Mona Lake Celery Flats Reconnection
Pre-Restoration Monitoring Report

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Introduction

A proposal to restore the former celery flat ponds located adjacent to Black Creek in Muskegon County, MI was funded by NOAA through the Great Lakes Restoration Initiative. These shallow ponds are separated from the Creek by an earthen berm; restoration of this site involves the removal of the berm to create a flow-through marsh, thereby improving both fish habitat and water quality. The Ruetz and Steinman Labs at GVSU's R.B. Annis Water Resources Institute were contracted by the Office of the Muskegon County Water Resources Commissioner to monitor the fish community and water quality, respectively, in these ponds. This report focuses on water quality. A separate report will focus on the fish monitoring results.

The water quality of these ponds was monitored in 2009 and found to have an excess of phosphorus. Total phosphorus (TP) concentrations in the water column of the ponds ranged from ~350 to 400 μg/L in the north pond and from ~740 to 835 μg/L in the south pond, compared to Black Creek inflow concentrations of ~20-35 μg/L (Steinman and Ogdahl 2011). Analyses of the pond sediments indicated that the sediments had mean TP concentrations of 6,137 mg/kg in the north pond and 817 mg/kg in the south pond. In addition, phosphorus (P) isotherms indicated these sediments served as a source of P to the water column (Steinman and Ogdahl 2011). As a consequence, it is important to monitor the water quality of these systems, both to ensure appropriate water quality for the fishes, as well as to ensure significant phosphorus loads are not entering Mona Lake and contributing to algal blooms downstream. Conversion of a similar P-rich celery farm pond to a flow-through marsh required sediment dredging to ensure water quality, and resulted in a reduction of water column TP concentrations from ~800 μg/L to ~30 μg/L (Oldenborg and Steinman 2019; Hassett and Steinman 2022).

Mona Lake has a history of algal blooms, although recent efforts have resulted in improved water quality. Hence, we want to avoid any backsliding in Mona Lake water quality in an effort to improve fish and wildlife habitat. Our goal for this study was to assess the current water quality conditions in the water column and sediments of the ponds and compare these data with the data we previously collected in 2009-2010, which will allow us to: 1) identify any changes in water quality over the past decade; and 2) establish a new baseline for pre-restoration conditions, allowing us to assess the effects of restoration on water quality post-construction activities.

Methods

Water quality and sediment chemistry monitoring sites were selected from sites previously studied by the Steinman lab within the Mona Lake Watershed (Steinman and Ogdahl 2011). A total of seven sites were chosen, distributed across the north pond (n=3), the south pond (n=2), and Black Creek (n=2; Figure 1). Water quality and sediment chemistry were sampled in the north pond on 23 June 2023 and in both the south pond and Black Creek on 28 June 2023. Additional sediment porewater was sampled from two locations within the north pond. Porewater samplers were installed on 23 June and incubated onsite until retrieval on 7 July 2023, two weeks after deployment. Throughout this study period, road construction occurred on a nearby road-stream crossing for a BUS-31 (Seaway Drive in Norton Shores, MI) bridge that overpasses Black Creek about 150 m from the downstream Black Creek sampling site. Sediment curtains were deployed during construction, and presumably, there was minimal or no impact from road construction on results from this study.

Physical and chemical water quality parameters including temperature, dissolved oxygen, pH, specific conductance, total dissolved solids, and turbidity were measured on each sampling date using a YSI EXO2 sonde (YSI, Inc., Yellow Springs, OH). Surface water grab samples were collected in 250-mL and 1-L bottles, kept on ice, and returned to the laboratory for measurement of soluble reactive phosphorus (SRP), total phosphorus (TP), and chlorophyll *a* (chl *a*). Upon returning to the lab, subsamples for the SRP analyses were filtered through 0.45-µm membrane filters into scintillation vials, which were refrigerated at 4°C until being analyzed on a Seal AQ2 discrete autoanalyzer (USEPA 1993). Chl *a* samples were vacuum-filtered on a GF/F membrane and frozen until extracted and analyzed on a Shimadzu UV-1601 spectrophotometer (APHA 1992).

Sediment cores were collected using a modified piston corer (Oldenborg and Steinman 2019) and taken back to the laboratory, where sediment was extruded from each core and split into 0-10 cm (surface) and 20-30 cm (bottom) depths. Sediment core segments were refrigerated, separately homogenized, and subsampled for analyses of sediment organic matter, sediment TP, and sediment metals (calcium, iron, and manganese).

