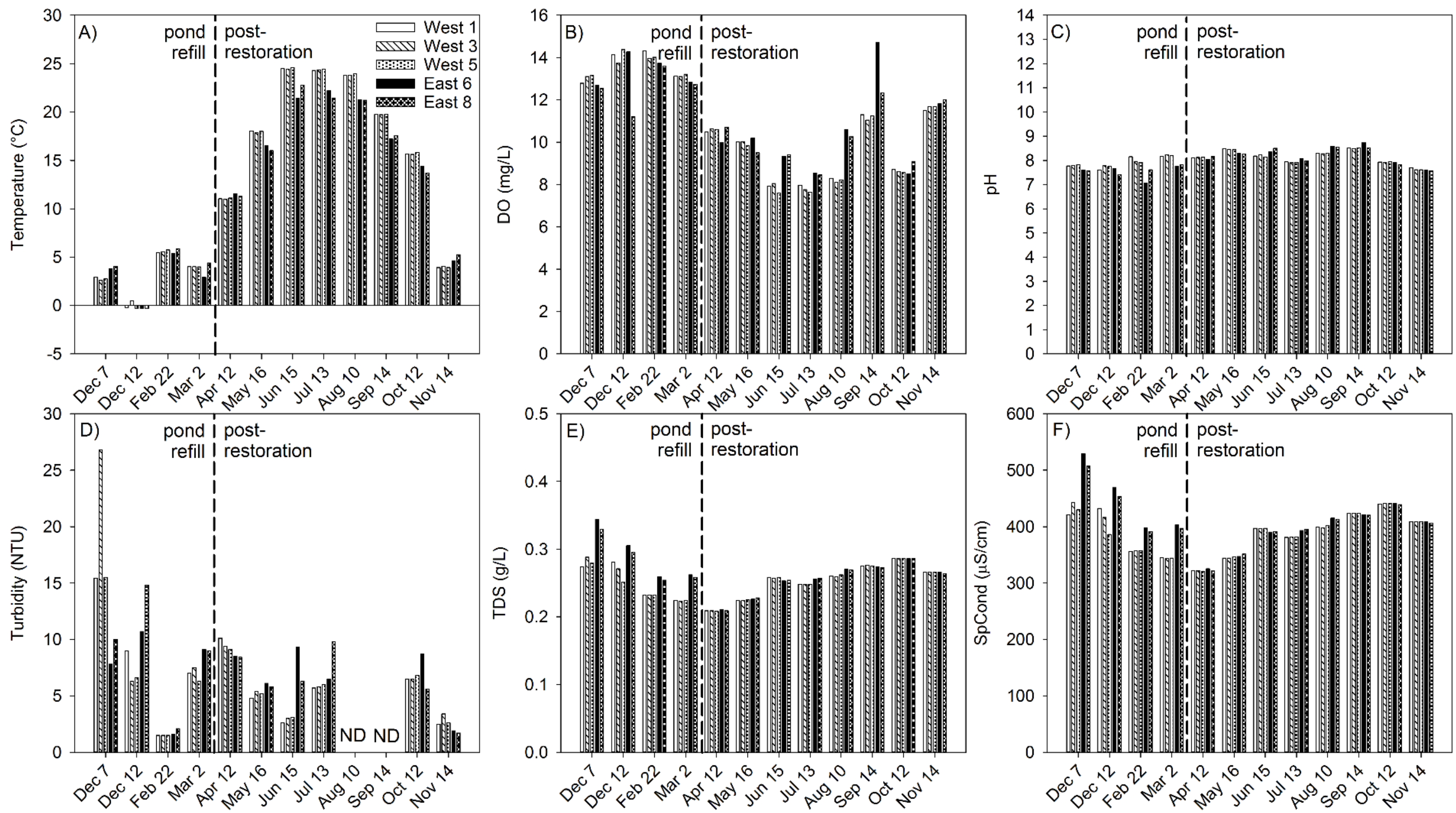

Figure 6. Temperature, dissolved oxygen (DO), pH, turbidity, total dissolved solids (TDS), and specific conductance (SpCond) of West and East pond sites during pond refill (Dec. 2016 – Mar. 2017), berm removal (Apr. 2017), and post-filling (May – Nov. 2017) periods. ND = no data (due to turbidity sensor error in August and September).

