Lower Muskegon River Reconnection Project
Post-Restoration Monitoring Report

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Introduction

Muskegon Lake is a 4,150-acre (1,680-ha) drowned river mouth-lake that connects directly to Lake Michigan through a navigation channel. It was designated an Area of Concern (AOC) in 1985 due to ecological problems caused by industrial discharges, shoreline alterations, and the filling of open water and coastal wetlands. Historic sawmill debris, foundry sand, and slag filled 798 acres of open water and emergent wetlands in this AOC. Approximately 65 percent of the shoreline was hardened with wood pilings, sheet metal, and concrete (Steinman et al. 2008a). This resulted in the loss and degradation of shallow water benthic communities, isolation and fragmentation of coastal wetlands, and the associated degradation of water quality and fish and wildlife populations. Both the benthos and habitat have improved since the end of lake-filling practices and wastewater diversion in 1973 (Steinman and Ogdahl 2011; Nelson and Steinman 2013; Orzechowski and Steinman in press), although additional fish and wildlife habitat restoration was needed to meet the AOC restoration targets. Fish and wildlife populations, including lake sturgeon, walleye, white bass, and various species of reptiles, amphibians, and water birds, were impaired by the loss of habitat.

Loss of fish and wildlife habitat is one of the beneficial use impairments (BUIs) that had not yet met its restoration target in 2017, when the 53.5-acre, former Bosma Brothers Celery Farm property (now known as the Lower Muskegon River Reconnection Project: LMRRP), was identified as a restoration project. This site, near where the north branch of the Muskegon River enters Muskegon Lake, includes floodplain acreage that was hydrologically separated from the river by an earthen berm. Reconnection would provide important floodplain habitat for fish and wildlife. However, similar to the restoration of the Willbrandt ponds, just a few miles away in the Bear Creek watershed (Steinman and Ogdahl 2016), the land was formerly used for celery farming. The Bosma property was farmed until 1976, and subsequently hayed, off and on, through 2015. Pumping had kept standing water out of the diked fields until relatively recently. As a consequence, there were concerns that the sediment contained legacy phosphorus (P) that could be a major source of P to Muskegon Lake after reconnection. Currently, Muskegon Lake's P concentrations are meeting the restoration target for AOC delisting (Steinman et al. 2008a) but contributing additional P through hydrologic reconnection and sediment P release to overlying water clearly would be undesirable.

Restoration of the site was delayed several years following the pre-restoration monitoring that was conducted in 2016. Issues associated with an adjacent restoration project (Zephyr Oil Refinery; see below) prevented the start of LMRRP restoration. Construction consisted of dewatering the site, followed by sculpting of the restoration site, which involved both fill (~55,000 m^3) and excavation (~77,870 m^3) that varied in height and depth, respectively, throughout the site (Appendix Fig. 10). The highest P sediment was moved off-site, with the majority of fill placement occurring at an elevation above the 100-yr floodplain to minimize interaction with the water. A limited number of fill samples, after it was mixed with the sand on site, were analyzed for P content with concentrations of between 150 mg/kg and 470 mg/kg (Brian Majka, pers. comm.).

Following the completion of LMRRP construction, a post-restoration analysis of the sediment and water quality was conducted. The focus for the post-restoration monitoring was to determine to what degree phosphorus concentrations in the sediment and overlying water had been reduced. This, in turn, allowed us to assess the potential impact of restoration on water quality of Muskegon Lake.

Methods

Site Description

The LMRRP wetland is located in the Lower Muskegon River watershed, approximately 1 mile upstream from Muskegon Lake in Muskegon, MI. An earthen berm was constructed during historic farming operations to separate the periodically flooded former agricultural fields from the Muskegon River. Two additional north-south berms further separated the property into west, central, and east wetland regions (Figs. 1-3). The focus of our restoration monitoring was on the east (sites 1-4) and central (sites 5-15) wetland cells. We further split the central wetland region into north central (sites 5-8) and south central (sites 9-15) wetland cells. Prior to the start of our pre-restoration monitoring in 2016, attempts were made to draw down the standing water in the central and east wetland cells by mechanical pumping, but due to heavy rainfall many cells remained inundated at the time of sampling (see below). Restoration was originally planned for 2017 but was delayed due to ecological restoration of the former Zephyr Oil Refinery property, which competed for road access and was granted a priority status. After the Zephyr restoration concluded and after delays due to COVID-19 restrictions, restoration at the LMRRP wetland began in 2021. Post-restoration monitoring took place after restoration sediment dredging and landscaping had taken place in 2021 but before the berm removal occurred and hydrologically reconnected the wetland to the Muskegon River via surface flow.

To the greatest degree practical, the same sites were used for both pre-restoration and post-restoration studies and site selection was previously described in the pre-restoration monitoring report (Steinman et al. 2017a). Briefly, sampling locations were determined using stratified random methods. First, an aerial photograph of the 53-acre wetland restoration area was traced and outlined in ArcGIS (Environmental Systems Research Institute). A grid mesh was overlaid on the outline and manually grouped together by region to create 15 parcel areas each averaging 3.5 (±0.4 SD) acres (Fig. 2). Mesh squares in each parcel were assigned a number and a random number generator was used to select one square per parcel; points landing on roadways, earthen berms, and trees were re-rolled. For each location a latitude and longitude were recorded using a handheld Garmin eTrex Venture HC 12-channel GPS at the location where the core was collected (Fig. 2, Table 1). Four sites (#1, 5, 12, 13) were removed from the post-restoration isotherm analysis due to the sites' close proximities and similarities during pre-restoration monitoring.

Figure 1A,B. Google Earth aerial images of LMRRP wetland monitoring site locations (n=15) during active farming (A, 2013) and flooded conditions typical of 2016 pre-restoration conditions prior to water draw-down for sediment core sampling (B, 2018).

Figure 1C. Google Earth aerial images of LMRRP wetland monitoring site locations (n=15) from post-restoration sampling conditions prior to hydrologic reconnection (2021).

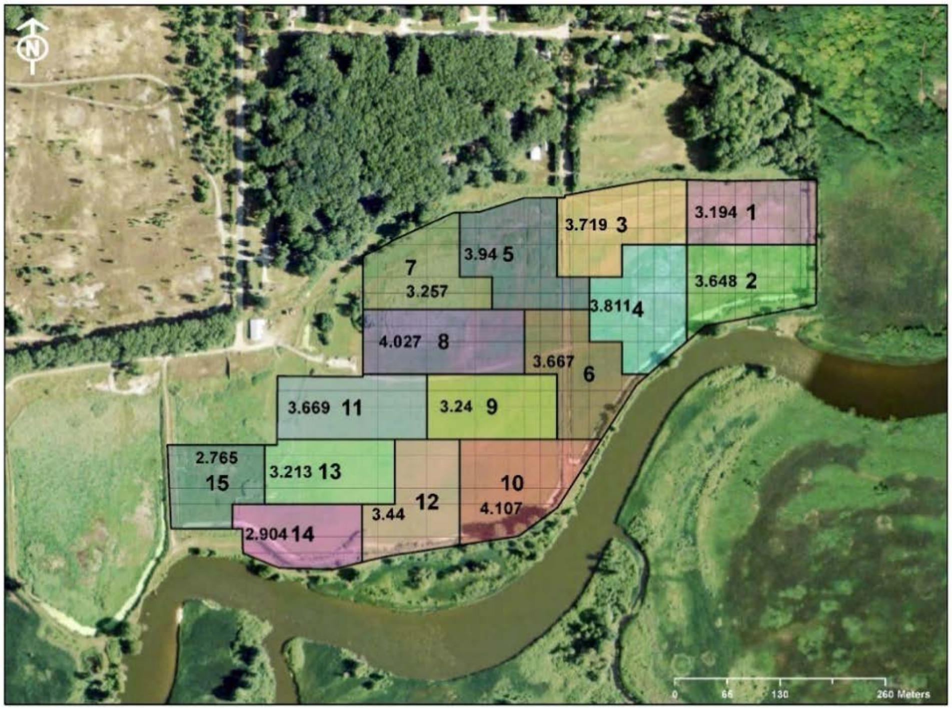

Figure 2. LMRRP wetland pre-restoration monitoring parcel areas. Large numbers inside each area represent their numeric designator (1-15); small numbers represent acreage of each parcel. Mean (±SD) area per site parcel = 3.5 (± 0.4) acres.

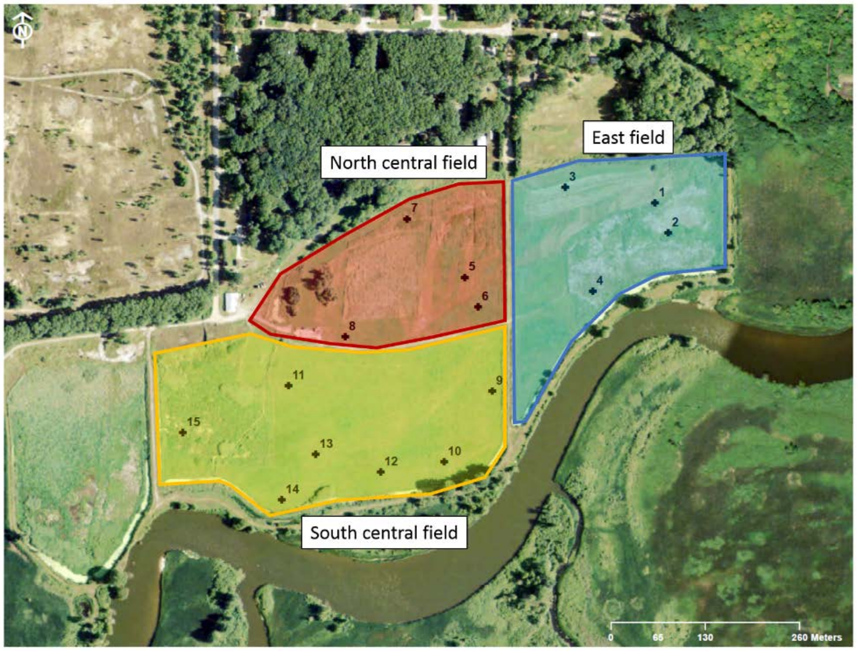

Figure 3. LMRRP wetland monitoring sites aggregated into zones.

Table 1. LMRRP wetland monitoring site location coordinates.

Wetland Zone	Site #	Latitude (°N)	Longitude (°W)
East	1	43.27222	86.22581
	2	43.27185	86.22559
	3	43.27242	86.22733
	4	43.27113	86.22688
North Central	5	43.27132	86.22905
	6	43.27095	86.22883
	7	43.27205	86.23002
	8	43.27060	86.23109
South Central	9	43.26991	86.22860
	10	43.26904	86.22943
	11	43.27000	86.23206
	12	43.26892	86.23051
	13	43.26915	86.23161
	14	43.26859	86.23219
	15	43.26943	86.23386

Summer 2021 – Post-Restoration P isotherms

During August 2021, we collected one sediment core from each of the study sites, sampling approximately 2 sites at a time over multiple days until all sites within the restoration area were sampled.

Sediment cores of 7 cm diameter were obtained using a modified piston coring apparatus (Fisher et al. 1992; Davis and Steinman 1998). The modified piston corer was constructed of a 0.6-m long, ~7-cm inner diameter, 7.6-cm outer diameter polycarbonate tube that was marked in 1-cm increments. The modified corer was positioned vertically at the sediment water interface and was hammered into the sediment, which was necessary due to the highly compacted soil within the cells, to a depth of 30 cm. The top and bottom of each core was sealed with a rubber stopper and duct tape. The cores were stored upright and transported back to the lab within 5 hours. At sites where standing water was present, water depth was recorded. Where it was deep enough for water collection, a water sample was collected for total P (TP) and soluble reactive P (SRP); the latter sample was filtered (0.45 μm). Water samples were stored on ice until transported back to the lab where they were stored at 4°C until analyzed on a Seal AQ2 Discrete Analyzer (U.S. EPA 1993). Where water was collected, general water quality variables were measured using a YSI EXO2 data sonde, which included temperature, dissolved oxygen (DO) concentration and percent, pH, specific conductance (SpCond), total dissolved solids (TDS), and turbidity (NTU).

In the lab, sediment was extruded from each core and separated into a 0-10 cm *surface* sample and a 20-30 cm *bottom* sample, stored in plastic bags, and refrigerated at 4°C until additional analysis. Sediment samples were homogenized by hand and subsampled for analysis of organic matter (OM), ash-free dry mass (AFDM), sediment TP and P isotherm measurements. Sediment OM and AFDM were determined using gravimetric procedures (i.e., dry for 24 hours at 105˚C, weigh, ash at 550˚C for 1 hour, re-weigh; Steinman et al. 2017b). The resultant ashed material was used for analysis of sediment TP on a Seal AQ2 Discrete Analyzer (U.S. EPA 1993). Additional subsamples were dried, ashed, and analyzed for metals at Trace Analytical Laboratories (Muskegon, MI).

The remaining wet sediment was used and subsampled to run P isotherms to calculate Equilibrium P Concentrations (EPC_0). P isotherms, which provide an indication of the propensity of sediments to release or take up P from overlying water, were determined in triplicate for each 0-10 cm surface and 20-30 cm bottom section of sediment cores (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, 0.01, 0.1, 1, 5, 10, 50, 100, or 500 mg P/L to 50 mL centrifuge tubes containing 3 g of wet sediment. During pre-restoration analyses at each concentration and within each site, one of the triplicate samples served as a killed control by using chloroform, while the other two were left as is. This technique was dropped during post-restoration sampling, resulting in three "as is" triplicate samples per each P concentration within each site. The centrifuge tubes were incubated for 24 hr on an orbital shaker table at 250 RPM. Samples were centrifuged for 20 minutes at 3600 RPM and supernatant was filtered through a 0.45 μm filter before undergoing SRP analysis as described above. Phosphorus sorption is calculated as the difference between the amount of P initially added to the tube and that in the solution at equilibrium. Calculations were as follows (after Olila and Reddy 1993):

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

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

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) was 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) was 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 $S_1 = 0$ was calculated from the equation:

$$EPC = S_0/b$$

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

Summer 2021 – Post-Restoration Sediment re-wetting experiment and P fractionation

Two additional sediment cores were collected in July 2021 from the same 15 sites described above using a shorter (but still 7.5 cm diameter) modified sediment sampler (Davis and Steinman 1998) and similar methods as described above. The shorter core tubes were driven to a minimum depth of only 10 cm. All sediment cores were transported upright back to the lab within 5 hr of collection for a sediment desiccation and rewetting experiment, with subsequent P fractionation. The second set of cores from each site were used for sediment characterization (organic matter, ash-free dry mass, TP) and sediment metals analyses.

Before coring, the core tubes used in the desiccation and rewetting experiment were pre-drilled with 5 sampling ports along the length of the tube at 3 cm intervals, starting at 1.5 cm up from the bottom of the core tube. The sampling ports were covered with electrical tape to prevent sample loss during coring.

After transportation back to the lab, both sets of cores were allowed to settle for several hours and any overlying water was carefully drawn off via peristaltic pump and a Pasteur pipette. The height of the sediment cores within the core tube was adjusted to 10 cm, if needed, by removing excess sediment from the bottom.

The first set of cores was used for the sediment characterization and were extruded into plastic bags and refrigerated until further analysis of AFDM and OM, as described above, and metal analysis (Fe, Ca, and Mn) using EPA Method 6010B (U.S. EPA 1996).

The second set of cores was used in a desiccation and rewetting experiment and was placed in holding racks under metal halide lamps operated on a 12:12 L:D photoperiod (photosynthetically active radiation [PAR] at 118 $\mu mol/m^2/sec$ for entire incubation period near sediment surface) and allowed to dry naturally under ambient temperature conditions. Sediment moisture content was monitored throughout the drying period using a soil moisture probe (Extech Instruments, model number MO750). Cores were rotated weekly under the drying lamps and all cores were dried until they reached <1% soil moisture. Once standing water had evaporated during the drying period, electrical tape was removed from sampling ports and ports were used to insert rhizons at 2 depths, at the top and near bottom of cores, for nondestructive sampling of pore water (Seeberg-Elverfeldt et al. 2005). Due to leaks experienced during the pre-restoration version of this experiment, rhizons and any unused sampling ports were sealed with marine epoxy (Waterweld, J-B Weld, Marietta, GA) before rewetting in order to prevent water sample loss during later stages of this experiment.

Water from the Muskegon River, adjacent to the restoration area, was collected on 9 September 2021. Water quality was measured in situ with a YSI EXO2 sonde and a grab sample was collected for TP and SRP analyses, as described above. Each core was gently rewetted with 500 mL of homogenized filtered river water and allowed to incubate for a total 48 hr under static conditions. We sampled at 24 and 48 hr after rewetting. Syringes were used to subsample 130 mL from each of the overlying water column and both rhizon porewater depths: 20 mL each for TP and SRP analysis, which was stored and analyzed as described above, 20 mL each for anions and cations, and 50 mL for dissolved iron (Fe[II]), which were analyzed at Trace Analytical Laboratories (Muskegon, MI). P samples were used to calculate P flux. Ion analyses included Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, Br^-, NO_3^-, and SO_4^{2-} (see Appendix). Rhizons clogged before complete sample sets could be collected from both depths in all cores.

A subsample of 2 g of sediment was placed in centrifuge tubes for sequential fractionation (Psenner et al. 1998; modified from Hupfer et al. 2009). Extracts were analyzed for the following sediment P fractions: 1) NH_4Cl-extracted labile P (loosely sorbed); 2) BD-extracted reductant-soluble P (iron hydroxides, Mn-bound); 3) NaOH-extracted Fe- and Al-bound P; and 4) HCl-extracted Ca- and Mg-bound P.

Results

Summer 2021 – Post-Restoration Site Characterization

Surface water depths varied among sites in 2021, with some sites remaining dry in upland conditions and others were inundated with as much as 1 m of water; interestingly, mean water depth was greater post-restoration at the East and North sites, but was lower at the South sites (Table 2).

Post-restoration mean surface water SRP was <11 ug/L at all measurable sites except for site 15 (150 ug/L), where we anecdotally observed that much organic matter remained in the benthos (Table 2, Fig. 4B). TP ranged 42-293 ug/L and was highest at site 15 and other southern sites (Table 2, Fig. 4A). Barring site 15, surface SRP concentrations were less than that of the Muskegon River, but surface TP was similar or almost 6x greater than the Muskegon River (Table 2). Post-restoration sites in the east and north area had lower P concentrations than their pre-restoration measurements, but southern sites saw an increase in surface water mean SRP and TP after restoration (Table 2, Fig. 4).