Sediment pore water was sampled using modified Hesslein in-situ pore water samplers (i.e., peepers). The peepers were prepared in the laboratory by filling the compartments with deoxygenated deionized (DI) water and covering them with a 5-µm dialysis membrane and slotted cover. The peepers remained submerged in deoxygenated DI water overnight before deployment in the field. Duplicate sets of peepers were deployed at both locations and were installed to a sediment depth of approximately 20 cm. Peepers were collected after 14 days and sampled using a syringe needle to pierce the membrane and evacuate the liquid from 10 compartments of each peeper. These samples represented a profile from the water column to approximately 20 cm sediment depth. Samples were processed and analyzed for SRP as described above.

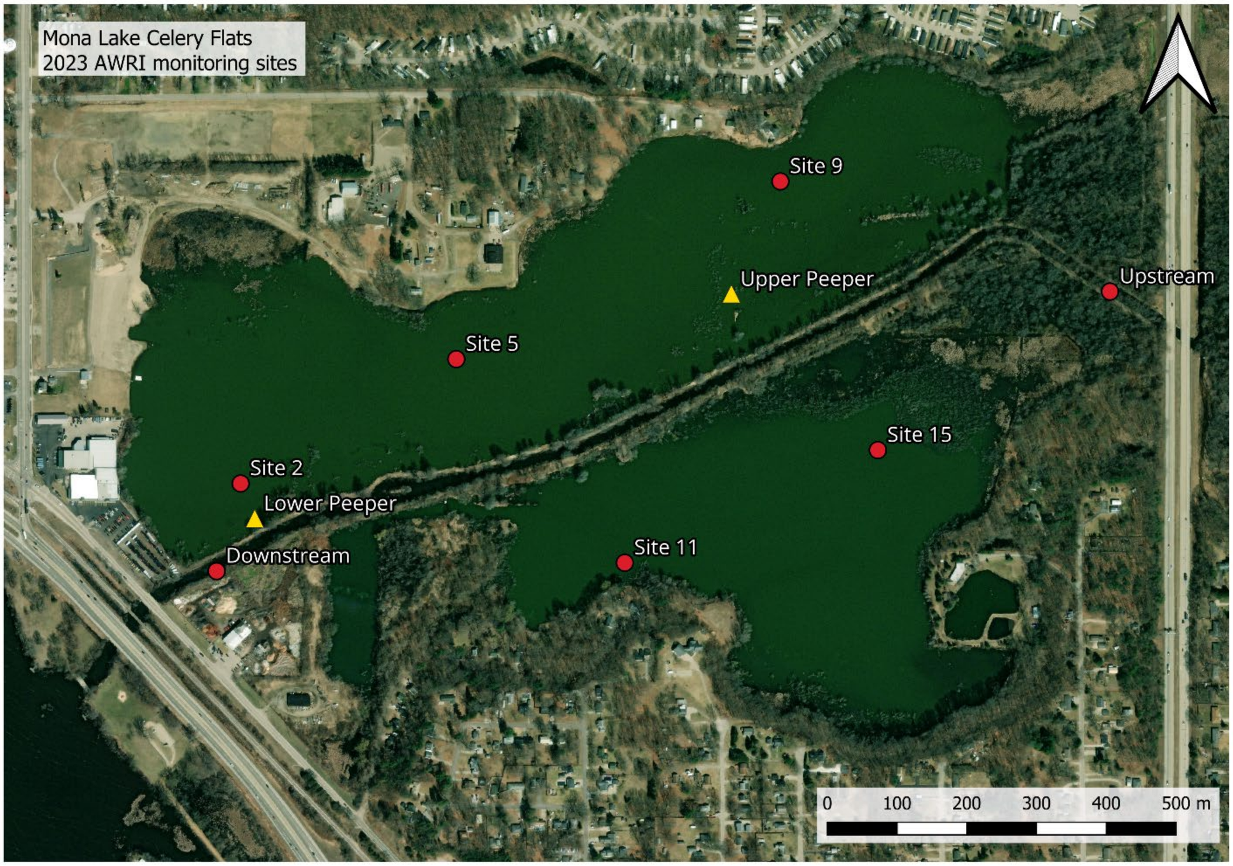

Figure 1. Mona Lake celery flat monitoring sites for water quality and sediment coring, shown as red circles in the north pond, Black Creek, and south pond. Numbers correspond to the numbering system used in Steinman and Ogdahl (2011) to facilitate comparisons. Additional sites for groundwater sampling via peepers in the north pond are shown as yellow triangles.

Results and Discussion

Water Quality

Water quality parameters measured in the ponds indicate supersaturated oxygen conditions, with high DO across all sites. In addition, pH was elevated in both ponds (>9.5); taken together, these values are indicative of active photosynthesis. Both DO saturation and pH were higher in the north pond compared to the south pond, and values in both ponds were higher than those measured in Black Creek (Table 1). Turbidity was also much higher in the ponds than in the creek. Within Black Creek, values for all measurements increased between the upstream and downstream sites (Table 1), suggesting inflows from the ponds into the creek potentially through breaches in the dikes or subsurface connections.