Table 4. West pond means (±SD) and pre- vs. post-restoration general water quality means (±SD) and statistical analysis results using paired t-tests (t) or Wilcoxon signed rank test (r). For all parameters, n=7 monthly sampling events in the same months (April – November) during 2014 pre-restoration and 2017 post-restoration, except for Turbidity which had n=5 events due to sensor error in 2017 post-restoration sampling. Statistically significant results ($p<0.05$) are indicated with bold text and marginally significant results ($p<0.10$) are indicated with italic text. Data are color-coded by site to improve readability. Chl *a* = chlorophyll *a*; DO = dissolved oxygen; SpCond = specific conductance; ORP = oxidation-reduction potential; TDS = total dissolved solids; BGA = blue-green algae.

Parameter	West 1				West 3				West 5			
	Pre	Post	p-value	test	Pre	Post	p-value	test	Pre	Post	p-value	test
TP (µg/L)	955 (316)	25 (11)	**<0.001**	**t**	891 (216)	26 (12)	**<0.001**	**t**	902 (254)	28 (13)	**<0.001**	**t**
SRP (µg/L)	740 (314)	4 (3)	**<0.001**	**t**	701 (216)	5 (2)	**<0.001**	**t**	701 (273)	5 (2)	**<0.001**	**t**
Part-P (µg/L)	215 (58)	21 (12)	**<0.001**	**t**	190 (65)	22 (14)	**<0.001**	**t**	202 (79)	23 (14)	**0.002**	**t**
Chl *a* (µg/L)	19.5 (15.5)	8.0 (4.9)	0.111	t	9.5 (9.4)	7.2 (4.8)	0.582	t	10.8 (13.1)	7.7 (5.2)	0.594	t
Temperature (°C)	17.7 (5.3)	18.6 (7.3)	0.687	t	17.8 (5.3)	18.6 (7.3)	0.711	t	17.3 (5.4)	18.6 (7.3)	0.537	t
DO (mg/L)	8.6 (2.7)	9.4 (1.5)	0.509	t	7.1 (3.4)	9.3 (1.6)	0.151	t	7.5 (3.6)	9.3 (1.7)	0.309	t
DO (%)	90 (27)	99 (13)	0.414	t	74 (32)	98 (12)	0.103	t	77 (34)	98 (13)	0.219	t
pH	8.3 (0.8)	8.1 (0.3)	0.813	r	8.2 (0.7)	8.1 (0.3)	0.375	r	8.1 (0.8)	8.1 (0.3)	0.578	r
SpCond (µS/cm)	679 (81)	399 (31)	**<0.001**	**t**	679 (80)	399 (31)	**<0.001**	**t**	684 (78)	400 (31)	**<0.001**	**t**
ORP (mV)	385 (27)	396 (48)	0.653	t	391 (25)	405 (43)	1.000	r	387 (25)	404 (43)	0.813	r
TDS (g/L)	0.442 (0.053)	0.260 (0.020)	**<0.001**	**t**	0.441 (0.052)	0.259 (0.020)	**<0.001**	**t**	0.445 (0.051)	0.260 (0.020)	**<0.001**	**t**
Turbidity (NTU)	3 (3)	4 (2)	0.285	t	2 (2)	5 (2)	*0.053*	*t*	4 (3)	5 (2)	**0.028**	**t**
BGA (cells/mL)	5966 (4662)	677 (1646)	**0.025**	**t**	4044 (2472)	3390 (7103)	0.297	r	5232 (2561)	481 (1163)	**0.005**	**t**