General water quality parameters varied by location across restoration periods, as may be expected by the varying restoration construction designs throughout the wetland; however, mean turbidity was seen to have decreased throughout all sites (Table 2). Site 6, the only site from the North that was measured during both sampling periods, showed a marked improvement in DO, increasing from 1.48 to 9.74 mg/L (Table 2).

Sediment conditions were variable among sites, depths, within regions, and between restoration periods (Fig. 5A,B). Post-restoration sediment TP ranged 56-1096 mg/kg dry wt in surface samples and 21-1539 mg/kg dry wt in bottom samples (Table 3, Fig. 5A,B). Mean sediment TP concentrations greatly decreased among all sites combined compared to pre-restoration values and saw reductions of 80% at surface depth (0-10 cm) and 75% at bottom depth (20-30 cm) ($P<0.001$ and $P=0.004$ respectively; Table 3).

Post-restoration organic matter ranged 0.8-35% in surface samples and 0.2-15% in bottom samples (Table 3, Fig. 5C,D). This is expected due to restoration dredging activity removing sediments and we observed many sites had sandy topsoils. Similarly to sediment TP, mean organic matter greatly decreased between restoration periods with an 80% decrease at the surface and 70% decrease at bottom depths (Table 3, Figs. 5C,D).

Compared to sediment TP concentrations measured at other west Michigan lakes and flooded celery fields sampled by AWRI, LMRRP pre-restoration sediment TP means fell within the range measured at other sites (Fig. 6). Following restoration, mean sediment TP declined substantially, similar to the response measured in the Bear Creek East Muck Field (Fig. 6), another site that also experienced sediment dredging (Oldenborg and Steinman 2019).

Table 2. Mean (1 SD) water quality of surface waters at the wetland sites and the adjacent Muskegon River measured during pre-restoration (2016) and post-restoration (2021) sampling. SRP = soluble reactive P, TP = total P, DO = dissolved O_2, SpCond = specific conductance, TDS = total dissolved solids. ND = no data; NA = not applicable.

	East		North		South		River	
	Pre (n=1)	Post (n=2)	Pre (n=1)	Post (n=1)	Pre (n=7)	Post (n=4)	Pre (n=1)	Post (n=1)
Water Depth (m)	0.47 (NA)	0.71 (0.14)	0.36 (NA)	1.00 (NA)	0.45 (0.12)	0.33 (0.38)	ND	ND
SRP (µg/L)	15 (NA)	3 (0)	579 (NA)	3 (NA)	15 (19)	41 (72)	7	26
TP (µg/L)	301 (NA)	103 (36)	619 (NA)	42 (NA)	134 (61)	161 (90)	24	49
Temp (°C)	30.08 (NA)	25.02 (1.92)	24.33 (NA)	24.25 (NA)	27.61 (1.62)	22.5 (1.82)	22.5	19.3
DO (mg/L)	9.79 (NA)	7.45 (0.28)	1.48 (NA)	9.74 (NA)	7.01 (3.40)	8.63 (2.82)	9.17	7.52
DO (%)	129.8 (NA)	90.3 (0.3)	17.8 (NA)	116.5 (NA)	88.2 (39.9)	100.7 (34.9)	106	82
pH	6.35 (NA)	8.13 (0.17)	6.39 (NA)	8.54 (NA)	6.89 (0.27)	8.29 (0.64)	7.95	8.02
SpCond (µS/cm)	395 (NA)	688 (99)	1179 (NA)	719 (NA)	680 (143)	730 (27)	404	409
TDS (mg/L)	261 (NA)	448 (64)	766 (NA)	468 (NA)	442 (93)	475 (17)	263	266
Turbidity (NTU)	257.0 (NA)	5.8 (6.4)	54.7 (NA)	20.8 (NA)	39.7 (27.1)	11.5 (4.9)	74.5	2.8

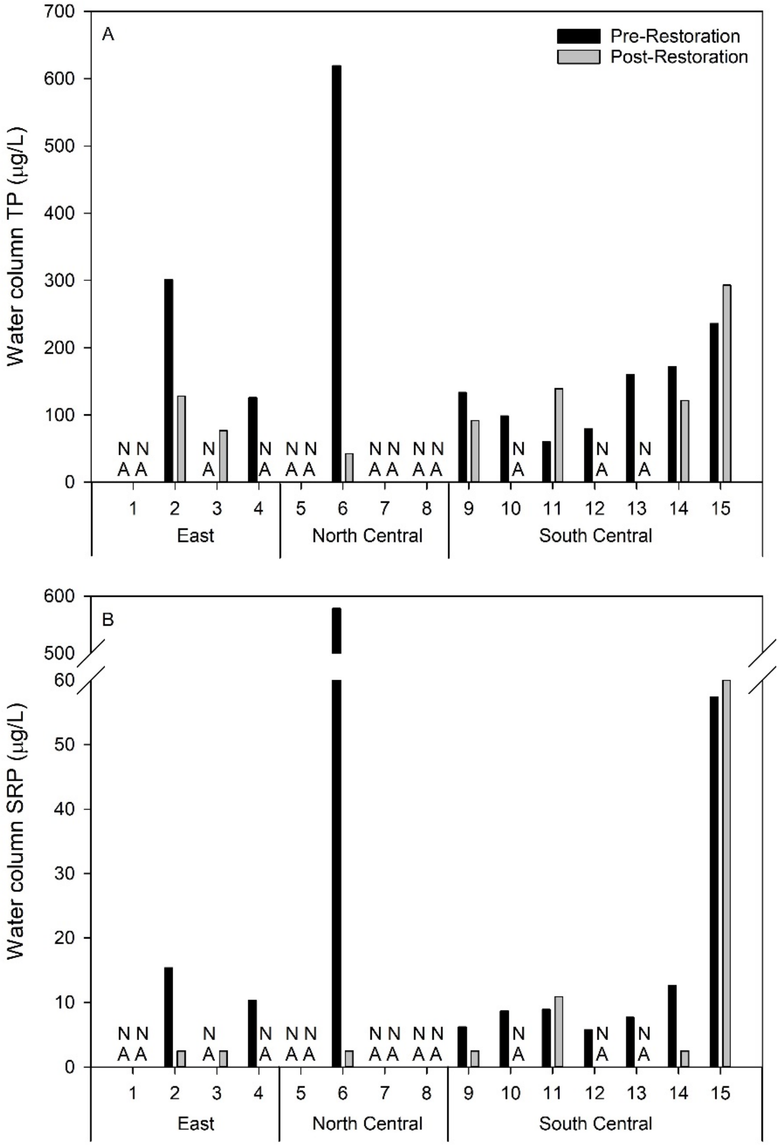

Figure 4. Water column total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations at each inundated site in the east, north central, and south central zones during pre- and post-restoration wetland monitoring. Numbers along x-axis refer to site # (refer to Fig. 3 for site locations). Sites marked NA (not applicable) were either dry or had insufficient water for collection and measurement. Note y-axis scales are different and panel B's y-axis has a break.

Table 3. Mean (±SD) sediment characteristics from pre- and post-restoration sediment cores respectively collected May 2016 and August 2021. Data at surface (0-10 cm) and bottom (20-30 cm) core depths are presented separately. TP = total phosphorus, OM = organic matter, EPC_0 = equilibrium phosphorus concentration, S_{max} = phosphorus sorption maximum. P-values represent results of comparing site core sediment parameters between restoration periods at each depth.

	Restoration	Depth	East (n=3)		North (n=3)		South (n=5)		All (n=11)	
			Mean (±SD)	test	Mean (±SD)	test	Mean (±SD)	test	Mean (±SD)	test
TP (mg/kg, dry wt.)	Pre	0-10 cm	2020 (937)	*P=0.077*	1977 (1176)	P=0.249	1539 (790)	**P=0.021**	1790 (853)	**P<0.001**
		20-30 cm	1402 (906)	P=0.148	1911 (582)	*P=0.082*	986 (472)	P=0.184	1352 (730)	**P=0.004**
	Post	0-10 cm	190 (116)		447 (533)		433 (480)		371 (414)	
		20-30 cm	268 (101)		174 (379)		464 (412)		331 (304)	
OM%	Pre	0-10 cm	43.6 (30.4)	P=0.132	29.3 (21.8)	P=0.170	32.9 (27.1)	**P=0.027**	34.8 (24.3)	**P<0.001**
		20-30 cm	25.6 (20.2)	P=0.197	31.1 (29.5)	P=0.176	18.8 (14.8)	P=0.551	24.0 (18.3)	**P=0.029**
	Post	0-10 cm	2.5 (1.6)		5.2 (1.4)		10.5 (16.9)		6.8 (11.4)	
		20-30 cm	2.1 (2.5)		2.4 (5.3)		13.1 (16.6)		7.2 (12.0)	
EPC_0 (µg/L)	Pre	0-10 cm	53 (45)	P=1.000	3972 (4176)	P=0.239	53 (80)	P=0.454	1122 (2560)	P=0.102
		20-30 cm	115 (90)	P=0.229	1374 (1350)	P=0.250	50 (65)	*P=0.062*	429 (787)	P=0.320
	Post	0-10 cm	42 (58)		478 (413)		20 (18)		151 (271)	
		20-30 cm	18 (22)		321 (289)		115 (95)		145 (186)	
S_{max} (mg/kg)	Pre	0-10 cm	793 (478)	*P=0.096*	669 (434)	P=0.295	1927 (1256)	**P=0.003**	1275 (1042)	**P<0.001**
		20-30 cm	1127 (626)	*P=0.098*	1019 (605)	*P=0.060*	2084 (516)	**P=0.034**	1533 (694)	**P<0.001**
	Post	0-10 cm	256 (167)		312 (165)		676 (870)		462 (599)	
		20-30 cm	296 (414)		143 (584)		1067 (1081)		604 (843)	

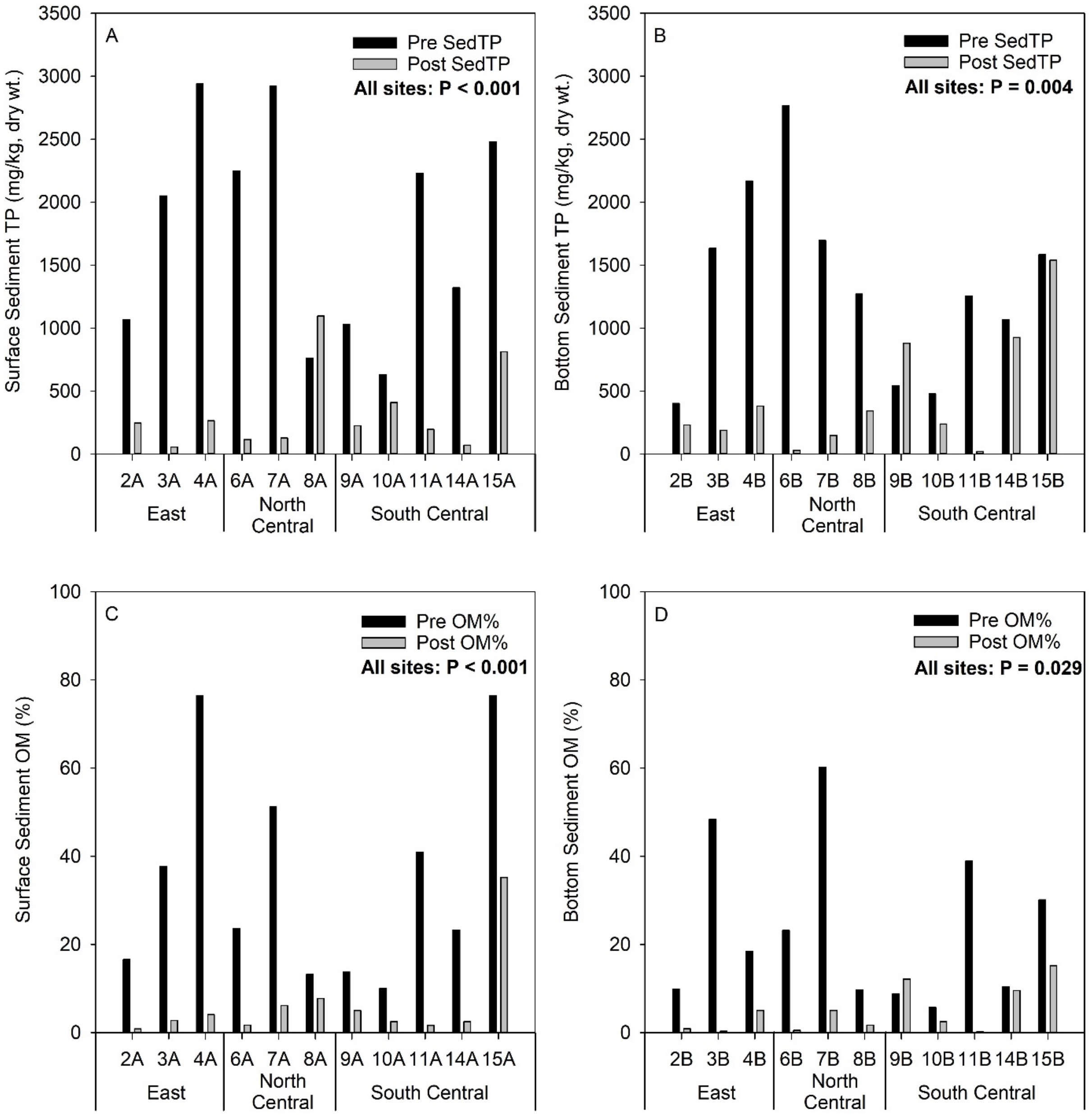

Figure 5. Pre- and post-restoration Sediment TP at surface (0-10 cm, A) and bottom depths (20-30 cm, B), and sediment organic matter at surface (C) and bottom depths (D) in the sediments of the east, north central, and south central areas of the wetland. P-values represent comparisons between restoration periods; see Table 3 for more details.

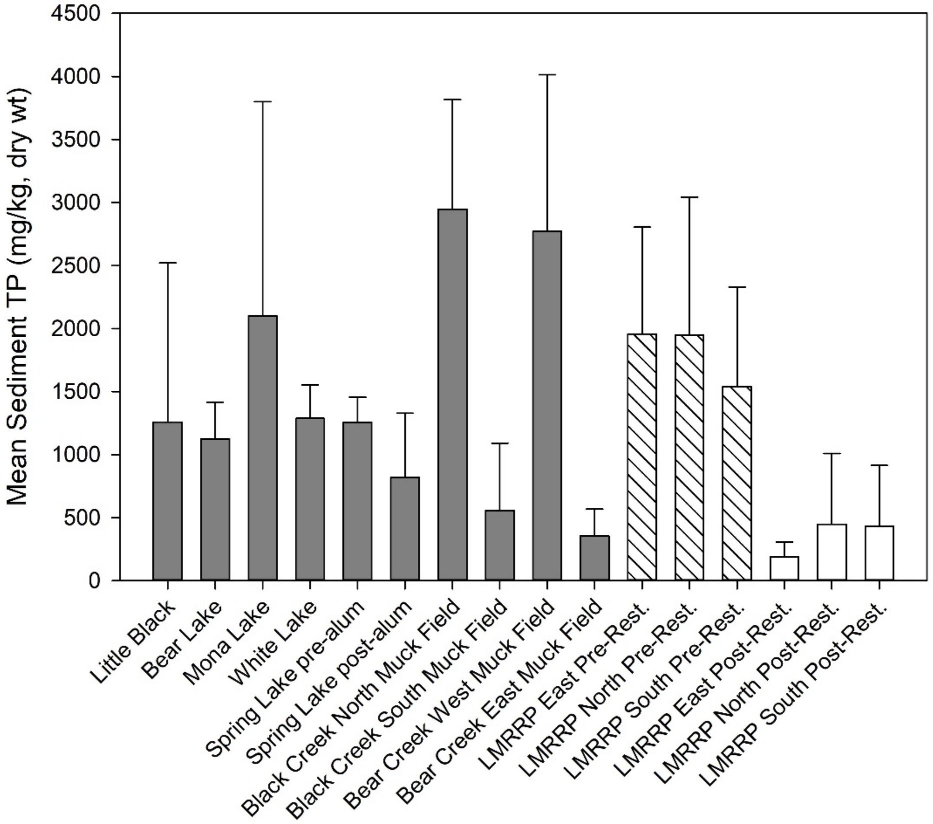

Figure 6. Comparison of mean (±SD) sediment TP measured in the LMRRP pre- and post-restoration wetland and other west Michigan waterbodies. LMRRP values include only surface sediment cores collected during isotherm sampling from both restoration periods. Sources: Little Black Lake: Steinman et al. 2011; Mona Lake: Steinman et al. 2009; White Lake: Steinman et al. 2008b; Spring Lake pre-alum: Steinman et al. 2004; Spring Lake post-alum: Steinman and Ogdahl 2008; Bear Lake: unpublished data; Black Creek muck fields: Steinman and Ogdahl 2011; Bear Creek: Steinman and Ogdahl 2013; LMRRP pre-restoration: Steinman et al. 2017a.

Summer 2021 – Post-Restoration P isotherms

Equilibrium phosphorus concentrations were highest in the drier northern sites and lowest in wetter eastern and southern sites - a trend previously seen during pre-restoration sampling in 2016 (Table 3, Fig. 7). Post-restoration EPC_0 values were generally greater than the SRP concentrations measured in the Muskegon River and any site water that was present during sampling (Fig. 7). These data indicate that sediments would likely serve as a P source to the overlying water column once inundated with Muskegon River water. Statistical testing showed no significant differences between pre- and post-restoration EPC_0 values, although means EPC_0 values tended to decline following restoration (Table 3), regardless of sediment depth.