Average TP concentrations in the north and south ponds were very high at 521 µg/L and 254 µg/L, respectively. These levels are ~10× greater than the upstream TP concentration in Black Creek (Table 2, Figure 2). Surface water SRP concentrations were below the detection limit at all sites, and the difference between TP and SRP concentrations suggests rapid uptake of phosphorus. Chl *a* concentrations averaged 239.7 µg/L in the north pond and 66.6 µg/L in the south pond, compared to an upstream concentration of 2.2 µg/L in Black Creek (Table 2, Figure 3). As with the water quality parameters described above, both TP and chl *a* increased substantially between the upstream and downstream sites within Black Creek; the downstream TP concentration was 3× greater than the upstream site and the chl *a* concentration was 30× greater (Table 2).

Table 1. Water quality parameters measured on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek). Temp = water temperature, SpCond = specific conductance, and TDS = total dissolved solids.

	North Pond (n=3)	South Pond (n=2)	Black Creek	
	Mean (SD)	Mean (SD)	Upstream	Downstream
Temp (°C)	25.90 (0.62)	21.58 (0.07)	15.97	17.65
DO (mg/L)	13.33 (0.52)	11.35 (1.48)	9.75	10.18
DO (%)	164.2 (8.0)	129.0 (17.0)	98.8	106.9
pH	9.89 (0.04)	9.54 (0.11)	8.28	8.61
SpCond (µS/cm)	468.9 (8.8)	464.1 (2.1)	407.0	421.3
TDS (mg/L)	305 (6)	302 (1)	265	274
Turbidity (FNU)	40.45 (1.36)	19.14 (1.63)	5.90	7.04

Table 2. Water chemistry parameters sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek).

	North Pond (n=3)	South Pond (n=2)	Black Creek	
	Mean (SD)	Mean (SD)	Upstream	Downstream
TP (µg/L)	521 (12)	253 (1)	36	118
SRP (µg/L)	<5 (0)	<5 (0)	<5	<5
Chlorophyll *a* (µg/L)	239.7 (36.6)	66.6 (6.1)	2.2	65.6

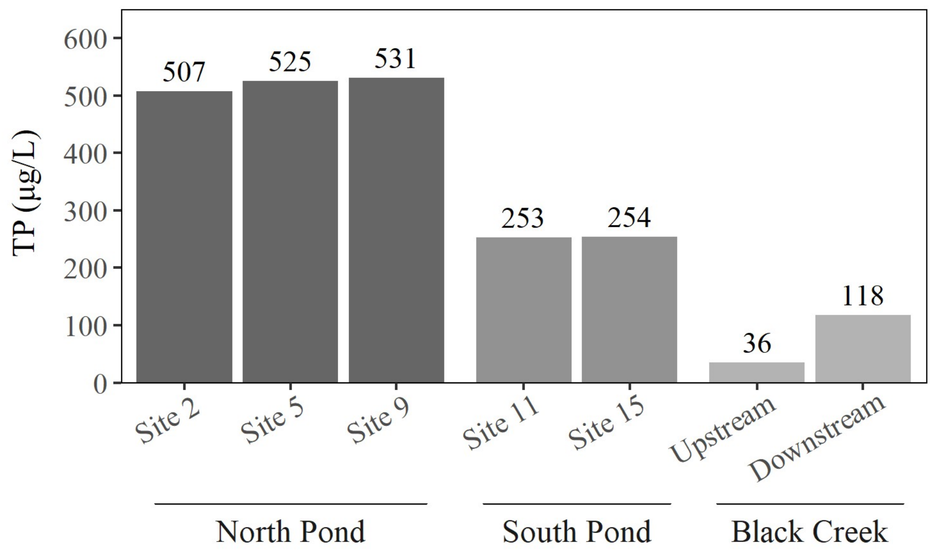

Figure 2. TP concentrations sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek).