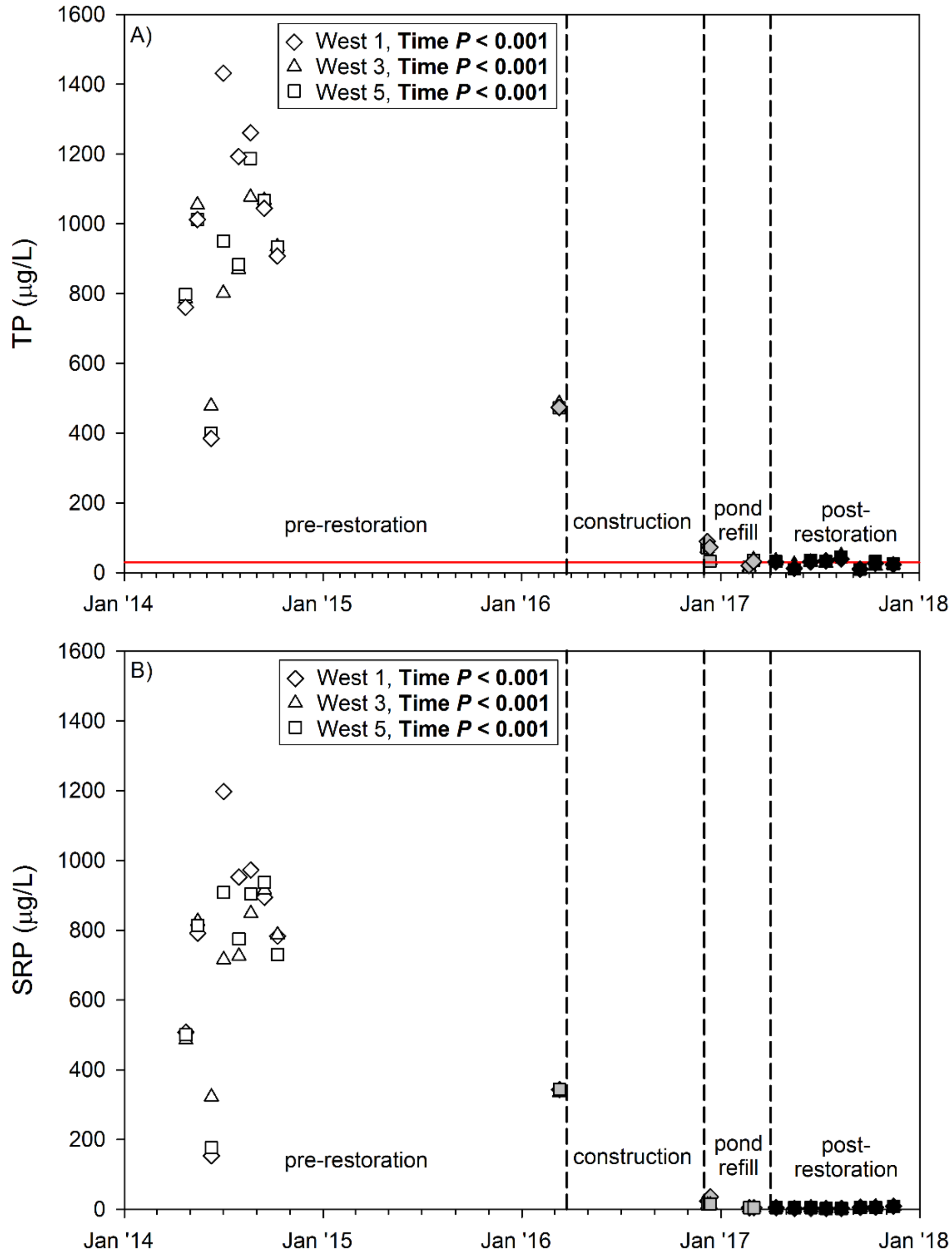

Figure 7. West pond TP (A) and SRP (B) site concentrations during 2014-2016 pre-restoration sampling and 2017 post-restoration sampling. P-values are results of pre- vs. post-restoration paired t-tests within sites. Pond refill samples (gray symbols) are not included in statistical analysis. Red reference lines at 30 µg/L represent TP target goal set by the Bear Lake TMDL (MDEQ 2008).

