Muskegon Lake AOC Habitat Restoration Design

Bear Lake Hydrologic Reconnection / Wetland Restoration

Final Project Report

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Project Background and Description

Muskegon Lake is a 4,150-acre drowned river mouth-lake that connects directly to Lake Michigan. 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. Within the AOC is Bear Lake, a shallow eutrophic lake that connects directly to Muskegon Lake through a navigation channel. Historic sawmill debris, foundry sand, and slag filled 798 acres of open water and emergent wetlands in the AOC. Approximately 65 percent of the shoreline was hardened with wood pilings, sheet metal, and concrete (Steinman et al. 2008b). 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. Although the benthos has improved since the end of lake-filling practices and wastewater diversion in 1973 (Carter et al. 2006, Nelson and Steinman 2013), shallow water benthic communities remain degraded. Fish and wildlife populations, including lake sturgeon, walleye, white bass, and various species of reptiles, amphibians, and water birds, have been significantly impaired by the loss of habitat (Bhagat and Ruetz 2011).

Restoration of the Bear Lake Hydrologic Reconnection and Wetland Restoration Area would address a portion of the remaining restoration needed to remove the Fish and Wildlife-related and the Eutrophication and Undesirable Algae Beneficial Use Impairments (BUIs) in the Muskegon Lake AOC. When combined with other currently-proposed and previously-completed restoration initiatives, this project will achieve habitat restoration targets that include shoreline softening, emergent and open water wetland creation, and improvement of unnatural fill areas, thus moving the AOC further along on the restoration trajectory that ultimately will result in the de-listing of the Muskegon Lake AOC.

The Bear Lake Hydrologic Reconnection and Wetland Restoration Area consists of 34 acres of isolated and degraded wetland that would be re-connected with its natural floodplain along Bear Creek and with the Muskegon Lake AOC/Bear Lake surface waters. Abandoned muck farms previously used for celery production, but now converted into shallow ponds, abut Bear Creek just before it enters Bear Lake. Since the 1930's, these muck fields have been disconnected from Bear Creek and Bear Lake, resulting in the loss of significant natural resource ecological values and functions. Restoration of this area would restore fish and wildlife habitat and nutrient removal functions of this former natural floodplain through the restoration of 34 acres of wetland, softening of 2,850 feet of shoreline, and removal of 5.2 acres of fill.

Flooded fields such as these can be converted to functional wetlands, which can result in both improved habitat for fish and wildlife, as well as efficient retention areas for phosphorus via sorption to sediments and biotic uptake by periphyton, macrophytes, and microbial communities (Reddy et al. 1999). However, given their location and past land use, these muck fields also could become major sources of phosphorus to Bear Lake as a result of hydrologic reconnection, at least in the short-term (Aldous et al. 2005, Newman and Pietro 2001). A recent study found that similarly abandoned celery fields located upstream of Mona Lake, another drowned river mouth system in Muskegon County, contributed a significant load of TP to Mona Lake through breaches in the levee (Steinman and Ogdahl 2011). Sediments were implicated as the source of phosphorus in the Mona Lake muck fields study (Steinman and Ogdahl 2011). The potential for sediments to release P to the overlying water depends on the relationship between sediment P sorption and water column P concentrations (Richardson 1985, Pant and Reddy 2001). The equilibrium P concentration (EPC_0) of sediment represents the aqueous P concentration at which no net sorption or desorption occurs when sediment is suspended in a water sample. When the water column P concentration is less than the sediment EPC_0, sediments can potentially release P to the water column and vice versa.

We conducted pre-restoration sampling of the muck fields' water quality and sediments to inform the restoration design and determine if detrimental impacts might result to Bear Creek/Lake as a function of hydrologic reconnection. Specifically, we measured: phosphorus concentrations in the water column, sediments, and pore water; general water quality parameters (e.g., dissolved oxygen, temperature, pH); and sediment organic matter. We also determined phosphorus isotherms for the muck field sediments, which allowed us to calculate the EPC_0 and maximum P sorption capacity (S_{max}) of the sediments. This information will be of value in the development of a restoration design that protects Bear Creek and Bear Lake, while benefitting fish and wildlife.

Methods

Site Description

The muck fields consist of two ponds adjacent to Bear Creek, isolated from each other by Witham Road and isolated from Bear Creek by a levee (Figure 1). Both ponds are on the south side of Bear Creek; the "west field" is located just downstream of the "east field" and ~250 meters upstream of Bear Lake (Figure 1). The surface areas of the east and west fields are 12 acres and 22 acres, respectively. Water from the muck fields was pumped out to facilitate celery farming beginning in the 1930s. Farming was terminated in the east field in 1995 and in the west field in 2002; the pumps were turned off in 2004, allowing the fields to re-flood (G. Mund, personal communication). Excavation for topsoil removal took place in the east field from ~1995-2002, varying in depth from 3-15 feet depending on the depth to sand (D. Willbrandt, personal communication). The west field was not excavated.