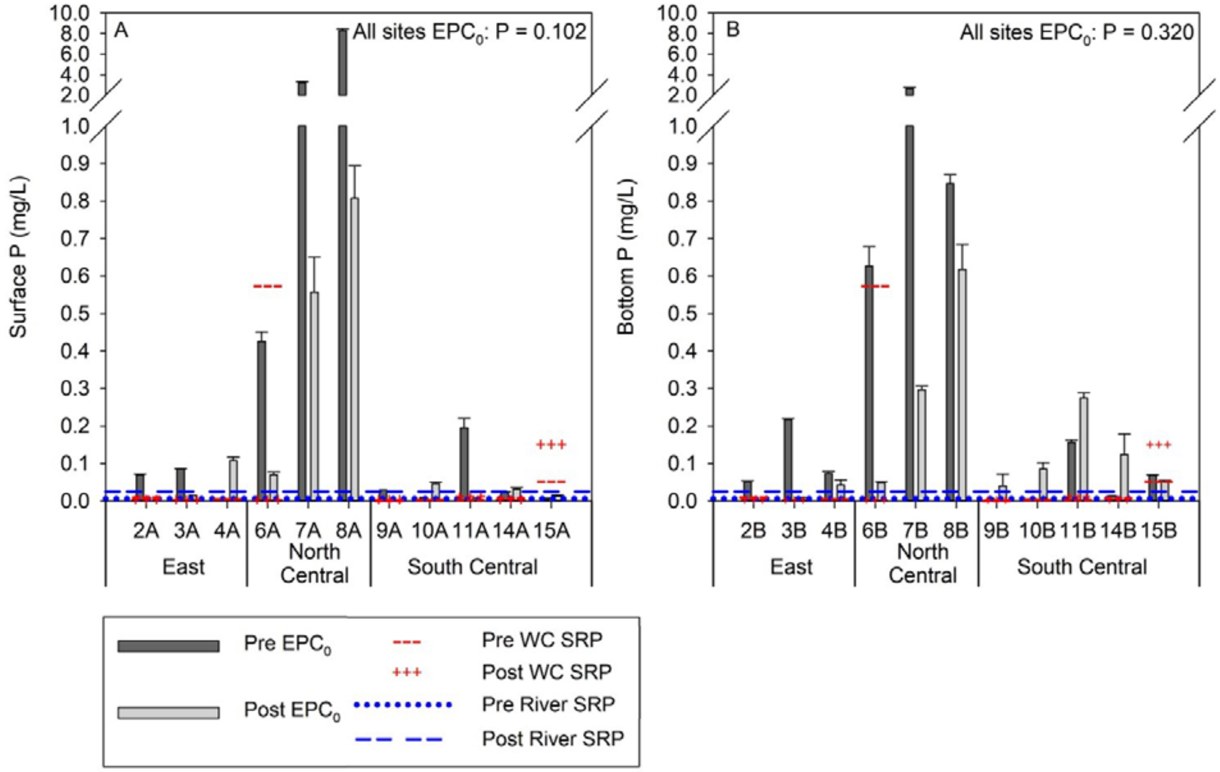

Figure 7. Mean (±SD) equilibrium P concentrations (EPC_0) in sediment cores at surface (A; 0-10 cm) and bottom depths (B; 20-30 cm). Water column SRP at inundated sites with sufficient water for collection is shown as red triple dashes (pre-restoration) and triple plus signs (post-restoration). Muskegon River SRP sampled adjacent to the wetland restoration area is shown as dotted (pre-restoration) and double-dash (post-restoration) blue horizontal reference lines. P-values represent comparisons across restoration periods; see Table 3 for more details.

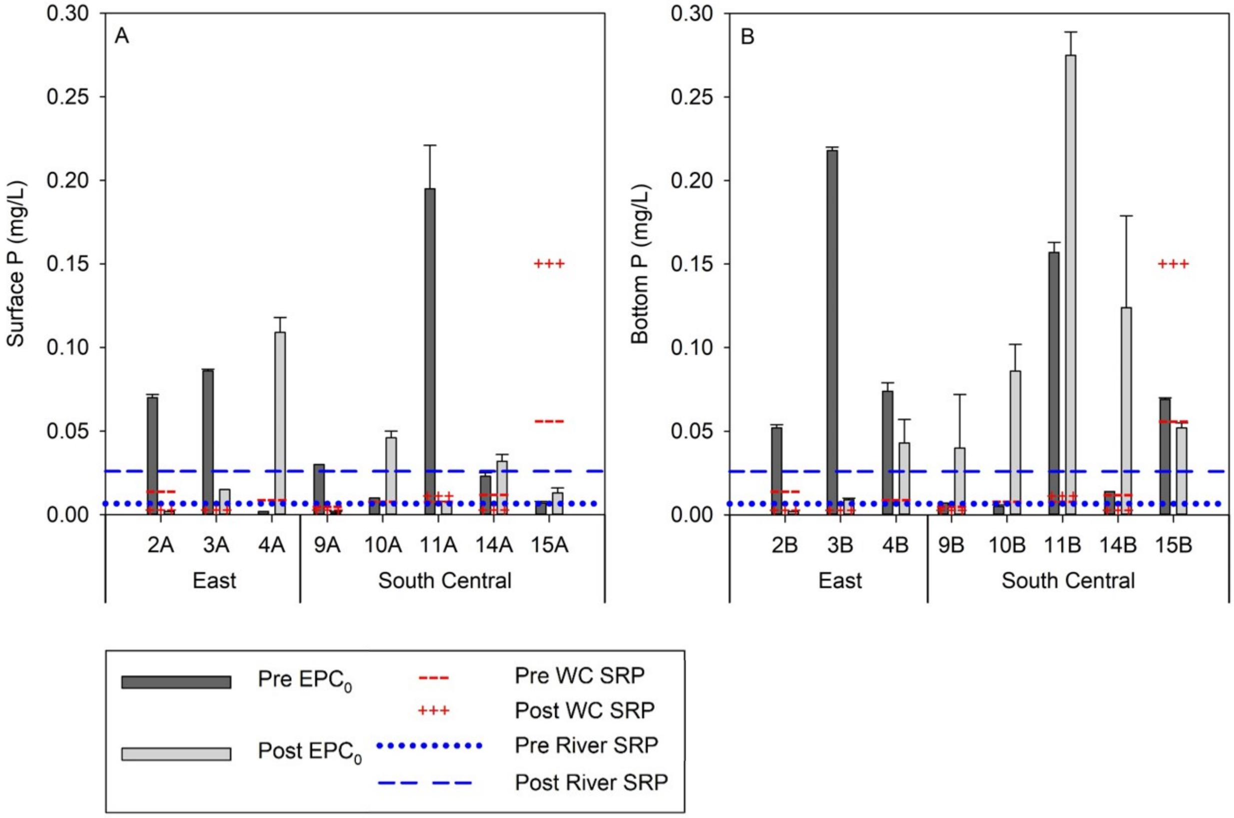

Figure 8. Additional detail of east and south central field mean (±SD) equilibrium P concentrations (EPC_0) at surface (A; 0-10 cm) and bottom depths (B; 20-30 cm). Water column SRP at inundated sites with sufficient water for collection is shown as red triple dashes (pre-restoration) and triple plus signs (post-restoration). Muskegon River SRP sampled adjacent to the wetland restoration area is shown as dotted (pre-restoration) and double-dash (post-restoration) blue horizontal reference lines. See Fig. 6 for comparison to the north central field.

Summer 2021 – Post-Restoration Sediment P fractionation

Sediment cores collected for fractionation occurred in July 2021, one month prior to isotherm coring in August 2021, and as a result, physicochemical conditions throughout the wetland were similar on both post-restoration sampling events (Tables 2, 4).

Sediment TP and OM values were variable among sites and regions (Table 5, Fig. 8). Post-restoration sediment TP ranged 55-2051 mg/kg dry wt, with the highest values of both parameters being seen at sites 7 and 15 (Table 5, Fig. 9A). Post-restoration OM ranged 0.9-46%, with site 15 having the highest concentrations (Table 5, Fig. 9B). Mean sediment TP and mean OM both significantly decreased compared to pre-restoration samples also collected for fractionation (Fig. 9).

Total sediment calcium and iron remain abundant at all sites, ranging from 580-30,000 mg/kg and 670-18,000 mg/kg, respectively (Fig. 10A,B). Manganese was found in lower concentrations than calcium and iron, ranging between 14-470 mg/kg (Fig. 9). Sediment metal concentrations varied spatially in the wetland and generally decreased compared to pre-restoration conditions, with the exception of notable increases at site 15 (Fig 10).

As previously seen during pre-restoration studies, P fractionation of the top 10 cm of sediment revealed that the loosely sorbed NH_4Cl-P fraction exists in minimal quantities (0-1 µg/g) throughout the wetland (Fig. 11). Post-restoration BD-P, NaOH-P, and HCl-P fractions each averaged 65-86 µg/g across the whole wetland (Fig. 11), with the BD-P fraction (Fe and Mn oxides and hydroxides) more dominant at the south-central sites (Fig. 11). Most sites experienced substantial reductions of each P fraction between restoration periods, but these reductions were smaller at sites 3 and 15 (Fig. 11).

Table 4. Mean (±SD) depth and general water quality variables of overlying water during sediment coring for P fractionation and the first pre-restoration drying-rewetting experiment in 2016 and the post-restoration experiment in 2021.

	East		North		South	
	Pre (n=1)	Post (n=1)	Pre (n=1)	Post (n=1)	Pre (n=2)	Post (n=5)
Water Depth (m)	0.44 (NA)	0.84 (NA)	0.41 (NA)	1.03 (NA)	0.74 (0.10)	41.7 (0.34)
Temp (°C)	17.66 (NA)	26.69 (NA)	16.85 (NA)	26.41 (NA)	18.02 (0.19)	27.2 (0.35)
DO (mg/L)	5.84 (NA)	7.99 (NA)	6.45 (NA)	9.27 (NA)	6.37 (0.83)	8.57 (0.49)
DO (%)	61.4 (NA)	100 (NA)	66.7 (NA)	115.4 (NA)	67.4 (8.6)	108.26 (6.74)
pH	7.75 (NA)	8.21 (NA)	8.14 (NA)	8.69 (NA)	8.19 (0.26)	8.5 (0.15)
SpCond (µS/cm)	590 (NA)	870 (NA)	841 (NA)	774 (NA)	634 (100)	818 (41)
TDS (mg/L)	384 (NA)	566 (NA)	547 (NA)	503 (NA)	412 (65)	532 (26)
Turbidity (NTU)	7.1 (NA)	2.3 (NA)	29.1 (NA)	8 (NA)	19.9 (3.1)	1.6 (1.6)

Table 5. Mean (±SD) sediment TP and organic matter (OM) in top 10 cm of cores collected for post-restoration P fractionation and the rewetting experiment in Summer 2021.

	East		North		South	
	Pre (n=4)	Post (n=4)	Pre (n=4)	Post (n=4)	Pre (n=7)	Post (n=7)
TP (mg/kg, dry wt)	825 (286)	781 (506)	1608 (652)	623 (955)	1200 (264)	583 (421)
OM (%)	15 (13)	10 (8)	23 (13)	3 (4)	22 (14)	10 (16)

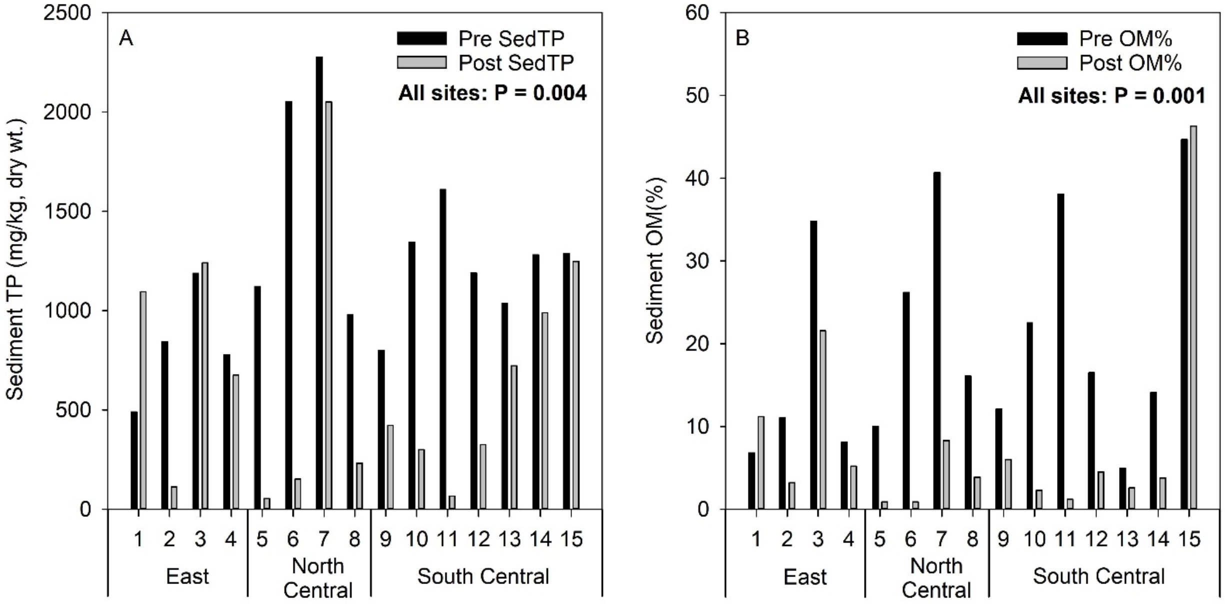

Figure 9. Pre- and post-restoration sediment TP (A) and organic matter (B) in cores collected for P fractionation and rewetting experiments in 2016 and 2021. P-values represent comparisons across restoration periods.

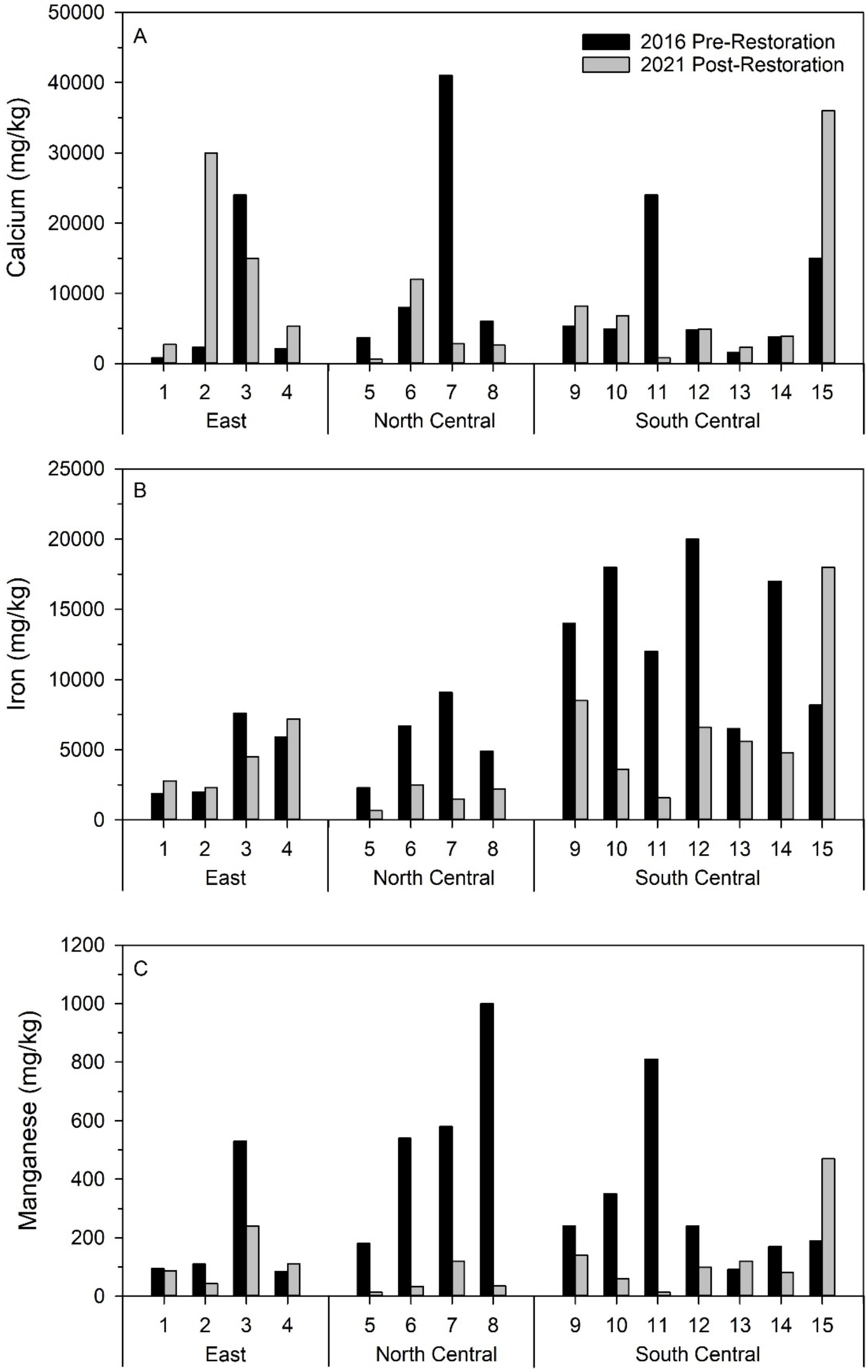

Figure 10. Sediment core concentrations of calcium (Ca), iron (Fe), and Manganese (Mn) from each pre-restoration (Summer 2016) and post-restoration (Summer 2021) wetland site. Note different scales for y-axes.

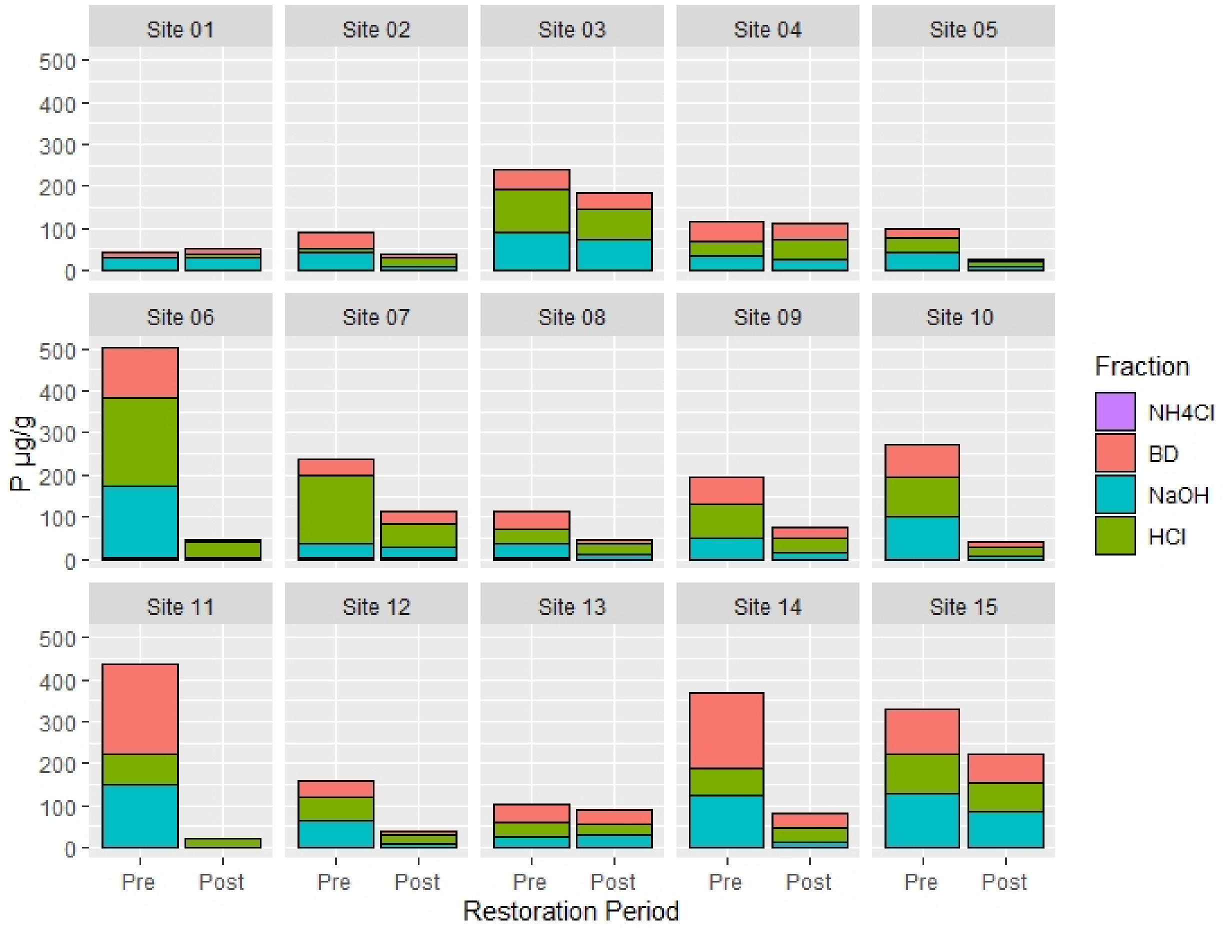

Figure 11. Sediment P fractions (top 0-10 cm) shown as stacked columns by site and by restoration period. Note that SRP concentrations from NH_4Cl (loosely sorbed P) are too small to appear in this figure.