Table 5. East pond mean (±SD) and pre- vs. post-restoration general water quality means (±SD) and statistical analysis results using paired t-tests (t) or Wilcoxon signed rank test (r). For all parameters, n=7 monthly sampling events in the same months (April – November) during 2014 pre-restoration and 2017 post-restoration, except for Turbidity which had n=5 events due to sensor error in 2017 post-restoration sampling. Statistically significant results ($p<0.05$) are indicated with bold text and marginally significant results ($p<0.10$) are indicated with italic text. Data are color-coded by site to improve readability. Chl *a* = chlorophyll *a*; DO = dissolved oxygen; SpCond = specific conductance; ORP = oxidation-reduction potential; TDS = total dissolved solids; BGA = blue-green algae.

Parameter	East 6				East 8			
	Pre	Post	p-value	test	Pre	Post	p-value	test
TP (µg/L)	137 (74)	31 (17)	**0.009**	**t**	131 (72)	23 (10)	**0.010**	**t**
SRP (µg/L)	4 (3)	5 (3)	0.403	t	3 (0)	5 (2)	**0.043**	**t**
Part-P (µg/L)	132 (72)	25 (17)	**0.008**	**t**	128 (72)	18 (11)	**0.010**	**t**
Chl *a* (µg/L)	67.5 (60.6)	14.7 (11.3)	*0.053*	*t*	47.4 (28.4)	8.8 (5.6)	**0.014**	**t**
Temperature (°C)	17.7 (5.5)	16.8 (6.1)	0.642	t	18.4 (5.2)	16.9 (6.1)	0.433	t
DO (mg/L)	11.1 (1.5)	10.5 (2.2)	0.599	t	11.4 (1.4)	10.2 (1.5)	0.155	t
DO (%)	116 (13)	108 (23)	0.407	t	121 (14)	104 (15)	**0.027**	**t**
pH	8.7 (0.4)	8.2 (0.4)	**0.018**	**t**	8.8 (0.3)	8.2 (0.4)	**<0.001**	**t**
SpCond (µS/cm)	561 (40)	402 (30)	**<0.001**	**t**	560 (41)	402 (28)	**<0.001**	**t**
ORP (mV)	357 (31)	408 (39)	**0.027**	**t**	343 (48)	410 (41)	*0.058*	*t*
TDS (g/L)	0.365 (0.026)	0.262 (0.019)	**<0.001**	**t**	0.364 (0.027)	0.262 (0.018)	**<0.001**	**t**
Turbidity (NTU)	27 (27)	7 (3)	0.263	t	25 (20)	6 (3)	0.215	t
BGA (cells/mL)	96671 (83370)	1413 (3438)	**0.043**	**r**	91132 (76962)	697 (1692)	**0.038**	**t**