We divided the two muck fields into 9 sections (west field = 5, east field = 4) and a sampling site was randomly chosen within each section (Figure 1). These sampling sites were used for water and sediment core collection. In addition, 2 locations were chosen in each field for deployment of sediment pore water samplers (i.e., peepers, Figure 1).

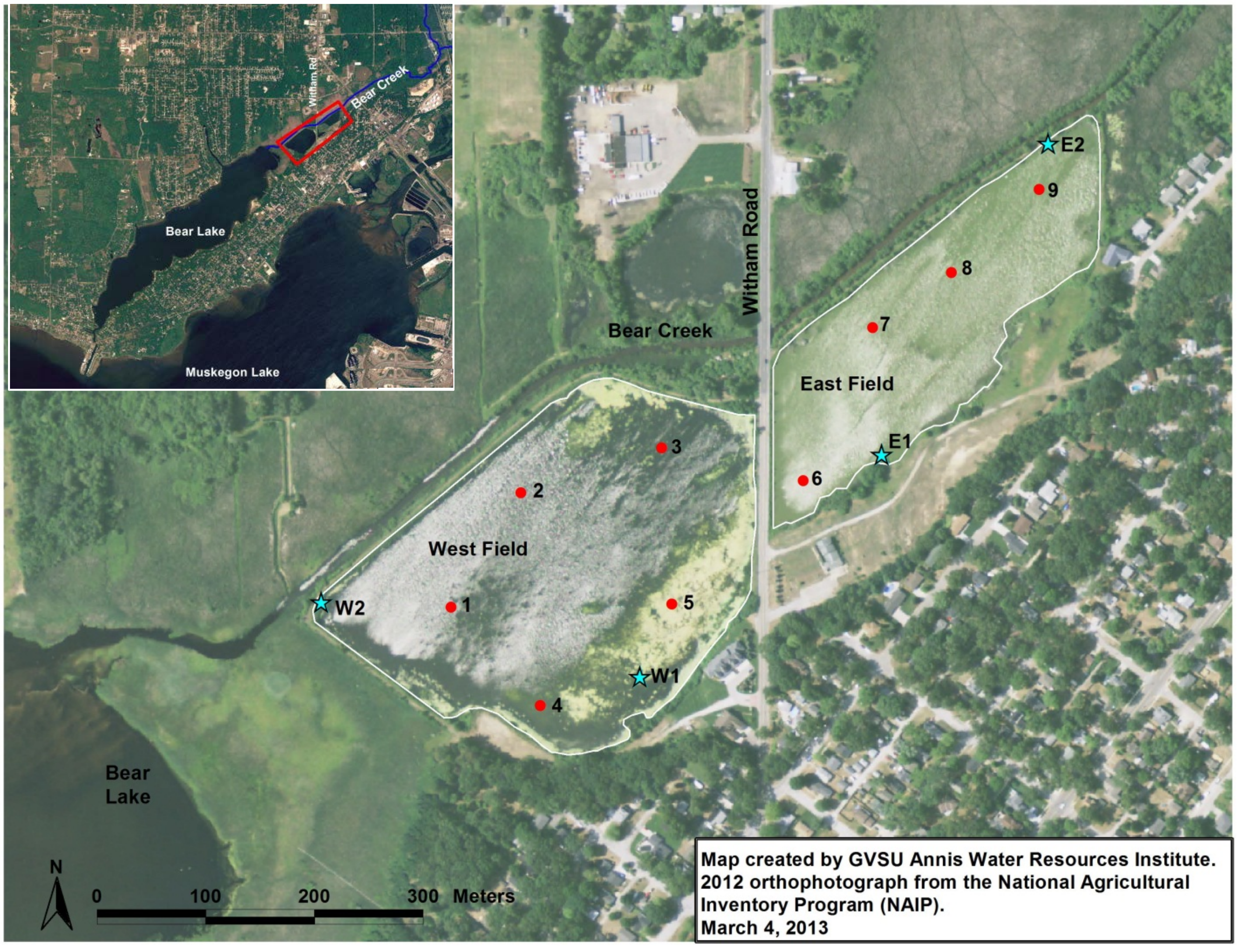

Figure 1. Map of the Bear Lake Hydrologic Reconnection and Wetland Restoration study area, including the east and west muck fields, Bear Creek, and its inflow to Bear Lake (far left). Red dots indicate the locations for water and sediment core collection; blue stars indicate the locations of sediment pore water sampling. The inset map shows the location of the study area (red box) in relation to Bear Lake and Muskegon Lake.