Summer 2021 – Post-Restoration Sediment re-wetting experiment

P flux was analyzed for samples collected 24 hr and 48 hr after rewetting and compared to the SRP concentrations of filtered Muskegon River water, which is the new source of overlying water following restoration. Flux normalized by both sediment core area (Fig. 12) and by sediment organic matter (Fig. 13) showed reductions of 1-2 orders of magnitude between pre- and post-restoration studies. At some sites, the sediment served as a sink for P, reducing P concentrations in the water column, especially in the south-central region. Statistical analysis of mean flux between restoration period showed significant decreases at the 24 hr mark and strong decreases at the 48 hr mark for both methods for flux normalization (Figs. 14 and 15).

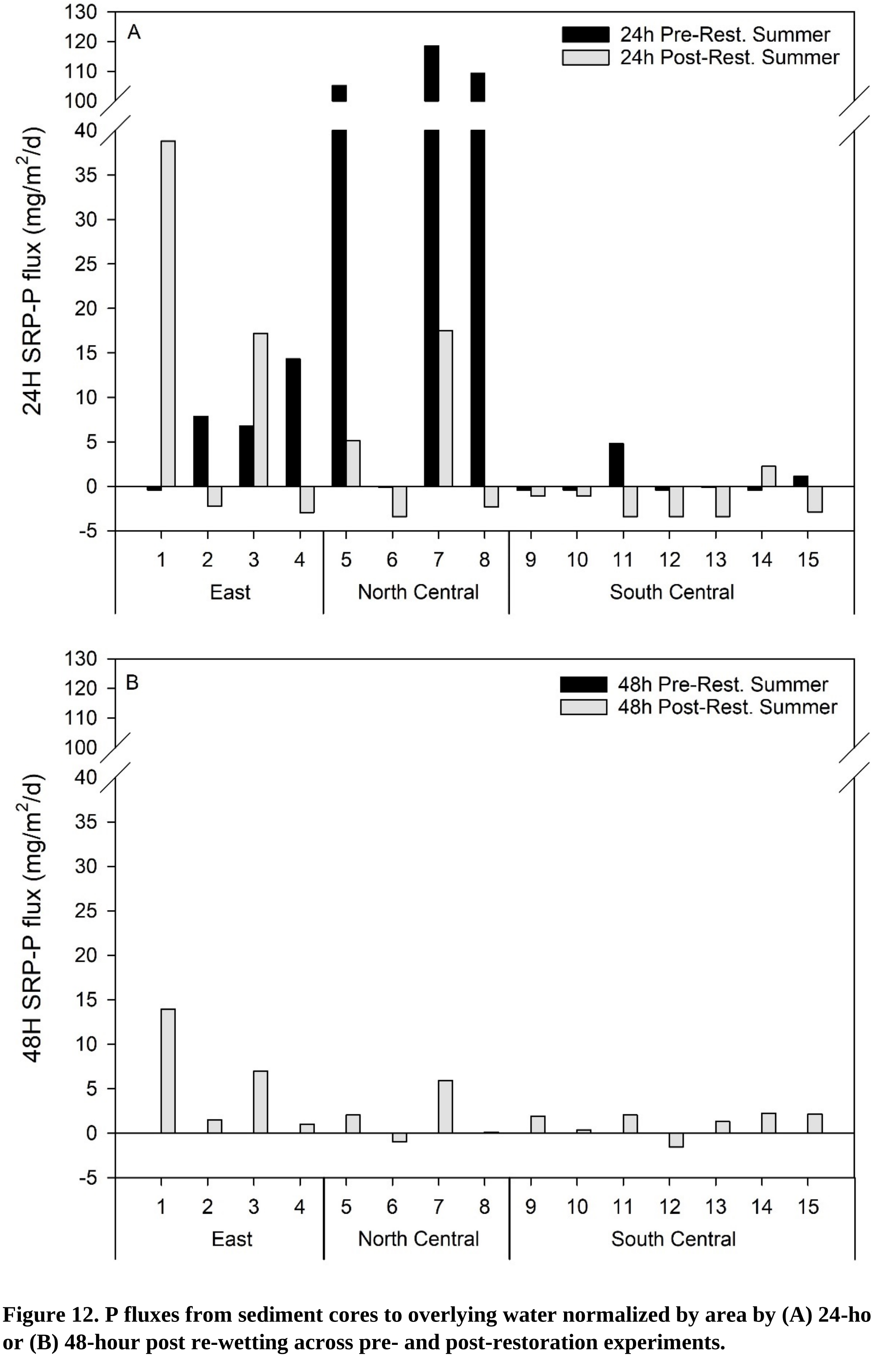

Figure 12. P fluxes from sediment cores to overlying water normalized by area by (A) 24-hour post-rewetting or (B) 48-hour post re-wetting across pre- and post-restoration experiments.

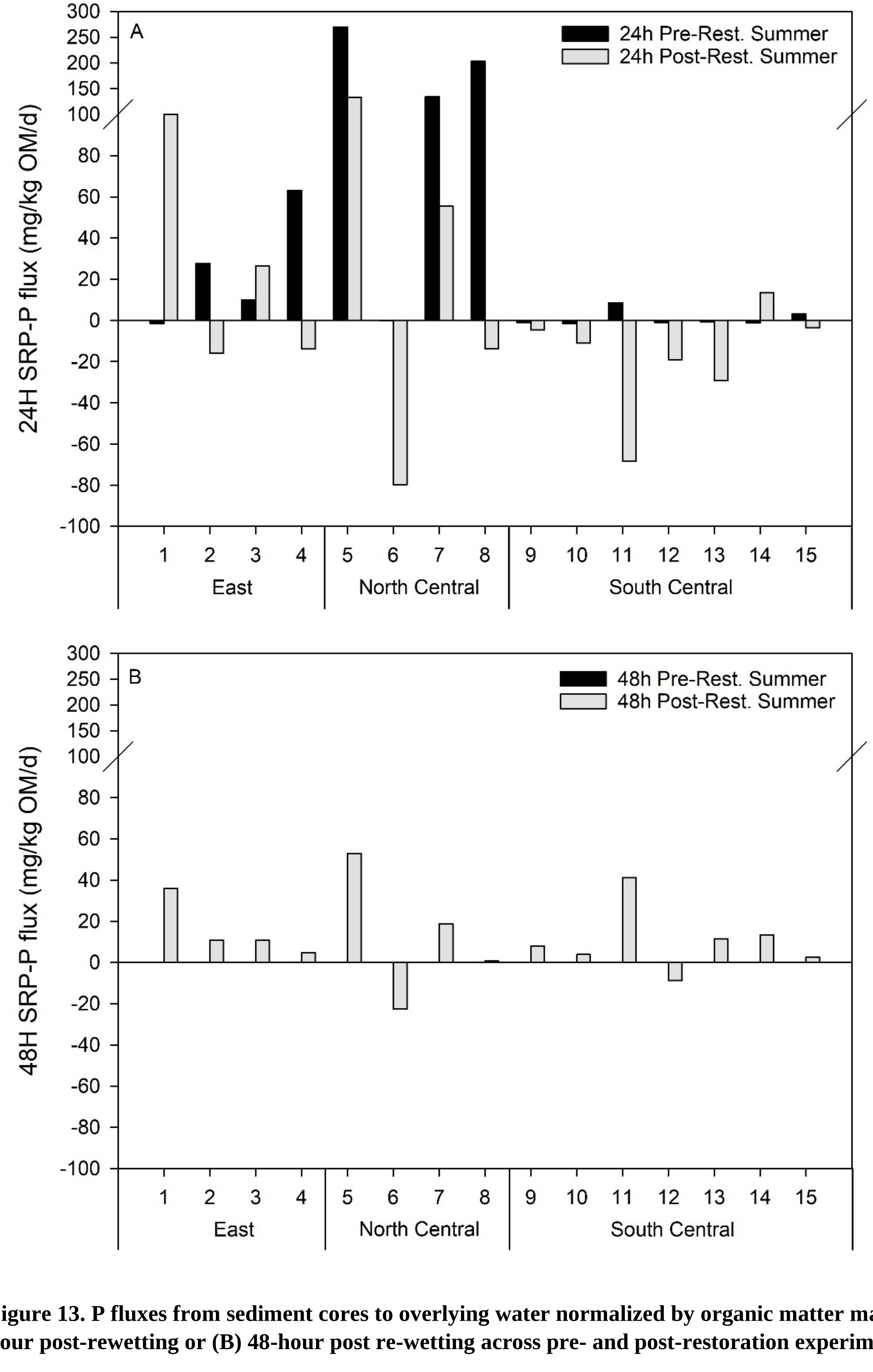

Figure 13. P fluxes from sediment cores to overlying water normalized by organic matter mass by (A) 24-hour post-rewetting or (B) 48-hour post re-wetting across pre- and post-restoration experiments.

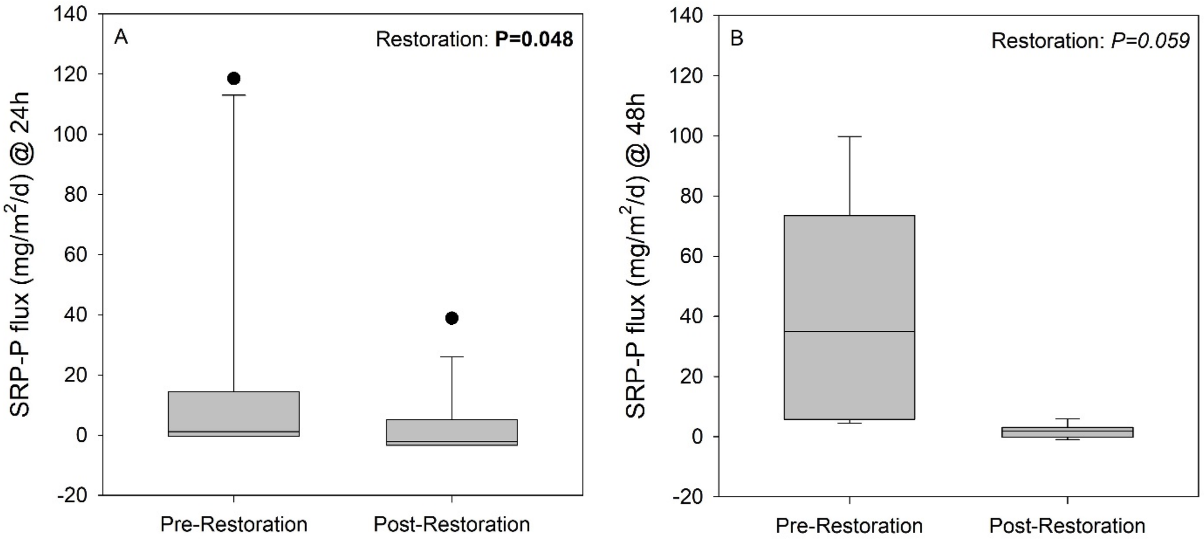

Figure 14. P fluxes, normalized by area, from sediments to overlying water at (A) 24 hours and (B) 48 hours after re-wetting during 2016 pre-restoration and 2021 post-restoration experiments. P-values are results of paired t-tests comparing fluxes in an equal number of sites per restoration period (24h n=15; 48h n=6).

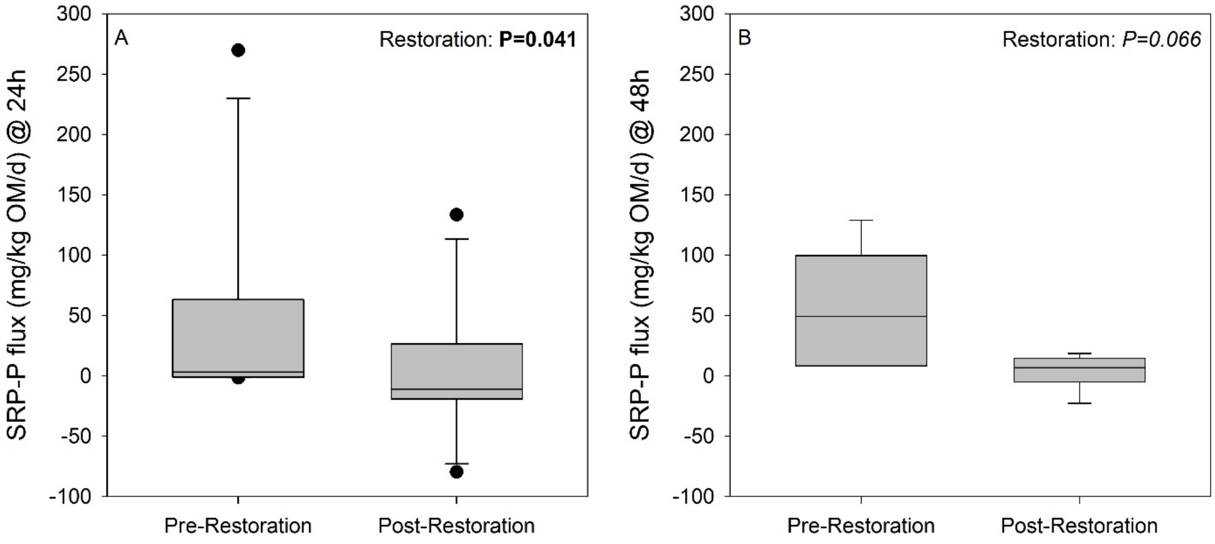

Figure 15. P fluxes, normalized by organic matter, from sediments to overlying water at (A) 24 hours and (B) 48 hours after re-wetting during 2016 pre-restoration and 2021 post-restoration experiments. P-values are results of paired t-tests comparing fluxes in an equal number of sites per restoration period (24h n=15; 48h n=6).

GIS interpolation of SRP flux from individual sites to the entire restoration wetland property provides dramatic visual differences when overlaid on maps. Pre-restoration maps indicated the presence of exceedingly high SRP release flux in the dry and upland northern area of the property (Fig. 16). These SRP hotspots are eliminated from this area in the post-restoration map at 24 hr after rewetting; however, a new SRP flux hotspot appeared in the eastern area (Fig. 17). After another day at 48 hours post-rewetting, flux decreased at this new hotspot and most of the post-restoration wetland sites experienced P flux at ~2 orders of magnitude smaller than were seen in the pre-restoration experiment (Fig. 18).

Major cation and anion concentrations in water samples are presented in the Appendix (Appendix Tables 1-10 and Appendix Figures 1-9). During the experiment, rhizons clogged during sampling and produced insufficient volume to analyze all parameters at every depth and core. In general, pre- and post-restoration ion concentrations in the porewater were elevated compared to the Muskegon River. High spatial variability was observed, with some evidence of likely historical pollution legacies that could be attributable to brines from petroleum wells (e.g., chloride and bromide: Appendix Figures 5-6). Sulfate also was elevated in porewaters and increased after restoration construction (Appendix Table 5, Appendix Figure 8).