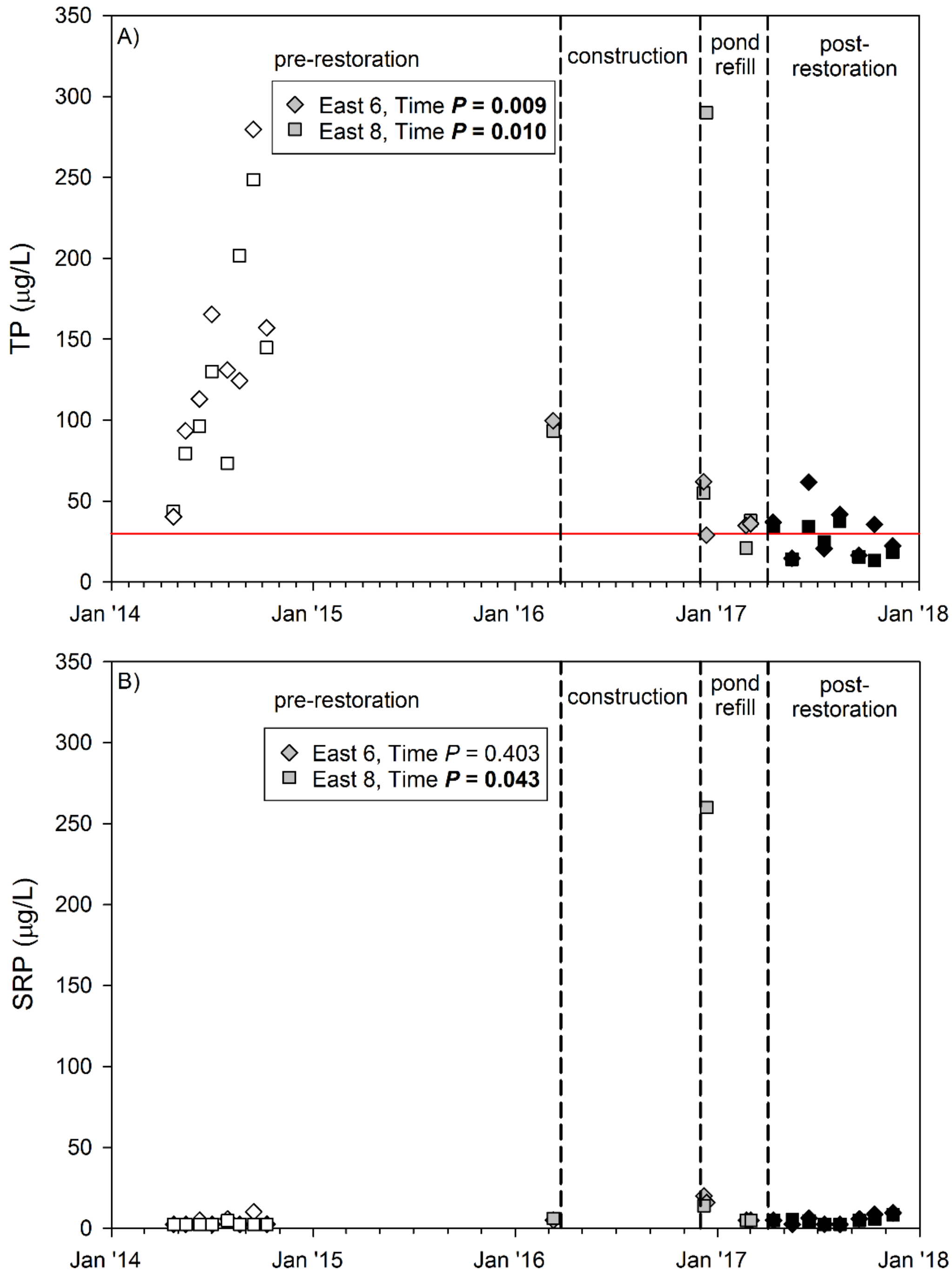

Figure 8. East pond TP (A) and SRP (B) site concentrations during 2014-2016 pre-restoration sampling and 2017 post-restoration sampling sampling. P-values are results of pre- vs. post-restoration paired t-tests within sites. Pond refill samples (gray symbols) are not included in statistical analysis. Red reference lines at 30 µg/L represent TP target goal set by the Bear Lake TMDL (MDEQ 2008).

Table 6. Mean (±SD) near-surface sediment (0-10 cm depth) characteristics from pre- and post-restoration sites collected on July 12, 2012 and June 27-28, 2017, respectively. TP = total phosphorus, OM = organic matter, EPC_0 = equilibrium phosphorus concentration, S_{max} = phosphorus sorption maximum. ND = no data, as Bear Creek sediment was not sampled in 2012. For EPC_0 and S_{max}, n=3 site core isotherm subsamples.