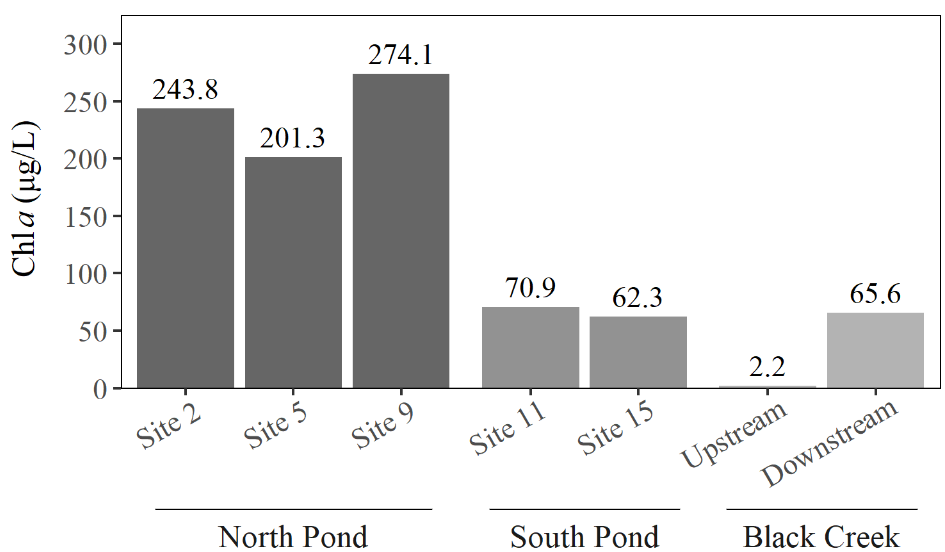

Figure 3. Chl *a* concentrations sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek).

It is instructive to compare the key 2023 water column values to those measured in 2009 (Steinman and Ogdahl 2009). Mean water column TP concentrations have increased in the north pond from 2009, from 368 to 521 µg/L, and decreased in the south pond from 810 to 253 µg/L. Changes in mean chl *a* from 2009 to 2023 mimicked those of phosphorus, with north pond concentrations increasing (106 to 240 μg/L) and south pond chl *a* levels decreasing (206 to 67 μg/L). These are relatively large changes and may reflect alterations in local land use or lakefront landowner activities.

Sediment Chemistry

Both sediment TP and organic matter (OM) were considerably higher in the north pond than in the south pond and Black Creek (Table 3). Values were especially high in north pond sites 5 and 9, where TP in sediment ranged from 4,003 to 5,618 mg/kg (Figure 4), and OM ranged from 43-53% (Figure 5). TP and OM in south pond and Black Creek sediments were more similar, ranging from 34-441 mg/kg and 0.2-5.2%, respectively (Table 3). Sediment in the north pond was typically mucky, while the south pond generally had greater sand content. The OM concentrations have declined in both ponds from 2009 based on our limited sampling (Steinman and Ogdahl 2011). In the south pond, where mean chl *a* concentrations have also decreased since 2009 (see above paragraph), this decline may explain the concomitant decline in OM; however, in the north pond, chl *a* has increased since 2009. Given the one-time sampling and small number of sample sites, the water column data may be artifacts of short-term, localized conditions. Nonetheless, water column TP and chl *a* concentrations are high, and indicate remedial actions are warranted.

Sediment depth influenced TP in the north pond to a limited extent, being higher in the top 10 cm compared to the 20-30 cm depth at Site 2 (but low in absolute amount); at Site 5, the opposite was true (Figure 4), and there was no difference at Site 9. In the south pond, sediment TP in the deeper stratum was greater than near the surface, although the overall concentrations were much lower than in the north pond (Figure 4). Interestingly, sediment TP was ~10×greater at the 20-30 cm depth than at the 0-10 cm depth at the upstream Black Creek site, whereas the difference in TP between depths was relatively limited at the downstream site (Figure 4). How TP varies with depth is critical for identifying the appropriate depth for sediment removal if sediment excavation is selected as the restoration approach. GEI created a sediment TP heat map (Appendix 1) for 3 depths in both ponds; their maps show similar overall trends to our data. It is clear from both studies that TP varies with depth, with some areas very high (>3,000 mg/kg) at the surface but declining quickly with depth at 0.5 and 1.0 m. In contrast, other areas remain high at all depths.

Sediment calcium and iron were abundant at all sites. In particular, two sites in the North Pond (sites 5 and 9) had calcium and iron (Fe) concentrations 10× greater than the other sampling locations, ranging from 27,000 to 80,000 mg/kg and 15,000 to 45,000 mg/kg, respectively (Figures 6, 7). These metals can bind phosphorus and potentially make it unavailable for uptake. Iron amendments to shallow lakes have been shown to reduce P concentrations in the water column, at least in the short-term (Münch et al. 2023). Long-term effectiveness depends on the concentrations of P and Fe, as well as the form of Fe, present in the sediment (Kleeberg et al. 2012, 2013). We measured only total Fe, so we are unable to speculate whether the current amount and form of Fe has the long-term ability to retain P. Given the high concentrations of TP in the water column of the ponds, it would suggest that current Fe concentrations are insufficient to effectively control phosphorus. Iron's efficacy also can be dependent on sulfur concentrations and organic matter content in the sediment. Sulfur can bind to Fe to form pyrite, which precludes

Fe from binding to P. A much more detailed biogeochemical analysis would be necessary to elucidate P-Fe-S interactions in these sediments.