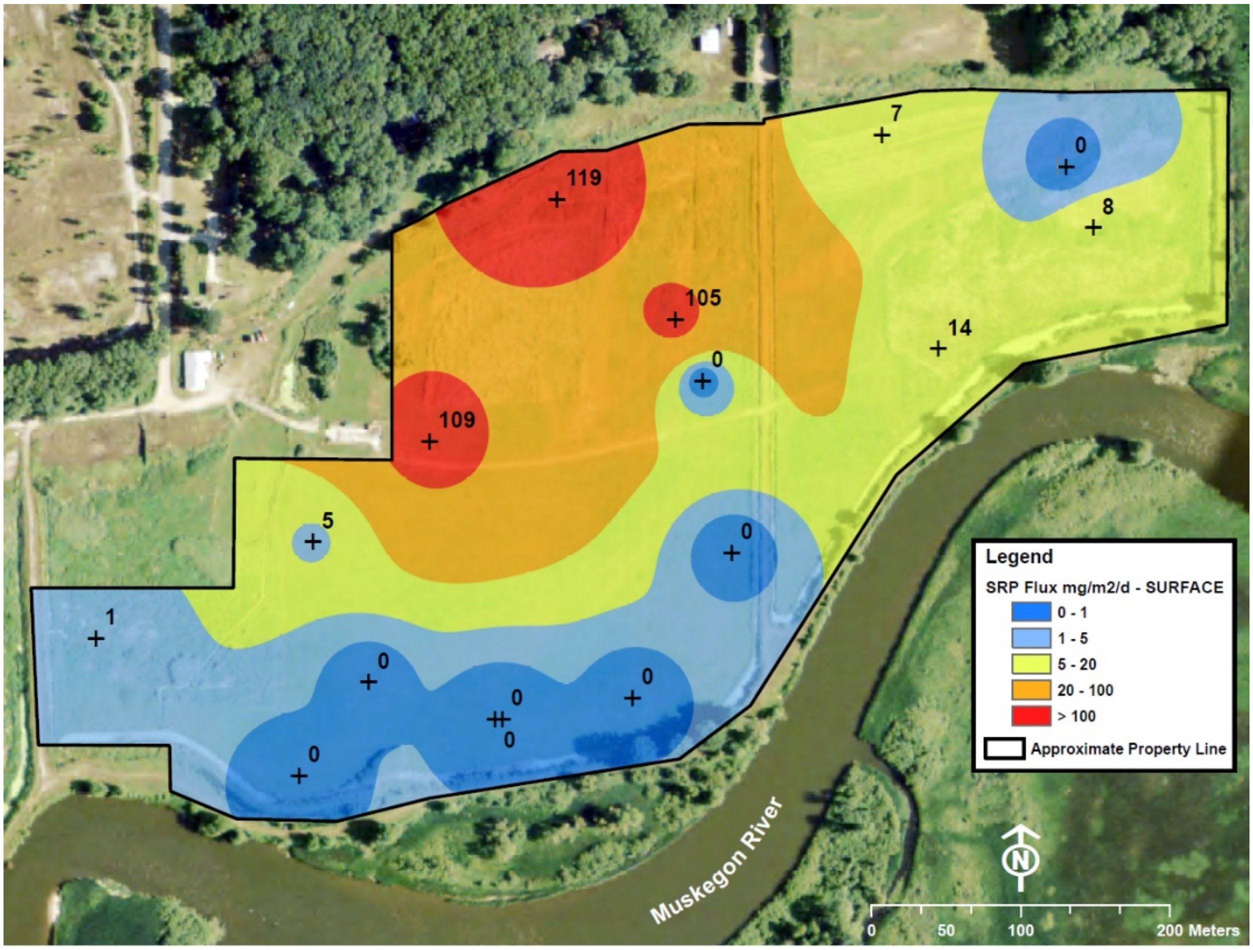

Figure 16. Map of 2016 pre-restoration water column SRP flux at 24 hours after core re-wetting, calculated using the Inverse Distance Weight interpolation method in ArcGIS 10.7.

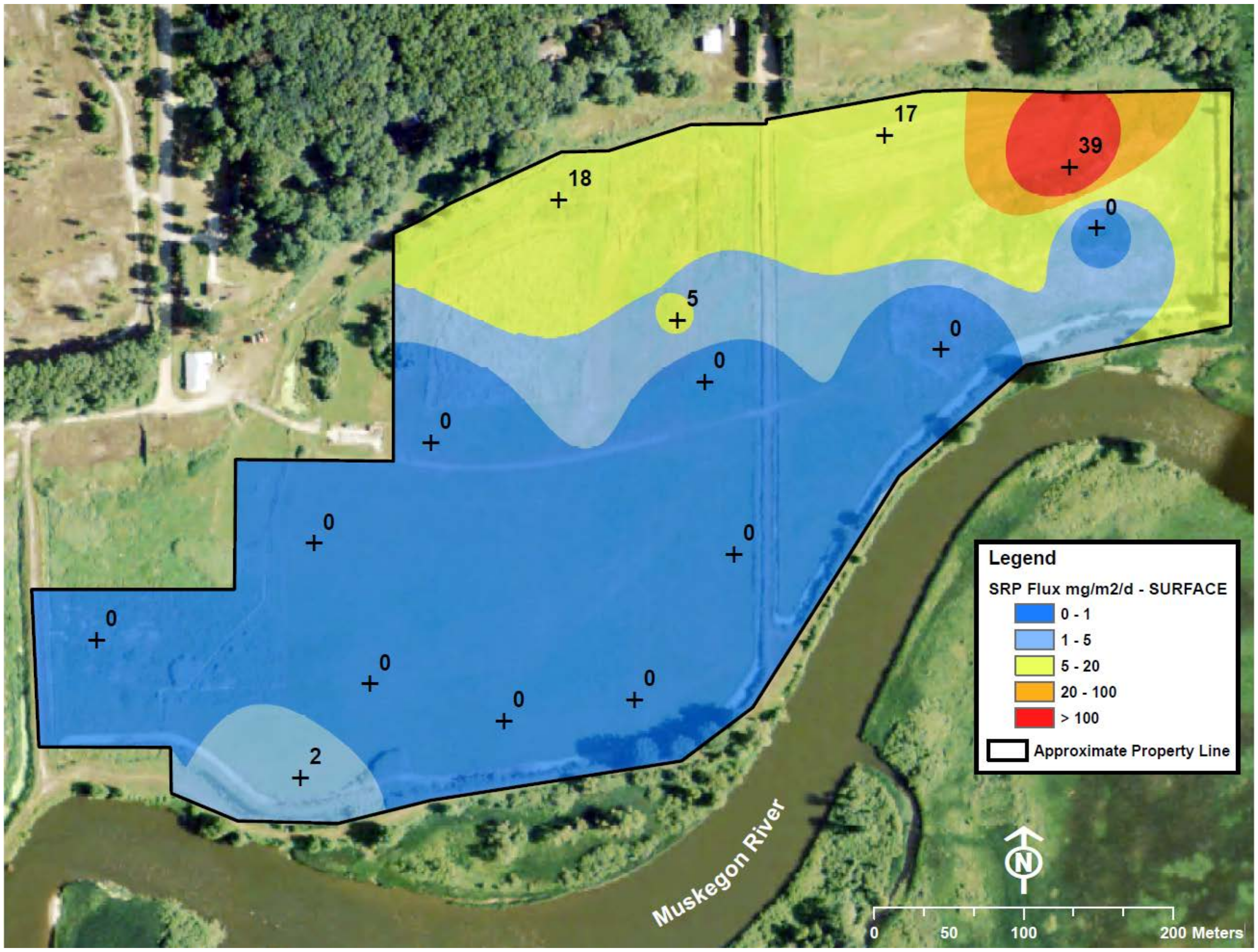

Figure 17. Map of 2021 post-restoration water column SRP flux at 24 hours after core re-wetting, calculated using the Inverse Distance Weight interpolation method in ArcGIS 10.7.

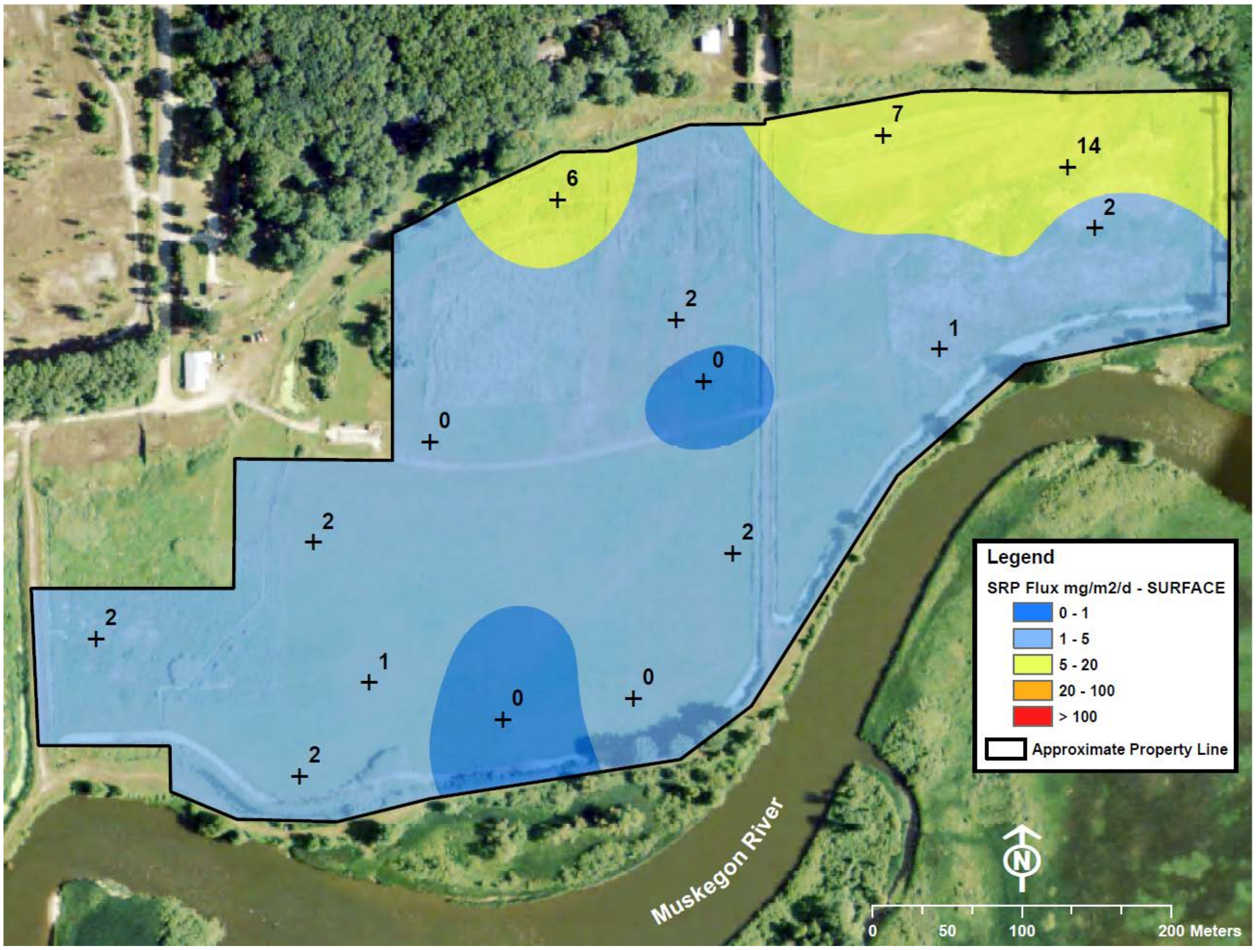

Figure 18. Map of 2021 post-restoration water column SRP flux at 48 hours after core re-wetting, calculated using the Inverse Distance Weight interpolation method in ArcGIS 10.7

Discussion

The Muskegon Lake Area of Concern, when first listed, suffered from nine beneficial use impairments (BUIs), with one of the most significant being loss of fish and wildlife habitat. A number of significant habitat restoration projects have taken place over time to address this BUI; completion of the final project, the Lower Muskegon River Reconnection Project, meets the habitat restoration target. The restoration site, which sits adjacent to the Muskegon River, provides valuable floodplain habitat, but also presented complications due to its prior use as a celery farm. Hence, a series of studies were conducted pre- and post-restoration to assess the site's ability to release or retain phosphorus, as downstream Muskegon Lake has another BUI focused on eutrophication and nuisance algae. Although TP concentrations in Muskegon Lake have declined dramatically since the rerouting of wastewater to the Muskegon County Wastewater Treatment Plant (Steinman et al. 2008a), both TP and chlorophyll *a* concentrations remain close to their restoration targets. Hence, it was essential that this habitat restoration project did not result in additional eutrophication of the lake.

It is well-recognized that reconverting agricultural lands to functional wetlands can restore critical ecosystem services, such as nutrient retention, contaminant filtration, and fish and wildlife habitat (An and Verhoeven 2019). However, legacy phosphorus held in soils (cf. Ardón et al. 2010; Steinman and Ogdahl 2011; Jarvie et al. 2013; Sharpley et al. 2013; Chen et al. 2018; Montgomery et al. 2021) can complicate restoration activities, as reflooding of drained, P-rich soils can mobilize phosphorus (Baldwin 1996; Pant and Reddy, 2003; Kinsman-Costello et al. 2014; Steinman and Ogdahl 2016; Montgomery et al. 2021).

The pre-restoration studies indicated there is considerable spatial variation in the P concentrations and dynamics of the sediment in the restoration footprint (Steinman et al. 2017a). The sampling sites in the north-central region generally had much higher sediment TP concentrations and P release rates (first release experiment) compared to the other regions, presumably because prior land use, with greater application of fertilizer in this more upland area, and the tendency to be more desiccated than the other regions. Prior studies have shown that exposed sediments release more phosphorus after inundation than sediments that remain inundated (DeBusk and Reddy 2003; Schönbrunner et al. 2012; Steinman et al. 2012). We also detected dissolved Fe(II) and sulfate in most sediment porewater samples, suggesting: (1) Fe oxyhydroxides could be important in P binding under oxidized conditions but would tend to release P under reducing conditions (i.e., reflooding), and (2) sulfate in the sediment porewaters would support bacterial sulfate reduction once iron reduction becomes limited by the availability of Fe oxyhydroxides, and the resultant sulfide could tie up Fe that would otherwise bind P, releasing the P into solution (Burgin et al. 2011).

For the post-restoration analyses, we resampled to the best of our ability a subset of the pre-restoration sites for phosphorus concentrations in the sediment and water, as well as P isotherms, release rates, and sediment fractions, and compared them with pre-restoration data to assess restoration effectiveness.

The post-restoration water quality data showed variation across the project footprint. This is not surprising given past land use at this site, where soil nutrient concentrations will vary based on both natural and anthropogenic sources, and this is consistent with similar studies (Steinman and Ogdahl 2011; Montgomery et al. 2021; Wiegman et al. 2022). Only a limited number of sites had sufficient standing water to compare water quality pre- and post-restoration but based on the data we did have, it is clear that phosphorus concentrations declined substantially at the east and north sites (Table 2); however, both SRP and TP increased in the overlying water at sites 15 (especially) and 11 in the south area (closest to the River). This increase may be related to several factors, including prior land use, enhanced exchange with

Muskegon River water, which had relatively high SRP (26 ppb) and TP (49 ppb) concentrations, following berm removal; and potentially high P concentrations in the fill material, as this site was within the fill zone (see Appendix Fig. 10) as part of the sculpting of the project footprint. Prior land use is the most likely reason for the increase as fill material (based on limited samples) had relatively low P concentrations and the other sites in the south, which experienced P declines (Fig. 4), were closer to the River.

Other changes in water quality included an increase in DO at the north and south sites, an increase in pH at all sites, and a decline in turbidity at all sites. It is impossible to identify the specific mechanism behind these changes, as the influence of hydrologic exchange with the Muskegon River is conflated with the impacts of excavation or fill. A prior study involving excavation to improve water quality at nearby Bear Lake revealed a significant reduction in phosphorus concentration and release rates and was attributed to the removal of P-laden sediment (Hassett and Steinman in press).

While the impact of restoration on water column P was variable but generally favorable, the effect on sediment P and percent organic matter was quite clear and consistent: both sediment TP and OM% declined significantly across the project footprint (Table 3). The removal of P-laden sediment is an expensive but effective method to reduce P concentrations, as evidenced in this study as well as others (Oldenborg and Steinman 2019; Zhu et al. 2022).

The isotherm results showed variable responses across the project area, consistent with the pre-restoration isotherm results (Figs. 7, 8). Although the EPC values declined at all the north central sites, the values were still well above the ambient SRP concentration in River water, suggesting the sediments in this region will serve as a source of P to the wetland's overlying water column. However, the sediment sorption maxima (S_{max}), at both the surface and bottom of each core in this region, remained below the ambient sediment TP concentration after restoration (Table 3), suggesting there was still potential for additional sorption. In addition, the post-restoration P fractionation results at sites 5-8 in the north central region are dominated by stable P fractions (Fig. 11). These latter two reasons may account for the low P concentrations in the overlying water column in the north central region despite EPC values suggesting P release potential.

The P release experiment also revealed variability across the project footprint, and even within a specific region (Fig. 12). The very high pre-restoration P release rates at sites 5, 7, and 8 declined substantially following restoration, which helps reduce the potential for future internal P loading. As with the other data, the extreme variation in P release rates could be a function of the sculpting design for restoration or prior land use. As expected, P release rates declined at most sites with the removal of P-rich sediment (cf. Oldenborg and Steinman 2019). However, sites 1 and 3 (east region) had significant increases in P release. These sites are in areas that were filled, so again it is possible the fill material had highly labile P, which was susceptible to release. There was a substantial decline in release rates between 24 and 48 hr (Fig. 12), which is likely due to a reduced P concentration gradient over time. Overall, post-restoration P release rates are more in line with literature values from mesotrophic to eutrophic systems (Nürnberg and LaZerte 2004), as opposed to the very high, short-term rates measured before restoration began.

Based on the results from the pre-restoration analyses, we generated a rough estimate that this 53-acre site accounted for approximately 2-4% of the total Muskegon River SRP load (Steinman et al. 2017a). This modest load is undoubtedly even lower following restoration, as indicated by our data. Of course, there are still likely hot spots within the project footprint, even after restoration, likely due to prior land use (e.g., fertilizer storage area) or restoration design. However, these should have minimal ecosystem-level impacts.

Conclusions

Restoration of the LMRRP resulted in an overall reduction of P both in the sediments and overlying water column, as well as in P release rates. These reductions were not universal across the project footprint, however. This variability may be due to prior land use, restoration design (excavation vs. fill areas), and/or natural differences in lithology (i.e., locations close to the river vs. uplands). Regardless of the mechanism(s) at work, it is clear from our data and prior calculations, this site is a very small contributor of phosphorus to Muskegon Lake, and likely serves as a sink in certain areas.

Excavation of P-rich sediment is an effective, albeit expensive, approach to control P release from sediments (Huser et al. 2020). In the case of the LMRRP, excavation has effectively removed a substantial amount of P, and in the process, left behind a benthic canvas to be sculpted to create new and more ecologically desirable habitat for this floodplain system. It will take several years before the system reaches some type of nutrient and biodiversity quasi-equilibrium, so we recommend occasional monitoring of water quality to ensure it is meeting restoration targets.

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Supplemental Table 1. Post-restoration July 2021 sediment core characterization sample summary. Sediment total phosphorus (TP), organic matter (OM) and water column soluble reactive phosphorus (SRP) were each sampled once per site. Equilibrium phosphorus concentration (EPC_0) and P sorption maximum (S_{max}) were each subsampled and measured three times (three replicates) from site sediment cores. Water column SRP at sites that were dry or had insufficient standing water to collect and measure are marked NA (not available). Likely outliers were removed from this summary and are marked ND (no data). The first row of each core depth is highlighted gray to improve readability.