Site	Time	Sediment TP (dry, mg/kg)	%OM	EPC_0 (µg/L)	S_{max} (mg/kg)
Downstream	pre	ND	ND	ND (ND)	ND (ND)
	post	1100	45.5%	3 (0)	148 (45)
West 1	pre	2382	19.7%	453 (18)	1310 (103)
	post	86	1.2%	53 (2)	47 (3)
West 3	pre	3226	22.3%	268 (8)	3333 (0)
	post	162	2.7%	77 (30)	9 (6)
West 5	pre	1773	16.1%	71 (2)	1587 (137)
	post	331	10.8%	8 (3)	163 (113)
East 6	pre	650	19.0%	29 (5)	763 (128)
	post	1337	34.0%	26 (0)	649 (388)
East 8	pre	674	18.6%	10 (1)	1508 (137)
	post	42	0.3%	14 (1)	35 (2)
Upstream	pre	ND	ND	ND (ND)	ND (ND)
	post	77	0.5%	83 (7)	81 (10)

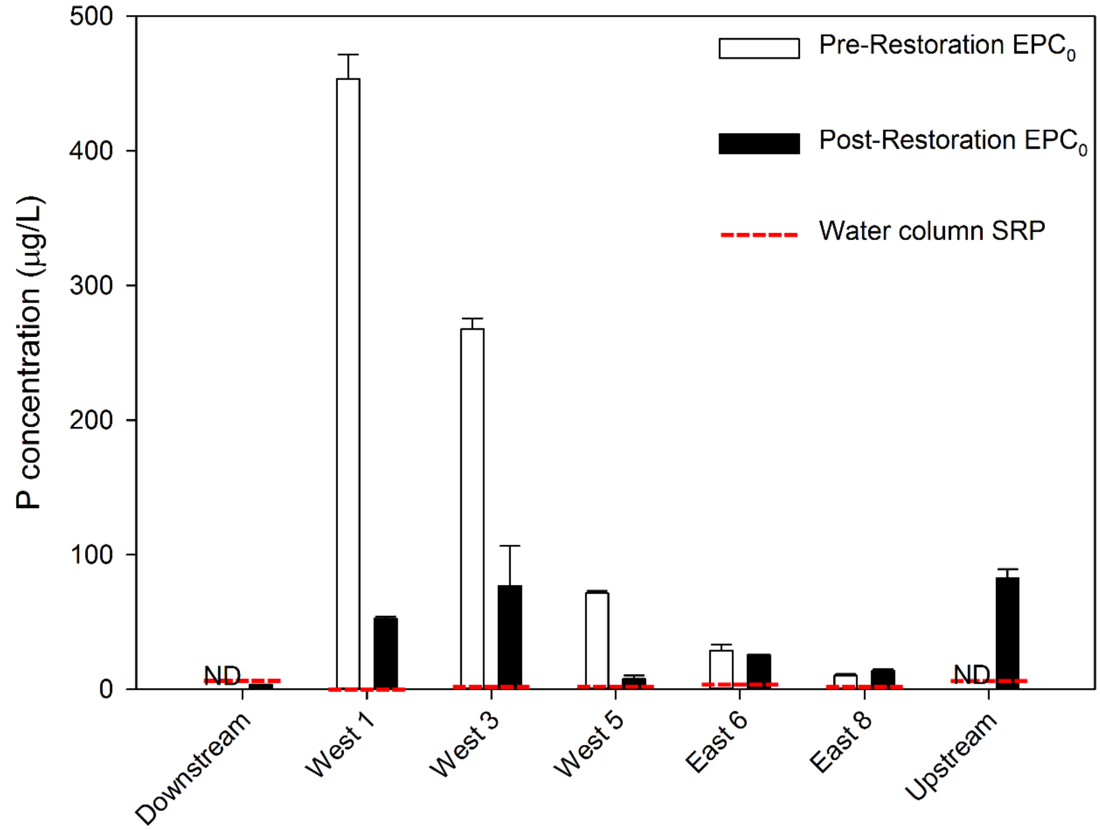

Figure 9. Sediment P isotherm data for pre-restoration (18 July 2012) and post-restoration (27-28 June 2017) sampling events at Bear Creek and pond sites. Red dashed lines represent water column SRP concentrations collected in June 2017. ND=no data (as sediment was not collected from Bear Creek sites for isotherm analysis in 2012).