Manganese was found in smaller concentrations than calcium and iron, ranging from 7 to 1,300 mg/kg. Manganese concentrations showed a similar spatial distribution to calcium and iron, with concentrations at sites 5 and 9 being 20× greater than at other sites (Figure 8). In general, metals concentrations were higher in the 0-10 cm sediment fractions than in the 20-30 cm fraction, with the exception of site 15 in the South Pond and the upstream site in Black Creek, where the opposite was true (Table 4).

Table 3. Sediment chemistry sampled on June 23, 2023 (North Pond) and June 28, 2023 (South Pond and Black Creek). Sediment TP values are given as mg/kg of dry weight.

		North Pond (n=3)	South Pond (n=2)	Black Creek	
	Depth	Mean (SD)	Mean (SD)	Upstream	Downstream
TP (mg/kg, dry wt.)	0-10 cm	3042 (1868)	119 (18)	53	107
	20-30 cm	3307 (2919)	356 (120)	482	34
OM (%)	0-10 cm	37.3 (24.5)	1.5 (0.4)	1.0	0.9
	20-30 cm	31.2 (27.1)	3.8 (2.0)	3.4	0.2

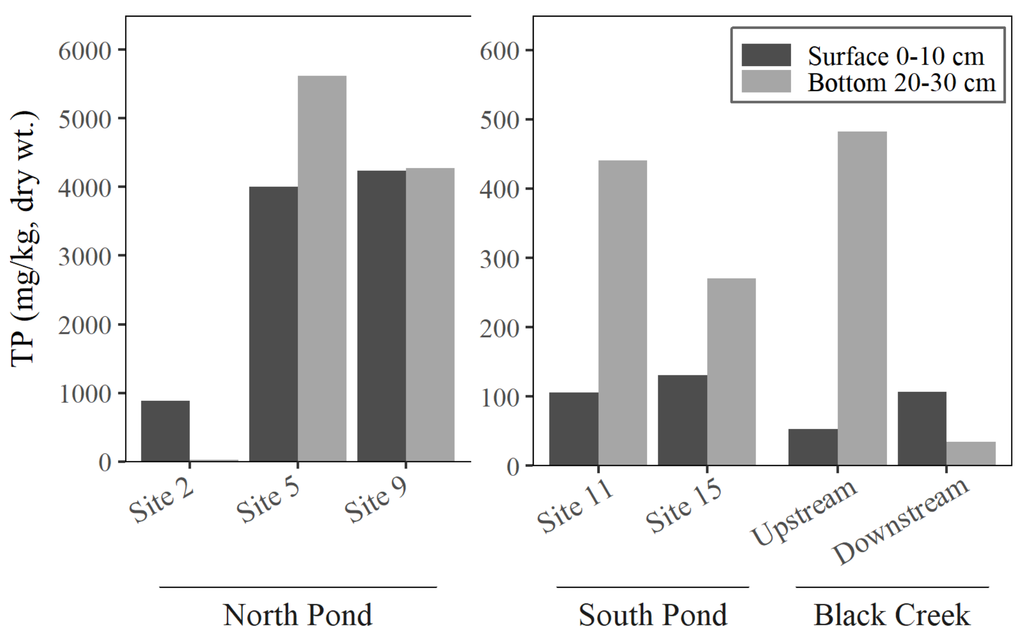

Figure 4. Sediment TP sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek). Samples from each site are divided into surface (0-10 cm) and bottom (20-30 cm) fractions. Site 2 bottom (20-30 cm) sediment TP concentration is 27 mg/kg, dry weight. Note y-axes differ between figure panels.