Site	Depth, cm	Replicate	Sediment TP (dry), mg/kg	Sediment OM, %	EPC$_0$, mg/L	S$_{max}$, mg/kg	Water column SRP, mg/L
2	surface (0-10)	L1	247	1%	0.002	230	0.003
		L2			0.002	154	
		L3			0.002	194	
	bottom (20-30)	L1	233	1%	0.002	52	0.003
		L2			ND	ND	
		L3			0.002	82	
3	surface (0-10)	L1	56	3%	ND	ND	0.003
		L2			0.015	385	
		L3			0.016	506	
	bottom (20-30)	L1	189	0%	0.009	86	0.003
		L2			0.007	38	
		L3			0.010	19	
4	surface (0-10)	L1	266	4%	0.104	154	NA
		L2			0.119	117	
		L3			0.103	117	
	bottom (20-30)	L1	383	5%	0.050	691	NA
		L2			0.027	961	
		L3			0.053	669	
6	surface (0-10)	L1	116	2%	0.060	99	0.003
		L2			0.075	183	
		L3			0.075	168	
	bottom (20-30)	L1	29	0%	0.045	11	0.003
		L2			0.052	11	
		L3			0.046	10	
7	surface (0-10)	L1	128	6%	0.483	225	NA
		L2			0.527	201	
		L3			0.662	283	
	bottom (20-30)	L1	149	5%	0.297	457	NA
		L2			0.288	413	
		L3			0.308	335	
8	surface (0-10)	L1	1096	8%	0.904	583	NA
		L2			0.782	542	
		L3			0.736	519	
	bottom (20-30)	L1	344	2%	0.695	11	NA
		L2			0.583	23	
		L3			0.573	14	

9	surface (0-10)	L1	226	5%	0.001	556	0.003
		L2			0.000	490	
		L3			0.002	417	
	bottom (20-30)	L1	880	12%	0.052	1190	0.003
		L2			0.065	1177	
		L3			0.005	1123	
10	surface (0-10)	L1	410	3%	0.050	168	NA
		L2			0.044	118	
		L3			0.043	128	
	bottom (20-30)	L1	239	2%	0.100	272	NA
		L2			0.069	282	
		L3			0.090	83	
11	surface (0-10)	L1	196	2%	0.008	78	0.011
		L2			0.007	281	
		L3			0.008	247	
	bottom (20-30)	L1	21	0%	0.275	11	0.011
		L2			0.289	6	
		L3			0.260	4	
14	surface (0-10)	L1	72	2%	0.034	261	0.003
		L2			0.028	378	
		L3			0.033	374	
	bottom (20-30)	L1	927	9%	0.078	1293	0.003
		L2			0.109	1216	
		L3			0.186	1124	
15	surface (0-10)	L1	1264	41%	0.016	2228	0.150
		L2			0.014	2237	
		L3			0.010	2174	
	bottom (20-30)	L1	252	42%	0.049	2511	0.150
		L2			0.052	2898	
		L3			0.055	2807	

Appendix

Ion Chromatography Table of contents:

- Table 1 - cations, all sites, overlying water
- Table 2 - cations, means, overlying water
- Table 3 - cations, all sites, rhizon water
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- Table 10 - iron, means, rhizon water
- Figs. 1-4 – cations (Na^+, K^+, Mg^{2+}, Ca^{2+}), river, overlying and rhizon water
- Figs. 5-8 – anions (Cl^-, Br^-, NO_3^--N, SO_4^{2-}), river, overlying and rhizon water
- Fig. 9 – dissolved Fe(II), means, rhizon and overlying water

Appendix Table 1. Concentrations (mg/L) of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in overlying surface water collected from sediment cores during pre- and post-restoration rewetting experiments and the filtered Muskegon River water used during rewetting.

	Sodium			Potassium			Magnesium			Calcium		
	Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
Muskegon River	19	15		1.4	1.6		15	15		47	46	
1	25	26	19	1.4	4.4	2.8	10	24	17	27	82	55
2	25	22	17	2.1	1.8	1.6	17	19	16	53	66	52
3	27	22	17	1.9	1.8	1.5	16	17	15	57	57	51
4	29	16	15	4.0	2.6	1.9	19	17	16	59	51	49
5	17	19	15	2.8	2.0	1.6	10	17	16	36	67	52
6	28	27	19	1.3	2.6	1.9	17	22	18	56	83	68
7	18	15	15	19.5	2.2	1.7	10	14	14	39	44	44
8	17	16	15	10.0	2.1	1.7	7	17	16	32	59	51
9	30	23	18	2.1	2.1	1.8	20	21	18	59	69	57
10	33	15	15	1.6	1.7	1.5	15	21	17	50	57	49
11	29	29	16	2.1	6.2	2.4	18	26	18	61	81	68
12	28	17	16	1.5	1.7	1.5	17	21	18	56	67	53
13	30	24	18	2.8	3.0	2.1	18	22	17	58	77	58
14	29	22	18	2.4	2.3	1.9	17	20	18	58	64	52
15	21	55	38	1.4	9.6	5.9	17	58	39	66	310	220

Appendix Table 2. Mean (±SD) concentrations (mg/L) of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in overlying surface water collected from sediment cores during pre- and post-restoration rewetting experiments and the filtered Muskegon River water used during rewetting. NA= not applicable.

	Sodium			Potassium			Magnesium			Calcium		
	Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
River (n=1)	19 (NA)	15 (NA)		1 (NA)	1.6 (NA)		15 (NA)	15 (NA)		47 (NA)	46 (NA)	
East (n=4)	26 (2)	21 (4)	17 (1)	2.3 (1.1)	2.6 (1.2)	1.9 (0.5)	15 (3)	19 (3)	16 (0)	48 (15)	64 (13)	51 (2)
North (n=4)	19 (5)	19 (5)	16 (2)	8.4 (8.3)	2.2 (0.2)	1.7 (0.1)	10 (4)	17 (3)	16 (1)	40 (10)	63 (16)	53 (10)
South (n=7)	28 (3)	26 (13)	19 (8)	1.9 (0.5)	3.8 (3)	2.4 (1.5)	17 (1)	27 (13)	20 (8)	58 (4)	103 (91)	79 (62)

Appendix Table 3. Concentrations (mg/L) of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in surface and bottom porewater collected via rhizon from sediment cores during pre- and post-restoration rewetting experiments. Rhizons produced insufficient sample volume for all analyses; samples that could not be analyzed are left blank to improve readability.

		Sodium			Potassium			Magnesium			Calcium		
		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	Depth	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
1	surface	27			2.0			3			7		
	bottom	50			3.8			2			6		
2	surface	43	32		3.9	2.8		18	28		61	100	
	bottom	45			6.4			16			42		
3	surface	56	60		3.2	2.5		14	25		71	110	
	bottom	105			3.3			27			146		
4	surface	51			11.0			20			61		
	bottom	62			19.5			15			43		
5	surface		30			3.3			13			76	
	bottom	19		49	2.6		4.5	9		12	62		87
6	surface	66	50		4.1	5.5		11	63		59	230	
	bottom	73			2.0			15			73		
7	surface	19			34.6			7			36		
	bottom	22		20	84.9		6.0	17		25	108		100
8	surface	18	16		6.8	3.1		5	18		29	71	
	bottom	19			4.9			7			42		
9	surface	53			4.7			24			63		
	bottom	48			8.9			30			69		
10	surface	42	28	15	1.5	4.9	2.9	12	87	28	41	190	61
	bottom	40		38	1.5		5.6	13		150	45		300
11	surface	59		17	3.3		4.9	18		24	86		140
	bottom	55		56	3.3		26.0	18		69	96		400
12	surface	52	42		2.0	5.8		15	89		56	280	
	bottom	52		53	2.5		7.3	14		220	54		550
13	surface	68	50		8.3	8.6		11	43		49	150	
	bottom	45			7.8			13			50		

14	surface	46	6.4	13	54
	bottom	42	7.6	14	54
15	surface	35	0.2	25	147
	bottom	33	0.4	26	133

Appendix Table 4. Mean (±SD) concentrations (mg/L) of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) cations in surface and bottom porewater collected via rhizon from sediment cores during pre- and post-restoration rewetting experiments. ND = no data; NA= not applicable.

		Sodium			Potassium			Magnesium			Calcium		
		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	Depth	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
East (n≤4)	surface	44 (12)	46 (19)	ND (NA)	5 (4)	2 (0)	ND (NA)	13 (7)	26 (2)	ND (NA)	50 (28)	105 (7)	ND (NA)
	bottom	65 (27)	ND (NA)	ND (NA)	8 (7)	ND (NA)	ND (NA)	14 (10)	ND (NA)	ND (NA)	59 (60)	ND (NA)	ND (NA)
North (n≤4)	surface	34 (27)	32 (17)	ND (NA)	15 (16)	3 (1)	ND (NA)	7 (2)	31 (27)	ND (NA)	41 (15)	125 (90)	ND (NA)
	bottom	33 (26)	ND (NA)	34 (20)	23 (40)	ND (NA)	5 (1)	11 (4)	ND (NA)	18 (9)	71 (27)	ND (NA)	93 (9)
South (n≤7)	surface	50 (10)	40 (11)	16 (1)	3 (2)	6 (1)	3 (1)	17 (5)	73 (26)	26 (2)	70 (36)	206 (66)	100 (55)
	bottom	45 (7)	ND (NA)	49 (9)	4 (3)	ND (NA)	12 (11)	18 (6)	ND (NA)	146 (75)	71 (32)	ND (NA)	416 (125)

Appendix Table 5. Concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate-N (NO_3^--N), and sulfate (SO_4^{2-}) anions in overlying surface water collected from sediment cores during pre- and post-restoration rewetting experiments and the filtered Muskegon River water used during rewetting.

	Chloride			Bromide			Nitrate			Sulfate		
	Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
Muskegon River	27	23		0.05	0.15		0.3	0.3		20	17	
1	34	40	29	0.07	0.15	0.15	1.7	11.0	1.0	28	99	44
2	35	41	27	0.05	0.15	0.15	11.0	0.5	0.3	26	65	28
3	55	46	25	0.30	0.15	0.15	0.1	1.8	0.3	21	36	22
4	43	25	23	0.05	0.15	0.15	9.5	1.4	0.5	29	26	20
5	25	35	26	0.07	0.15	0.15	10.4	0.4	0.3	31	54	25
6	44	71	33	0.07	0.15	0.15	1.7	0.5	0.2	38	98	74
7	28	36	23	0.07	0.15	0.15	1.5	0.4	0.3	23	18	17
8	34	24	22	0.06	0.15	0.15	5.7	0.4	0.2	24	44	22
9	48	38	26	0.08	0.15	0.15	3.1	0.9	0.2	44	76	32
10	57	25	22	0.04	0.15	0.15	4.8	0.4	0.3	50	76	27
11	44	41	24	0.04	0.15	0.15	1.2	2.9	0.3	52	95	86
12	44	22	24	0.05	0.15	0.15	4.4	0.4	0.3	32	82	53
13	48	42	28	0.05	0.15	0.15	3.7	1.3	0.3	36	99	40
14	47	37	27	0.06	0.15	0.15	1.2	0.7	0.3	42	62	31
15	27	56	78	0.05	0.15	0.15	3.4	18.0	5.3	64	190	390

Appendix Table 6. Mean (±SD) concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate (NO_3^--N), and sulfate (SO_4^{2-}) anions in overlying surface water collected during pre- and post-restoration rewetting experiments and the filtered Muskegon River water used during rewetting. NA= not applicable.

	Chloride			Bromide			Nitrate			Sulfate		
	Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
River (n=1)	26 (NA)	23 (NA)		0.05 (NA)	0.15 (NA)		0.3 (NA)	0.3 (NA)		19 (NA)	46 (NA)	
East (n=4)	41 (9)	38 (9)	26 (2)	0.11 (0.12)	0.15 (0)	0.15 (0)	5.5 (5.5)	3.6 (4.9)	0.4 (0.3)	26 (3)	56 (32)	28 (10)
North (n=4)	32 (8)	41 (20)	26 (4)	0.06 (0)	0.15 (0)	0.15 (0)	4.8 (4.1)	0.4 (0)	0.2 (0)	28 (7)	53 (33)	34 (26)
South (n=7)	45 (8)	37 (11)	32 (20)	0.05 (0.01)	0.15 (0)	0.15 (0)	3.1 (1.4)	3.5 (6.4)	0.9 (1.8)	45 (10)	97 (42)	94 (132)

Appendix Table 7. Concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate (NO_3^--N), and sulfate (SO_4^{2-}) anions in surface and bottom porewater collected via rhizon during pre- and post-restoration rewetting experiments and the filtered Muskegon River water used during rewetting. Rhizons produced insufficient sample volume for all analyses; samples that could not be analyzed are left blank to improve readability.

		Chloride			Bromide			Nitrate			Sulfate		
		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	Depth	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
1	surface	38	100		0.65	0.15		0.5	47.0		35	430	
	bottom	44		85	0.43		0.15	0.1		41.0	41		350
2	surface	53	99	130	0.54	0.15	0.15	31.5	0.1	0.1	51	220	34
	bottom	50			0.01			33.2			58		
3	surface	104	92		7.29	0.15		0.0	7.9		23	170	
	bottom	190		96	2.07		0.32	0.0		13.0	22		170
4	surface	75	63		1.04	0.15		21.6	5.9		62	310	
	bottom	109			0.29			6.8			79		
5	surface		55	33		0.15	0.15		0.1	0.1		100	35
	bottom	22			0.07			18.4			56		
6	surface	91	190		2.14	0.15		4.4	0.6		123	1000	
	bottom	91			0.01			9.3			129		
7	surface	30	29		0.43	0.15		0.7	9.1		25	91	
	bottom	60			0.06			29.4			86		
8	surface	37	49	28	0.36	0.15	0.15	2.2	0.1	0.1	28	130	38
	bottom	39			0.06			4.7			29		
9	surface	83	61	35	1.61	0.15	0.15	3.2	0.1	0.1	91	310	68
	bottom	83			0.12			4.4			92		
10	surface	65	81	25	0.64	0.15	0.15	1.9	0.1	0.1	64	1300	67
	bottom	62		54	0.04		0.15	3.8		1.7	57		880
11	surface	78	130	28	0.01	0.15	0.15	0.8	3.7	0.1	149	1500	380
	bottom	78		68	0.87		0.15	0.2		2.2	155		1200
12	surface	80	66		0.01	0.15		8.9	0.1		62	1800	
	bottom	84			0.05			5.7			71		
13	surface	87	130		0.08	0.15		4.9	0.1		76	380	
	bottom	68			0.08			5.1			59		

14	surface	75	120	1.00	0.15	1.4	0.1	81	210
	bottom	68		0.09		5.4		69	
15	surface	45	130	0.22	0.15	15.0	41.0	257	610
	bottom	41		0.01		12.1		240	

Appendix Table 8. Mean (±SD) concentrations (mg/L) of chloride (Cl^-), bromide (Br^-), nitrate (NO_3^--N), and sulfate (SO_4^{2-}) anions in surface and bottom porewater collected via rhizon during pre- and post-restoration rewetting experiments and the filtered Muskegon River water used during rewetting. ND = no data; NA= not applicable.

		Chloride			Bromide			Nitrate			Sulfate		
		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration		Pre-Restoration	Post-Restoration	
Site	Depth	24H	24H	48H	24H	24H	48H	24H	24H	48H	24H	24H	48H
East (n≤4)	surface	67 (28)	88 (17)	ND (NA)	2.38 (3.27)	0.15 (0)	ND (NA)	13.4 (15.7)	15.2 (21.4)	ND (NA)	42 (17)	282 (114)	ND (NA)
	bottom	97 (67)	ND (NA)	90 (7)	0.69 (0.92)	ND (NA)	0.23 (0.12)	10 (15.7)	ND (NA)	27 (19.7)	50 (24)	ND (NA)	260 (127)
North (n≤4)	surface	52 (33)	80 (73)	30 (3)	0.97 (1.01)	0.15 (0)	0.15 (0)	2.4 (1.8)	2.4 (4.4)	0 (0)	58 (55)	330 (446)	36 (2)
	bottom	52 (29)	ND (NA)	ND (NA)	0.05 (0.03)	ND (NA)	ND (NA)	15.4 (10.9)	ND (NA)	ND (NA)	75 (42)	ND (NA)	ND (NA)
South (n≤7)	surface	73 (14)	102 (31)	29 (5)	0.5 (0.61)	0.15 (0)	0.15 (0)	5.1 (5.1)	6.4 (15.3)	0 (0)	111 (70)	872 (645)	171 (180)
	bottom	69 (15)	ND (NA)	61 (9)	0.18 (0.3)	ND (NA)	0.15 (0)	5.2 (3.5)	ND (NA)	1.9 (0.3)	106 (68)	ND (NA)	1040 (226)

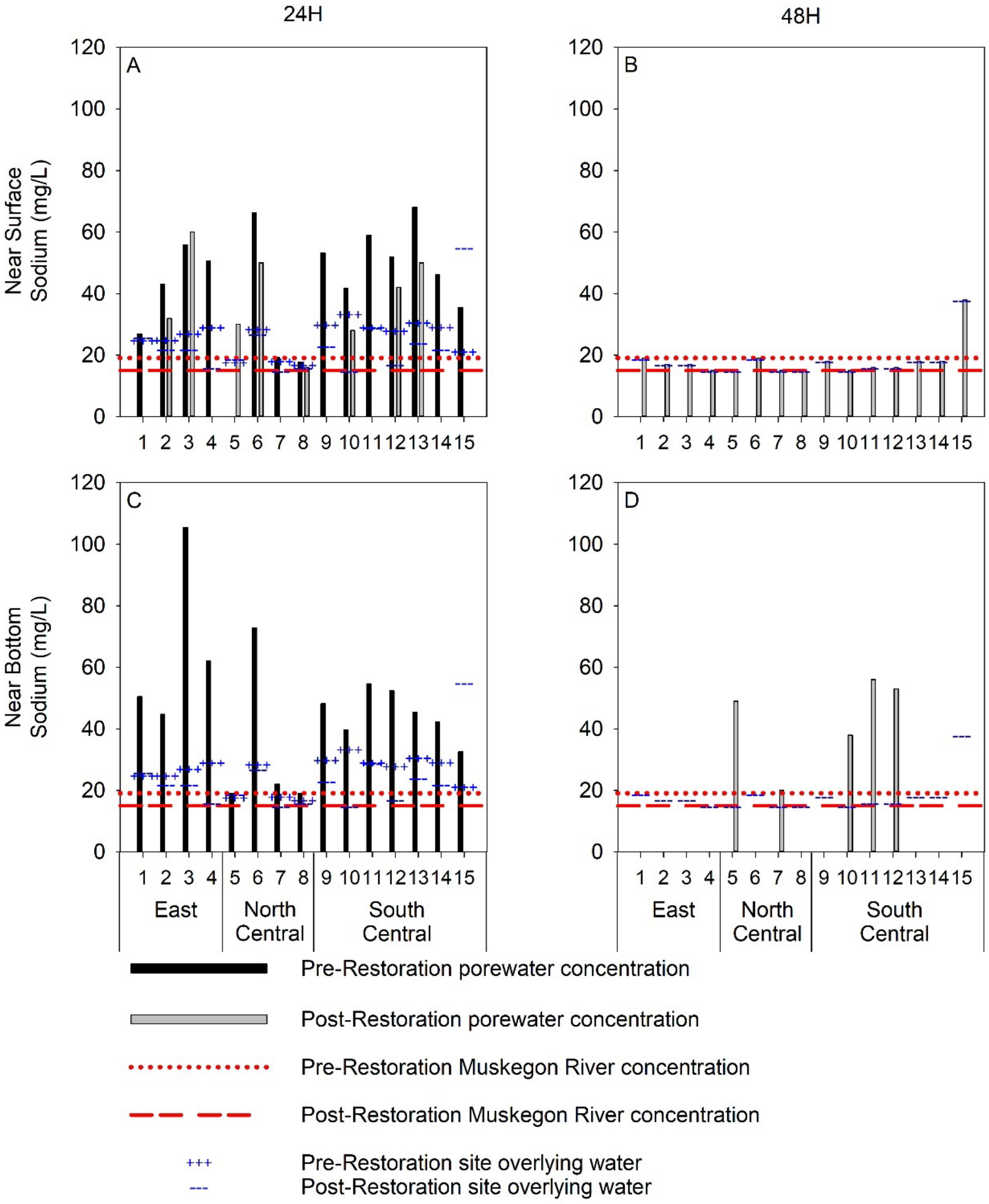
Appendix Table 9. Concentrations of iron (II) in surface and bottom porewater collected via rhizon from sediment cores during pre- and post-restoration rewetting experiments and the filtered Muskegon River water used during rewetting. Post-restoration porewater rhizon available sample volume was insufficient for iron (II) analysis, so overlying core water was collected as a surrogate comparison for porewater. ND = no data.