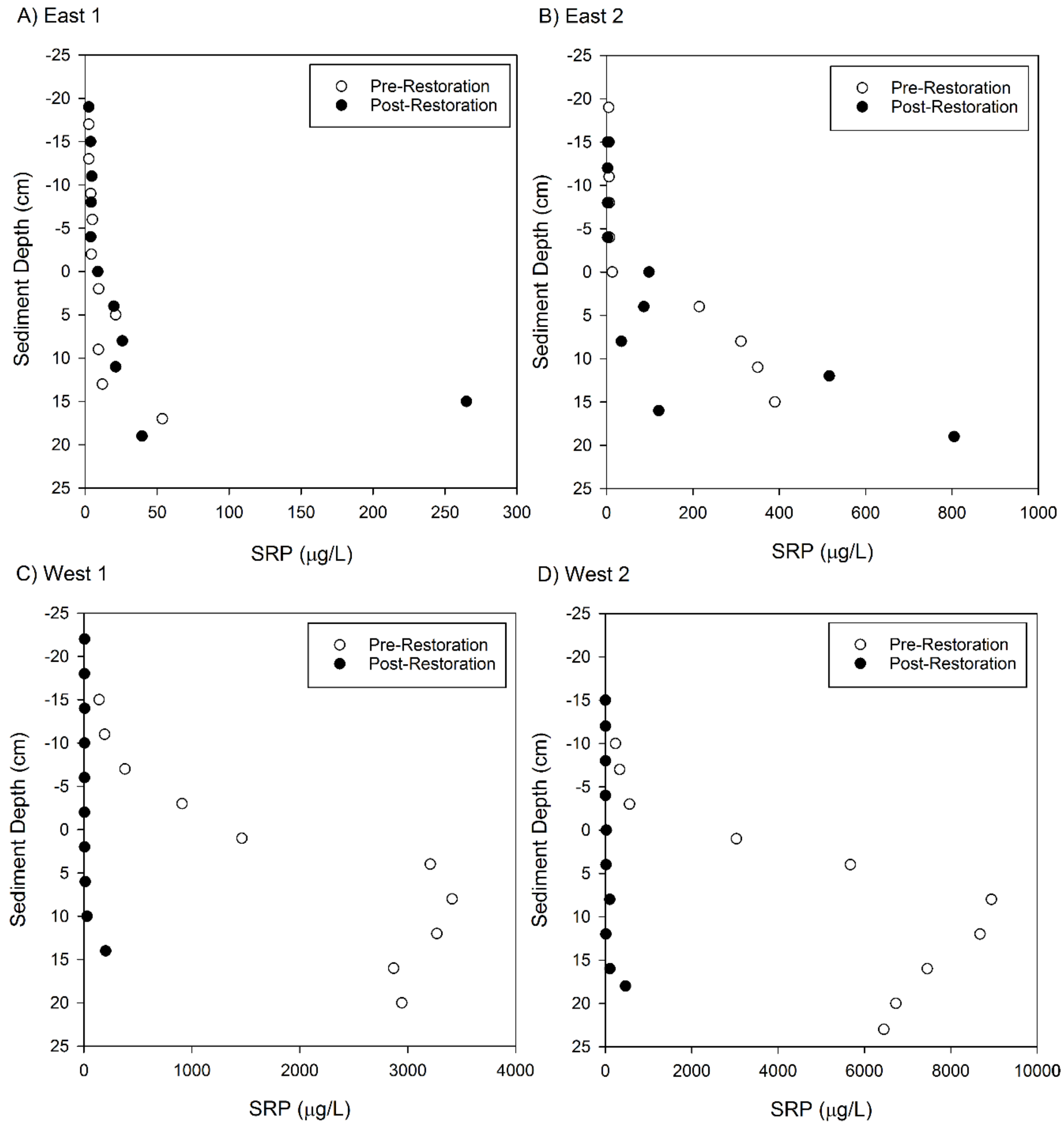

Figure 10. Pre- and post-restoration mean sediment porewater P by depth in restoration ponds. For each site, n=2 porewater sampling units. Pre-restoration peepers incubated in situ 18 July 2012 to 1 August 2012 and post-restoration peepers incubated in situ 31 August 2017 to 14 September 2017.

Table 7. West pond pre- and post-restoration means (±SD) of SRP at near-surface and deeper depths from sediment porewater samplers. Depths were tested separately across time (n=4 sampling devices) using paired t-tests. Near-surface data were log-transformed to meet assumptions of normality. P-values representing significant differences are presented in bold text.

	West Porewater SRP (µg/L)					
	Pre-Restoration		Post-Restoration			
Depth below sediment surface	Mean	SD	Mean	SD	P-value	Test
1-4 cm	2249	1433	11	6	**<0.001**	**t**
13.5-16 cm	5506	3377	154	146	**0.037**	**t**

Table 8. East pond pre- and post-restoration means (±SD) of SRP at near-surface and deeper depths from sediment porewater samplers. Depths were tested separately across time (n=4 sampling devices) using paired t-tests.

	East Porewater SRP (µg/L)					
	Pre-Restoration		Post-Restoration			
Depth below sediment surface	Mean	SD	Mean	SD	P-value	Test
2-4 cm	112	148	53	63	0.279	t
15.5-17 cm	222	198	193	190	0.864	t

Discussion

Wetland restoration and hydrologic reconnection of prior agricultural land use runs the risk of liberating legacy phosphorus, once these soils are exposed to low-P water (Aldous et al. 2005; Newman and Pietro 2001; Steinman and Ogdahl 2011, 2016). This potential was of particular concern for the current project's hydrologic reconnection design, given that the immediate downstream water body, Bear Lake, already was considered impaired because of excess phosphorus (MDEQ 2008).