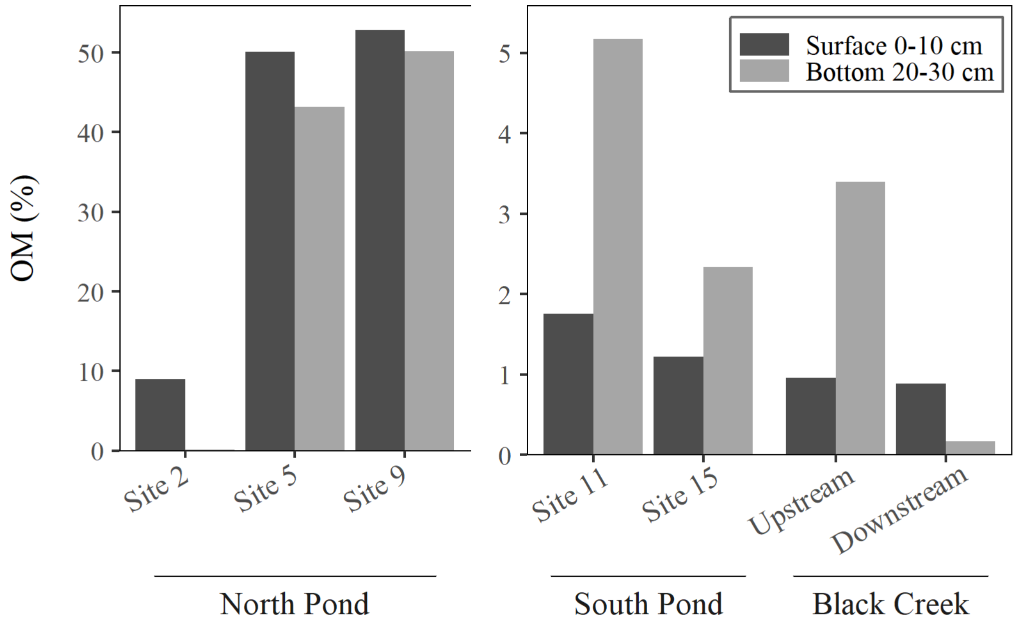

Figure 5. Percent organic matter in sediment sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek). Samples from each site are divided into surface (0-10 cm) and bottom (20-30 cm) fractions. Site 2 bottom (20-30 cm) OM% is 0.16%. Note y-axes differ between panels.

Table 4. Sediment metals in ash-free sediment sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek).

Location	Site Name	Depth	Calcium (mg/kg)	Iron (mg/kg)	Manganese (mg/kg)
North Pond	Site 2	0-10 cm	9400	6100	140
		20-30 cm	130	790	7
	Site 5	0-10 cm	64000	36000	1200
		20-30 cm	27000	15000	660
	Site 9	0-10 cm	80000	45000	1300
		20-30 cm	56000	39000	1100
South Pond	Site 11	0-10 cm	2200	1800	47
		20-30 cm	1700	1600	37
	Site 15	0-10 cm	940	1400	34
		20-30 cm	1200	2400	35
Black Creek	Upstream	0-10 cm	840	2800	76
		20-30 cm	1600	4300	92
	Downstream	0-10 cm	1400	2300	58
		20-30 cm	240	950	16

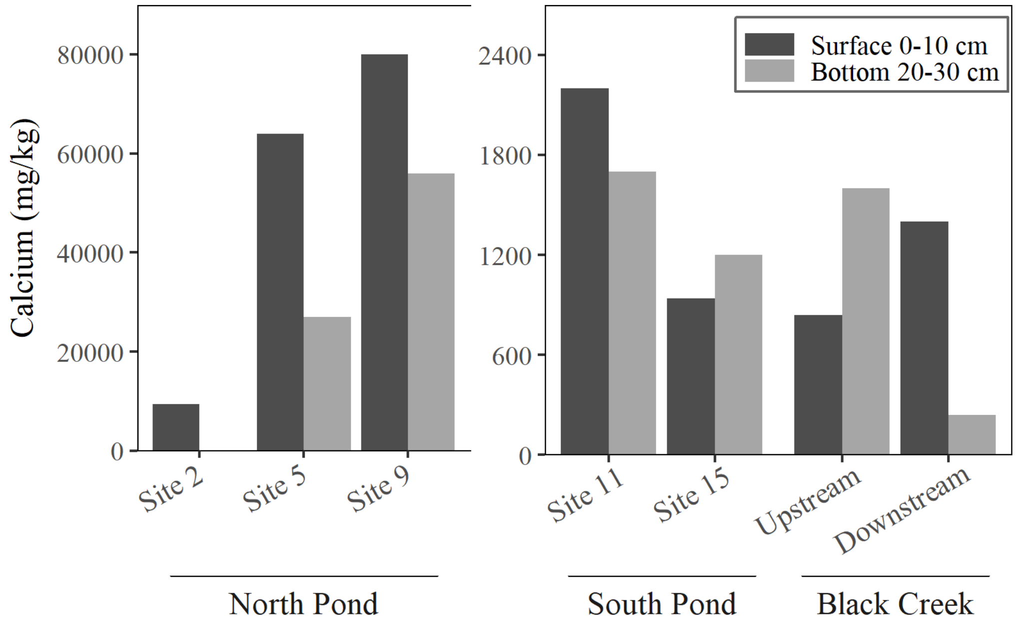

Figure 6. Sediment calcium in ash-free sediment sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek). Samples from each site are divided into surface (0-10 cm) and bottom (20-30 cm) fractions. Note y-axes differ between panels.