		Iron (II)		
Site	Depth	Pre	Post 24H	Post 48H
River		ND	0.010	
1	overlying		0.092	0.08
	surface	1.214		
	bottom	2.034		
2	overlying		0.010	0.057
	surface	0.125		
	bottom	0.184		
3	overlying		0.052	0.062
	surface	0.208		
	bottom	0.265		
4	overlying		0.077	0.027
	surface	0.222		
	bottom	0.458		
5	overlying		0.010	0.030
	surface	ND		
	bottom	0.436		
6	overlying		0.048	0.029
	surface	0.479		
	bottom	0.192		
7	overlying		0.010	0.038
	surface	0.057		
	bottom	0.068		
8	overlying		0.041	0.031
	surface	0.119		
	bottom	0.135		
9	overlying		0.026	0.036
	surface	0.030		
	bottom	0.037		
10	overlying		0.023	0.023
	surface	0.043		
	bottom	0.036		
11	overlying		0.010	0.026
	surface	0.029		
	bottom	0.050		
12	overlying		0.029	0.041
	surface	0.029		
	bottom	0.187		
13	overlying		0.010	0.026
	surface	ND		
	bottom	0.035		

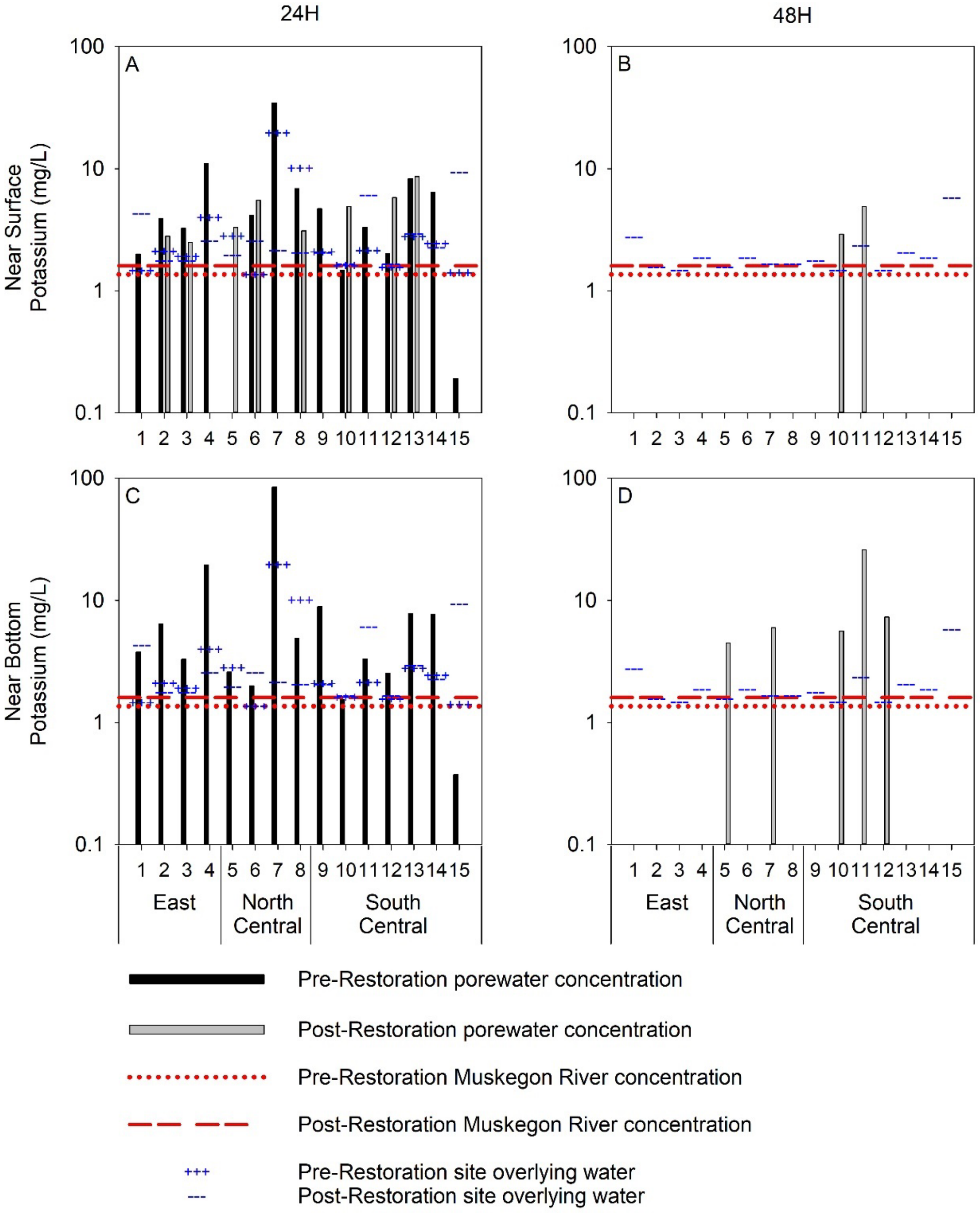
14	overlying		0.026	0.030
	surface	0.072		
	bottom	0.060		
15	overlying		0.021	0.062
	surface	0.076		
	bottom	0.025		

Appendix Table 10. Mean (±SD) concentrations by region of iron (II) in surface and bottom porewater collected via rhizon from sediment cores during pre- and post-restoration rewetting experiments. Post-restoration porewater rhizon available sample volume was insufficient for iron (II) analysis, so only overlying core water could be measured.

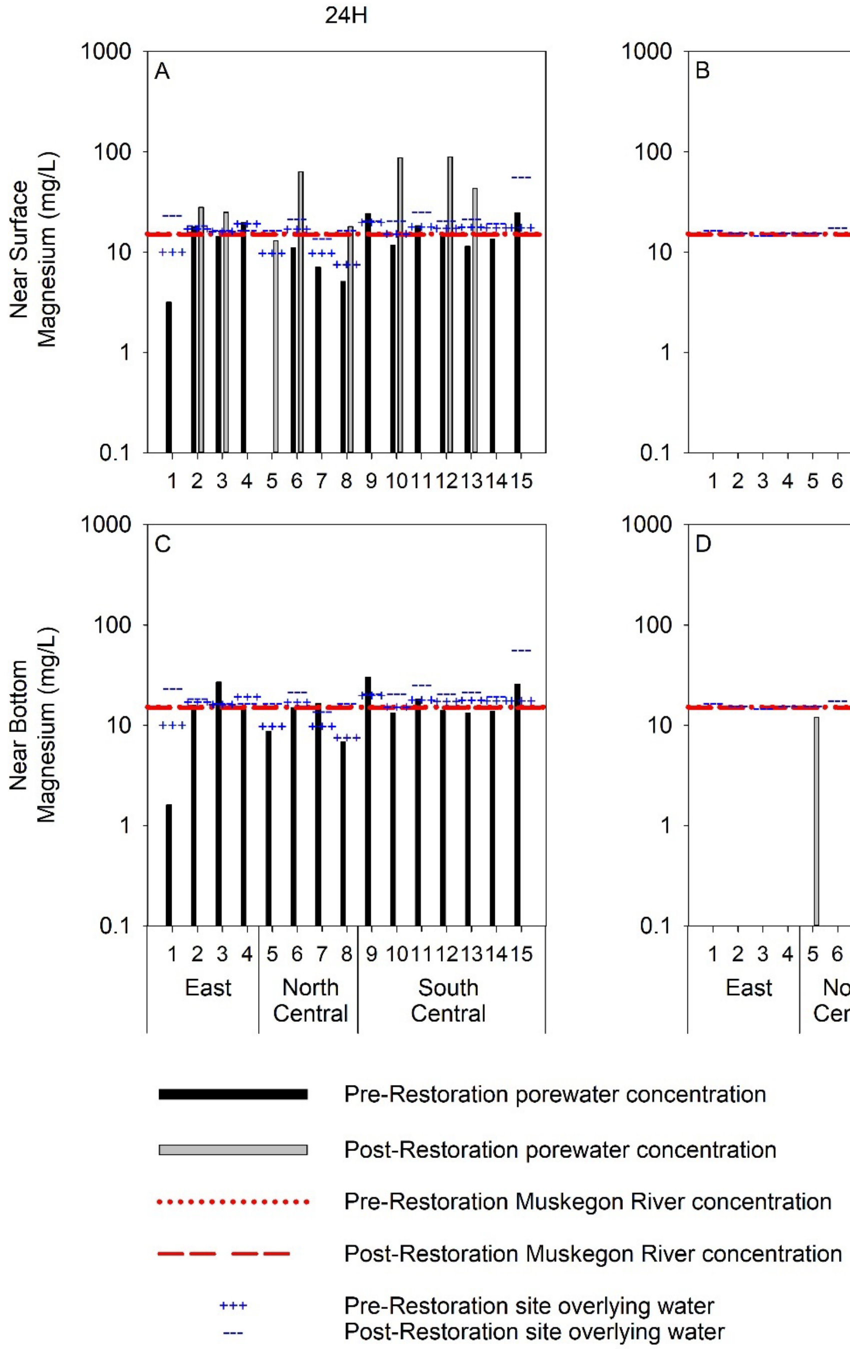
		Iron (II)		
Site	Depth	Pre	Post 24H	Post 48H
East n=4	overlying		0.057 (0.035)	0.056 (0.022)
	surface	0.442 (0.516)		
	bottom	0.735 (0.873)		
North n=4	overlying		0.027 (0.02)	0.032 (0.004)
	surface	0.218 (0.227)		
	bottom	0.207 (0.16)		
South n=7	overlying		0.02 (0.007)	0.034 (0.013)
	surface	0.046 (0.021)		
	bottom	0.061 (0.056)		



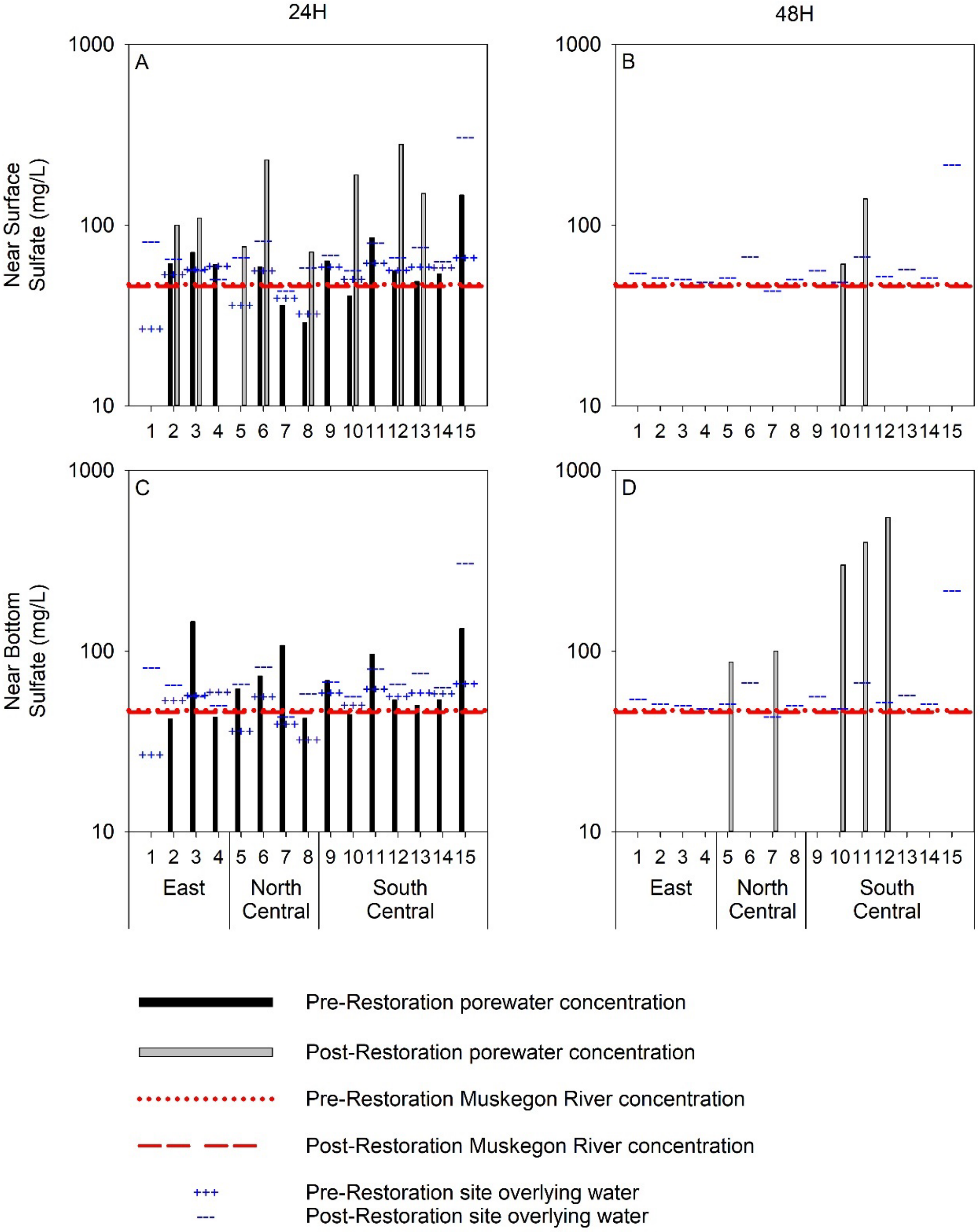
Appendix Figure 1. Pre- and post-restoration concentrations of sodium (Na^+) cations in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



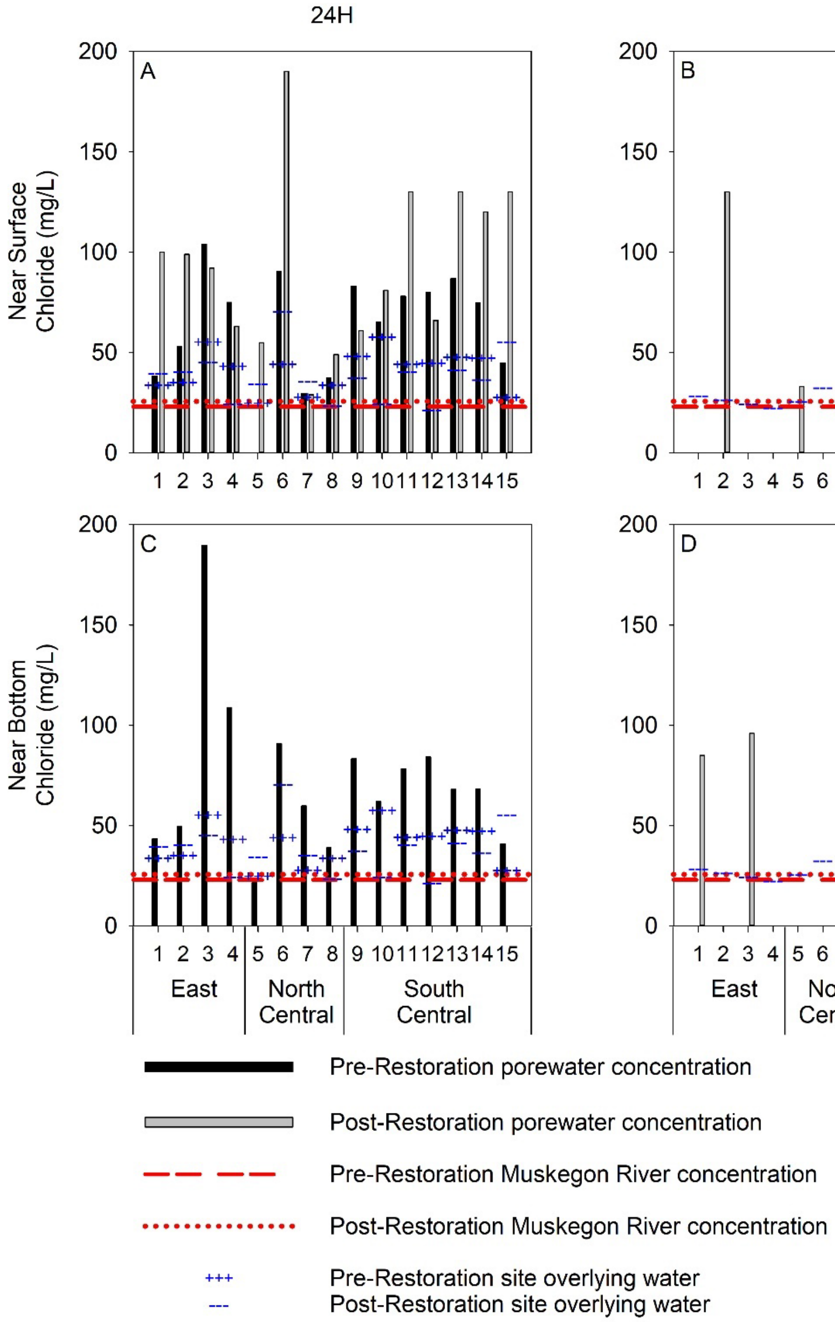
Appendix Figure 2. Pre- and post-restoration concentrations of potassium (K^+) cations in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