The results of this study provide encouraging results for Bear Creek habitat restoration efforts and the overall Muskegon Lake AOC delisting progress. Sediment dredging appears to have significantly reduced the amount of phosphorus leaving the existing sediments and from entering Bear Creek. Concentrations of SRP, the bioavailable form of P, were lower at the downstream site than those entering into the area from upstream. Mean TP concentrations in the west pond have been significantly reduced to only 2-3% of their 2014 means.

However, we note that mean TP concentrations in both the west and east ponds, as well as Bear Creek and Bear Lake, are still near or occasionally above the recommended TMDL concentration of 30 µg/L for Bear Lake. Continued monitoring at these sites, at a reduced time frequency, may be beneficial for measuring changes in phosphorus concentrations in water and sediment as the ponds are re-colonized by plants, which would promote biotic uptake by periphyton, macrophytes, and microbial communities (Reddy 1999). Additionally, macrophyte growth could slow-down sediment transport rates through the watershed, preventing P adsorbed to sediments from entering areas further downstream. If the ponds' conditions do not continue to improve as the restored ponds re-establish themselves, managers may consider using additional restoration strategies to build on the success of dredging.

These results build upon the body of previous work that suggest dredging as one potential restoration tool for reducing sediment phosphorus loads from wetlands (cf. Yu et al. 2017), which may be applicable to other areas in the Muskegon AOC in its progress towards hydrological reconnection, habitat restoration, and eventual delisting from AOC status.

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