Water quality

Water quality sampling took place on July 18, 2012 between 13:00 and 15:30. At each of the 9 sites (Figure 1), a 250-mL grab sample of the water column was collected at the water surface for analysis of SRP and TP on a Seal AQ2 Discrete Analyzer (U.S. EPA 1993). Water for SRP was syringe-filtered through 0.45-µm membrane filters into scintillation vials and frozen until analysis. A 1-L grab sample was also collected from each site for analysis of chlorophyll *a* on a Shimadzu UV-1601 spectrophotometer (APHA 1992; Method 10200H). General water quality parameters, including dissolved oxygen (DO), turbidity, pH, temperature, redox potential (ORP), specific conductance (SpCond), and total dissolved solids (TDS), were measured at the time of water collection using a YSI 6600 sonde.

Sediment characterization

Immediately following water collection, a ca. 5-cm diameter sediment core was collected from each of the 9 sites (Figure 1) using a modified core sampler (Davis and Steinman 1998). The top 15 cm was removed, placed in a zip-seal bag, and returned to the laboratory for analysis of TP, sediment organic matter (OM), ash-free dry mass (AFDM), and P isotherm measurements. Sediment OM and AFDM were determined using gravimetric procedures (i.e., dry for 24 hr at 105˚C, weigh, ash at 550˚C for 4 hr, re-weigh). The resultant ashed material was used for analysis of sediment TP, according to the method described above (Steinman et al. 2006a).

Phosphorus isotherms were determined in triplicate for each sediment core, according to a procedure modified from Mozaffari and Sims (1994) and Novak et al. (2004). Briefly, 50-mL centrifuge tubes containing 3 g of sediment with 20 mL of inorganic P solutions (KH_2PO_4 dissolved in 0.01 M KCl) containing 0, 0.01, 0.1, 1, 5, 10, 50, 100, 500 mg P/L were shaken for 24 h on an orbital shaker table at 250 RPM. After centrifugation and filtration (0.45 µm), the SRP in the supernatant was analyzed as described above. We chose KCl as the background electrolyte based on pH data that revealed alkaline conditions in the muck fields, which can cause precipitation of Ca when $CaCl_2$ is used (Graetz and Nair 2000, Steinman and Ogdahl 2011). After centrifugation and filtration (0.45 µm), the SRP in the supernatant was analyzed as described above. Equilibrium P concentration (EPC_0) and P sorption maximum (S_{max}) were calculated using the equations in Pant and Reddy (2001).

Sediment pore water sampling

Modified Hesslein in-situ pore water samplers (i.e., peepers) were deployed in the muck fields on July 18, 2012 and retrieved 14 days later, on August 1, 2012. Duplicate sets of peepers were placed at 2 locations within each muck field (Figure 1). 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 were submerged in deoxygenated DI water overnight before deployment in the field. Peepers were placed at each site so that approximately half of the compartments were within the sediment. Peepers were sampled after 14 days using a syringe needle to pierce the membrane and evacuate the liquid in 10 compartments from each peeper. These samples represented a vertical profile of SRP from the water column to at least 16 cm sediment depth. Samples were processed and analyzed for SRP as described above. General water quality parameters were measured at the time of pore water collection using a YSI 6600 sonde (see above).

Data analysis

Data were analyzed for differences in water quality and sediment characteristics between east and west muck fields using t-tests. Data that were not normally distributed or had unequal variance were transformed (ln, square root, reciprocal) prior to analysis. Data that still failed to meet normality and equal variance assumptions after transformation were analyzed using Mann-

Whitney Rank Sum test. Normality was tested using the Kolmogorov-Smirnov test. All statistical analyses were conducted using SigmaPlot (version 12.3; Systat).

Results

Water quality and sediment characterization

Despite their similar geographic proximity, the two muck fields had significantly different mean values of all water column and sediment variables, except pH and ORP (Table 1). Temperature, DO, turbidity, and chlorophyll *a* were all significantly greater in the east field than in the west field; the opposite trend was observed for SpCond and TDS (Table 1). Mean chlorophyll *a* concentrations were extremely high (270 μg/L) in the east field, where a dense algal bloom dominated by the cyanobacteria genera *Anabaena* and *Microcystis* was observed at the time of sampling (Table 1).

Water column and sediment phosphorus were significantly greater in the west field than in the east field (Figures 2 and 3). Mean water column TP was an order-of-magnitude lower in the east field (0.145 mg/L) than in the west field (1.675 mg/L), but even the east field concentrations were extremely high (Figure 2), falling within the hypereutrophic range. In contrast, mean water column SRP was low in the east field (0.006 mg/L) but was extremely high in the west field (1.123 mg/L) (Figure 2). Sediment TP ranged from 1,334 to 4,179 mg/kg in the west field and from 135 to 653 mg/kg in the east field. Similar to sediment TP, mean sediment OM was greater in the west than in the east field, but the statistical difference was only marginally significant (p=0.059).