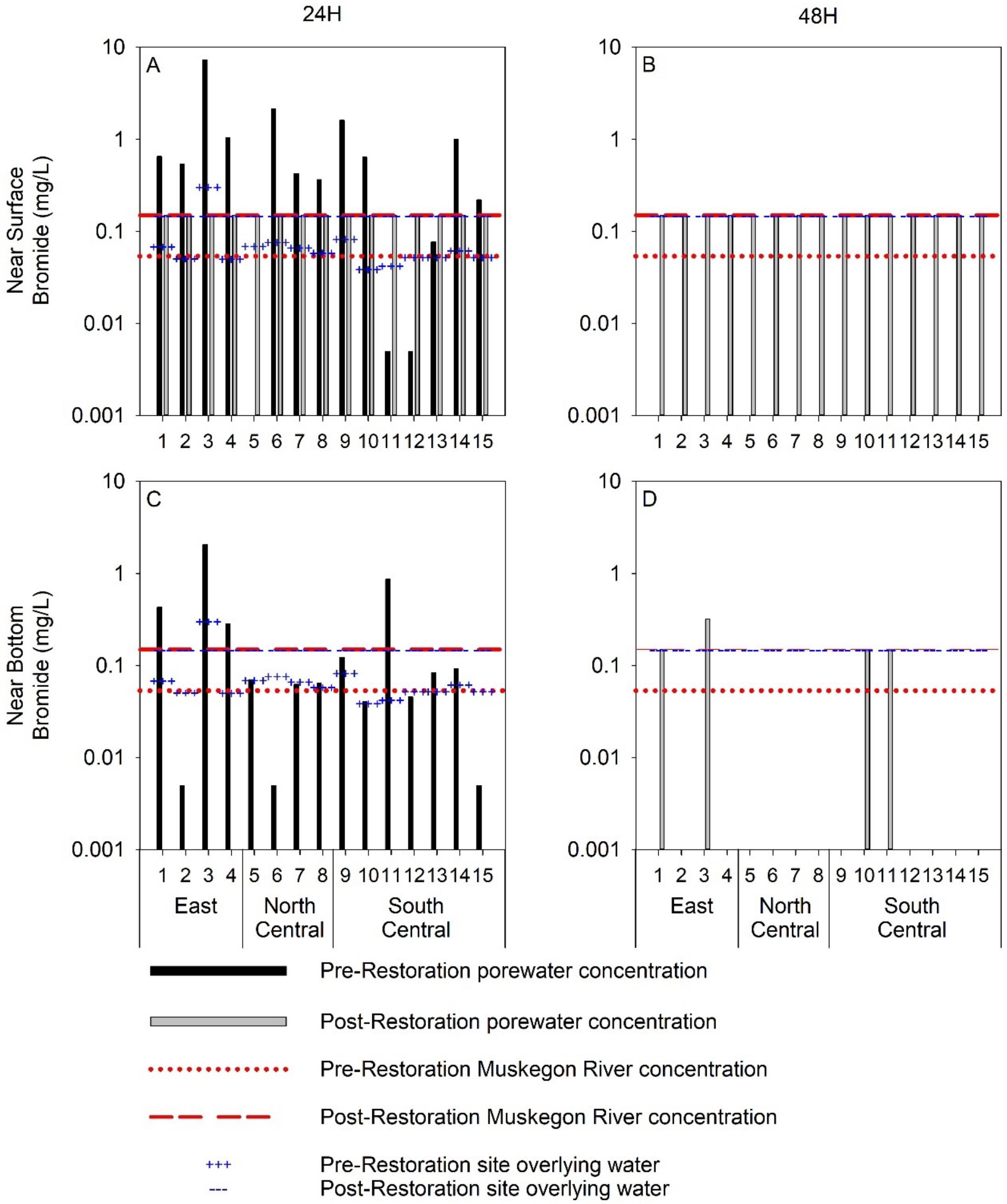
Appendix Figure 3. Pre- and post-restoration concentrations of magnesium (Mg^{2+}) cations in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



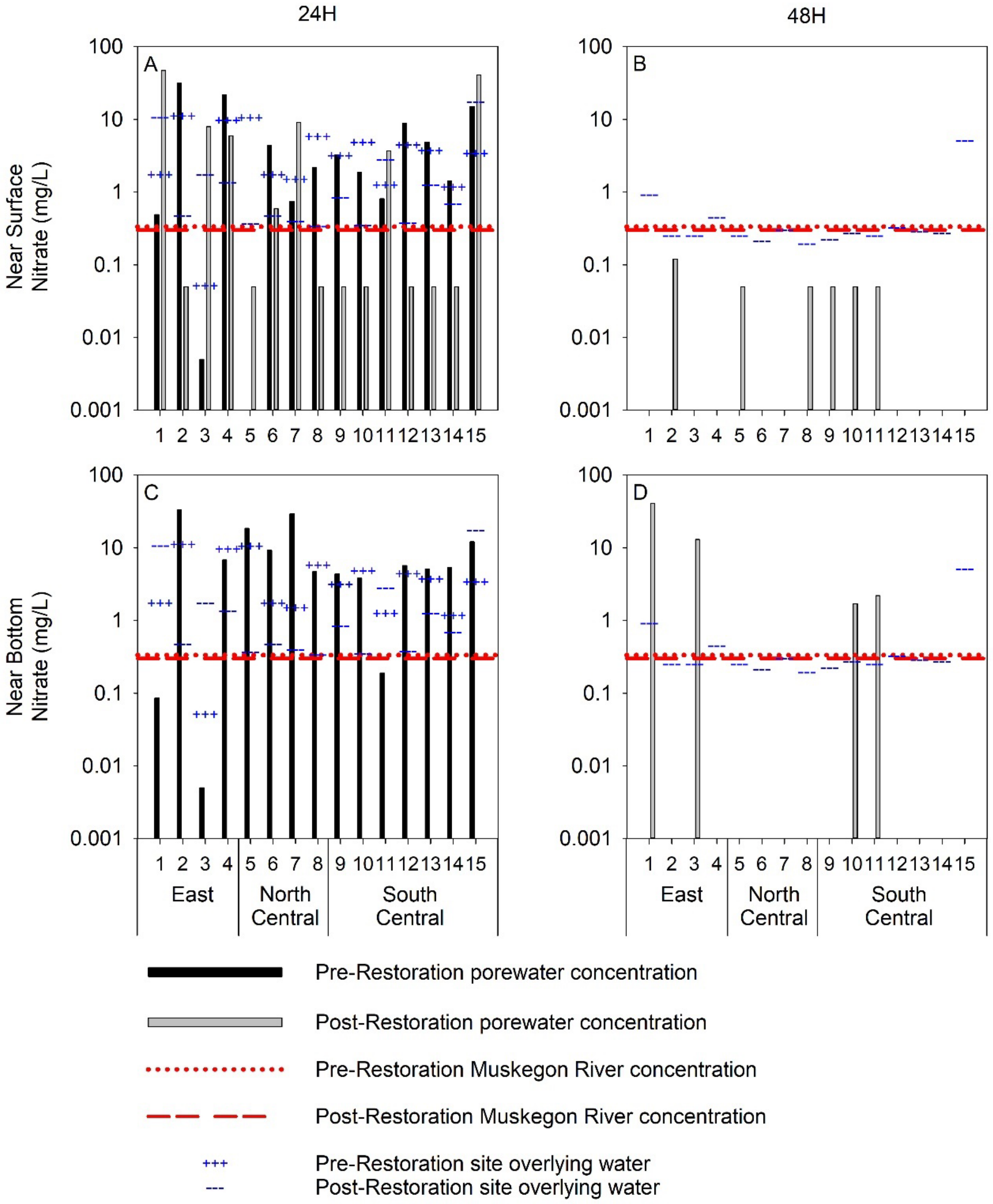
Appendix Figure 4. Pre- and post-restoration concentrations of calcium (Ca^{2+}) cations in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



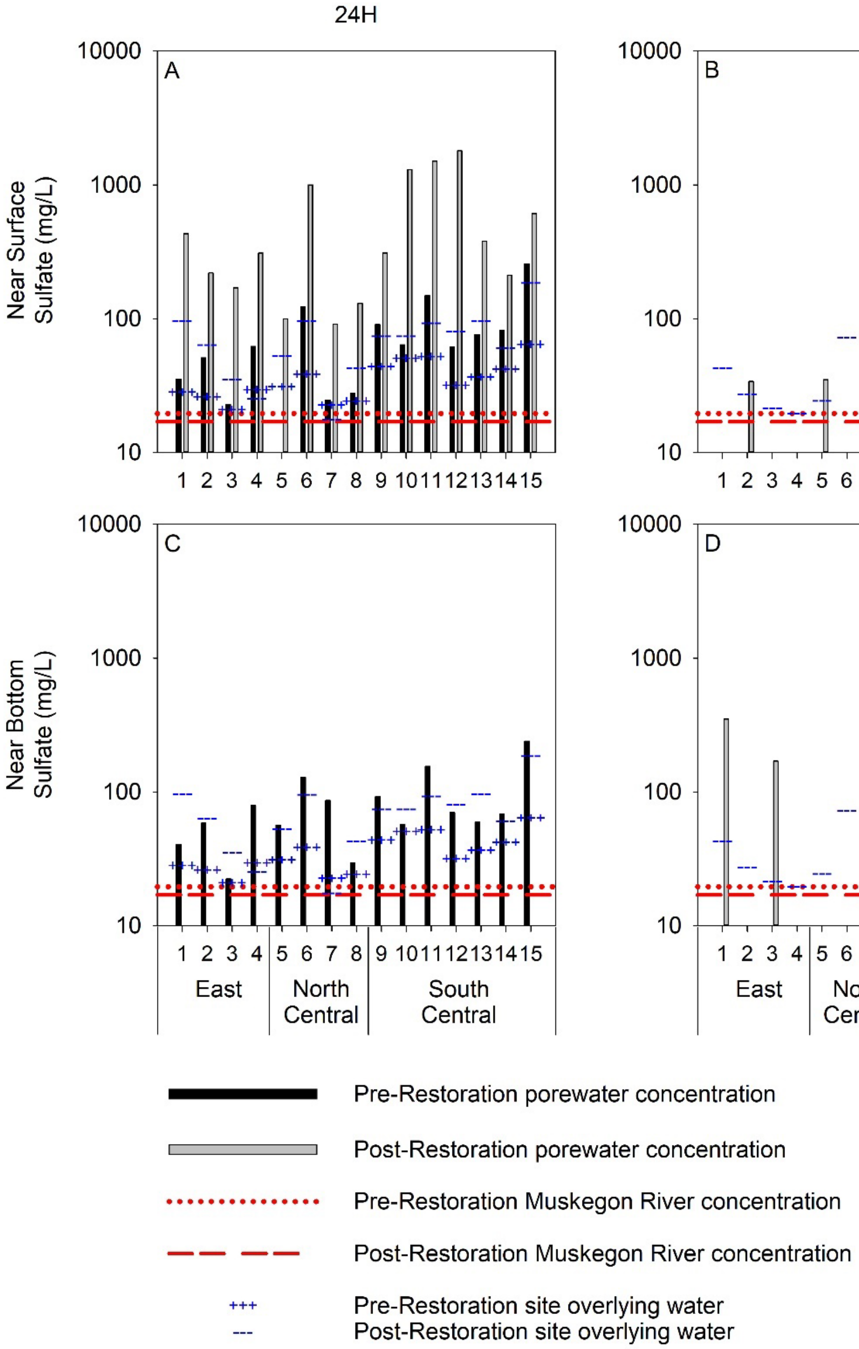
Appendix Figure 5. Pre- and post-restoration concentrations of chloride (Cl^-) anions in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



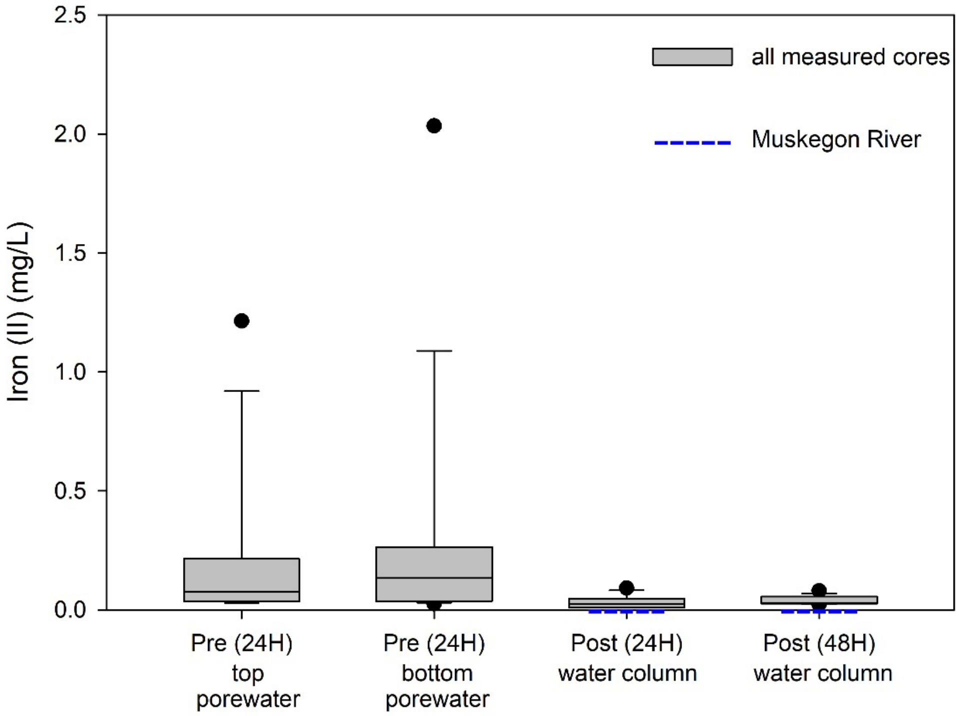
Appendix Figure 6. Pre- and post-restoration concentrations of bromide (Br^+) anions in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



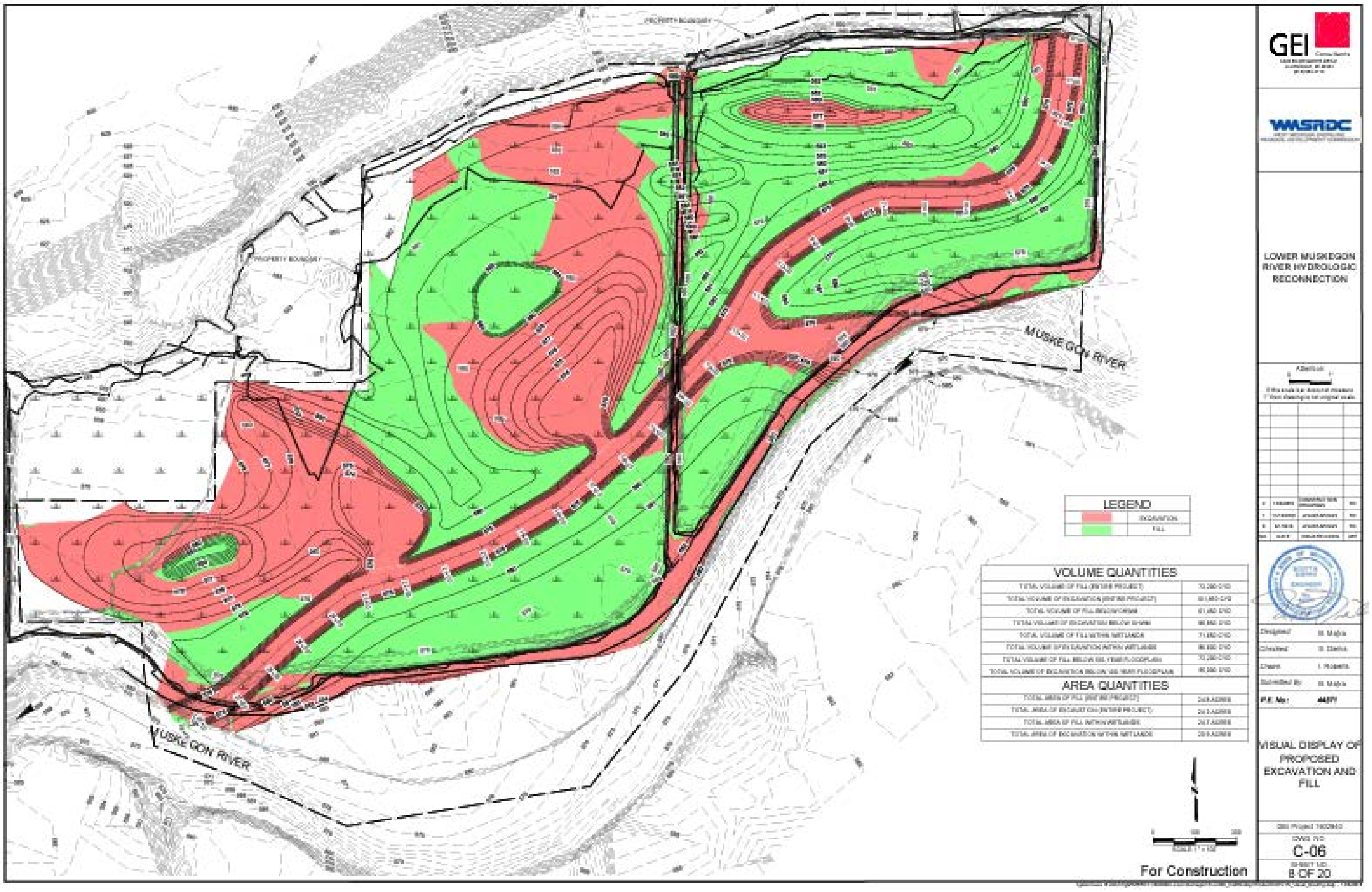
Appendix Figure 7. Pre- and post-restoration concentrations of nitrate ($NO3^-$) anions in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



Appendix Figure 8. Pre- and post-restoration concentrations of sulfate (SO_4^{2-}) anions in overlying core water and surface and bottom porewater accessed via rhizon during rewetting experiments and filtered Muskegon River water used during rewetting.



Appendix Figure 9. Iron (II) concentrations in surface and bottom porewater accessed via rhizon during the pre-restoration re-wetting experiment and from overlying water during the post-restoration rewetting experiment.



Appendix Figure 10. Proposed areas of fill (green) and excavation (pink) for the Lower Muskegon River hydrologic reconnection project.