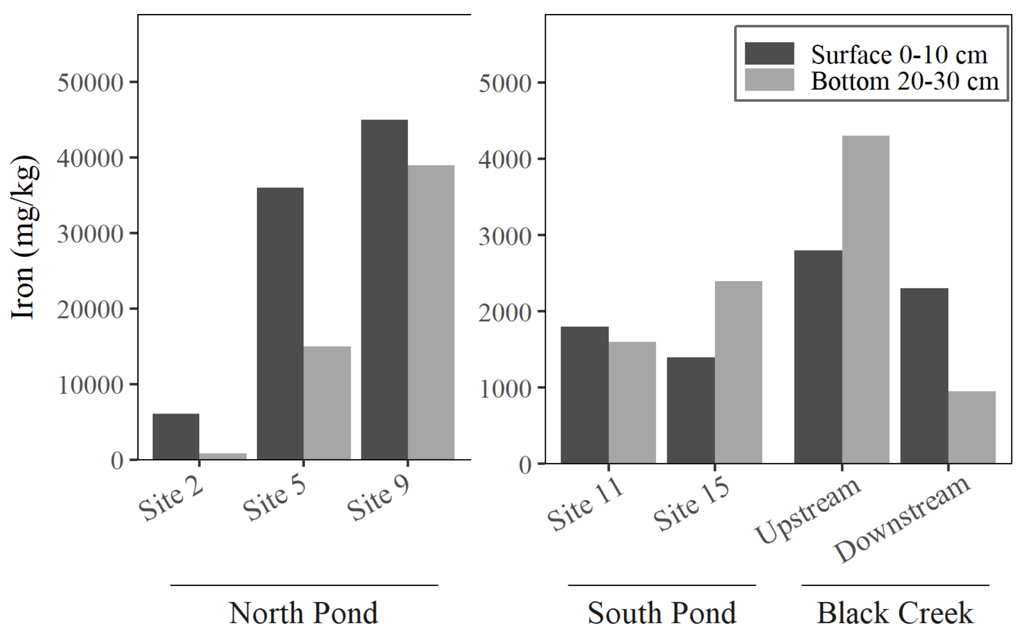

Figure 7. Sediment iron in ash-free sediment sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek). Samples from each site are divided into surface (0-10 cm) and bottom (20-30 cm) fractions. Note y-axes differ between panels.

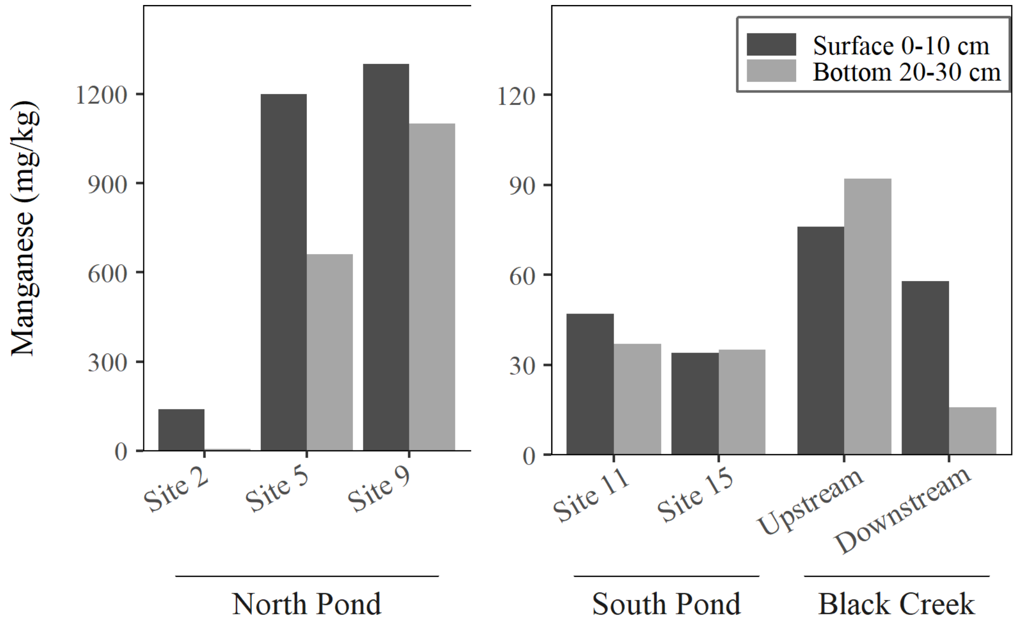

Figure 8. Sediment manganese in ash-free sediment sampled on June 23, 2023 (north pond) and June 28, 2023 (south pond and Black Creek). Samples from each site are divided into surface (0-10 cm) and bottom (20-30 cm) fractions. Note y-axes differ between panels.

Sediment Porewater

SRP concentrations in sediment porewater were generally similar between east and west sites within the north pond, ranging from 400 -1600 µg/L at the east site and 200 - 2000 µg/L at the west site (Figure 9). Concentrations tended to increase with increasing sediment depth; this trend was more pronounced in the west peepers than the east.

These concentrations are typical of highly impaired, shallow ponds in our region and are similar to what was measured in the north pond in 2009 (Steinman and Ogdahl 2011); peepers were not deployed in the south pond in the 2009 study. Given the high level of sediment mixing in these ponds due to fish bioturbation, it is likely that this SRP is being mobilized into the water column where it is rapidly taken up. These results have implications for restoration, as well. If chemical amendments and/or sediment capping are applied to these ponds, their effectiveness will depend on remaining in place and eventually being integrated into the sediment. Significant disturbance, such as by carp movement in the sediment, will limit the effectiveness of the treatment.

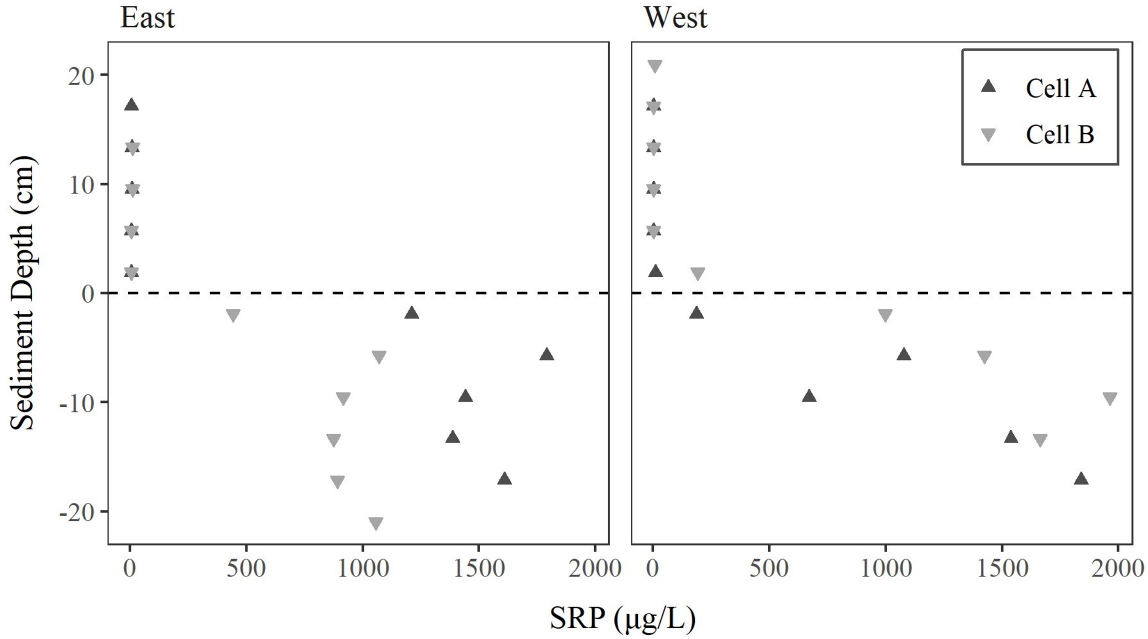

Figure 9. Sediment porewater SRP profiles from two locations within the North Pond (East and West). For each site, n=2 porewater sampling units (Cell A and Cell B). Peepers incubated *in situ* June 23, 2023 to July 7, 2023. Dashed line represents the sediment-water interface.

Conclusions

The current water quality conditions in the Mona Lake celery flat ponds indicate significant impairment with respect to excess phosphorus in both the water column and sediment. There have been minor improvements in some indicators, but overall, conditions remain highly eutrophic and represent a major threat to habitat restoration in these ponds, as well as a major source of phosphorus to Mona Lake. This drowned rivermouth lake has recently received several applications of alum to control internal phosphorus loading in targeted areas; to maintain long-term benefits of this expensive treatment, it is critical to limit external loads (Steinman et al. 2009; Steinman and Spears 2020).

A separate study being conducted by Kate Lucas for her graduate Thesis research in the Steinman lab has examined the effect of simulated dredging on phosphorus dynamics in these sediments. Although her analysis is still ongoing, her preliminary results indicate that P release rates, the equilibrium phosphorus concentration, and sediment P levels were all negatively affected by dredging, which is inconsistent with prior research results. This unexpected result is potentially due to uncovering mobile P fractions below the simulated dredging depth (Kang et al. 2023).

The results presented in this report have several direct management and restoration implications for the Mona Lake celery flats project:

- Phosphorus impairment remains a problem in both the water column and sediment;
- Regardless of external factors (e.g., cost, logistics), wide-scale sediment excavation should be carefully considered based on the initial results of the Lucas thesis study.

We suggest a 3-phased approach for P treatment:

1) Whole-pond water column treatment with a P-inactivation agent (e.g., Phoslock or alum) will help reduce P concentrations in the water column, if dewatering is not feasible;
2) Water column treatment could be followed by targeted excavation of P hot spots - excavation depth should be between 0.5m and 1.0m depending on location;
3) Excavation should be followed by sand capping (preferably impregnated with a P-binding agent) in sediment removal locations.

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Appendix 1. Sediment TP heat maps at three depths in the Mona Lake Celery Flat Ponds. Data from GEI.