Sediment TP was comparable to mean values reported for the Black Creek muck fields, which are located immediately upstream of Mona Lake (Figure 4) (Steinman and Ogdahl 2011). Similar to the Bear Creek muck fields, the Black Creek muck fields also were significantly different from one another (Steinman and Ogdahl 2011). Compared to other area lakes, including Bear Lake, the west-Bear Creek (this study) and north-Black Creek (Steinman and Ogdahl 2011) muck fields had the highest mean sediment TP concentrations compared to sediments sampled from other local wetlands and lakes (Figure 4).

Table 1. Summary of water quality parameters measured on July 18, 2012 in the west and east muck fields. P-values represent significance of west vs. east field comparisons using t-test (t) or Mann-Whitney Rank Sum Test (r). NS = not significant (p>0.05).

	West (*n* =5)		East (*n* =4)			
	Mean	SD	Mean	SD	Test	P-value
Bottom depth (m)	0.86	0.14	1.77	0.96	t	NS
Temp (C)	29.27	0.64	30.83	0.59	t	0.007
DO (mg/L)	7.76	1.82	14.66	1.60	t	<0.001
DO% (%)	101.68	24.69	197.20	23.30	t	<0.001
pH	8.88	0.51	9.28	0.12	t	NS
SpCond (μS/cm)	839	21	734	2	r	0.016
ORP (mV)	362	13	338	37	r	NS
TDS (g/L)	0.545	0.014	0.477	0.001	r	0.016
Turbidity (NTU)	9.3	5.3	51.1	8.1	t	0.007
Chlorophyll (μg/L)	10.4	5.1	270.3	355.8	t	<0.001
SRP-P (mg/L)	1.123	0.527	0.006	0.001	r	0.016
TP-P (mg/L)	1.675	0.766	0.145	0.013	r	0.016
Sediment TP, dry (mg/kg)	2771	1243	353	215	t	<0.001
Sediment OM (%)	0.289	0.129	0.121	0.083	t	0.059

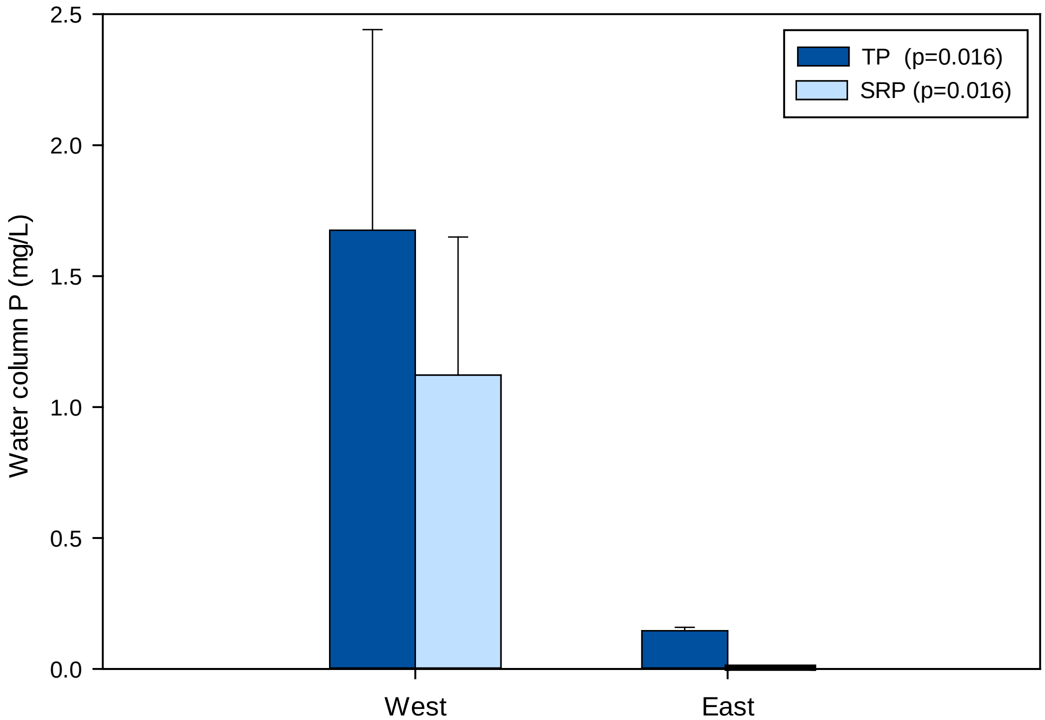

Figure 2. Mean (±SD) water column total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations in the west and east muck fields adjacent to Bear Creek. P-values represent significance of west vs. east field comparisons using Mann-Whitney Rank Sum Test (non-normally-distributed data).

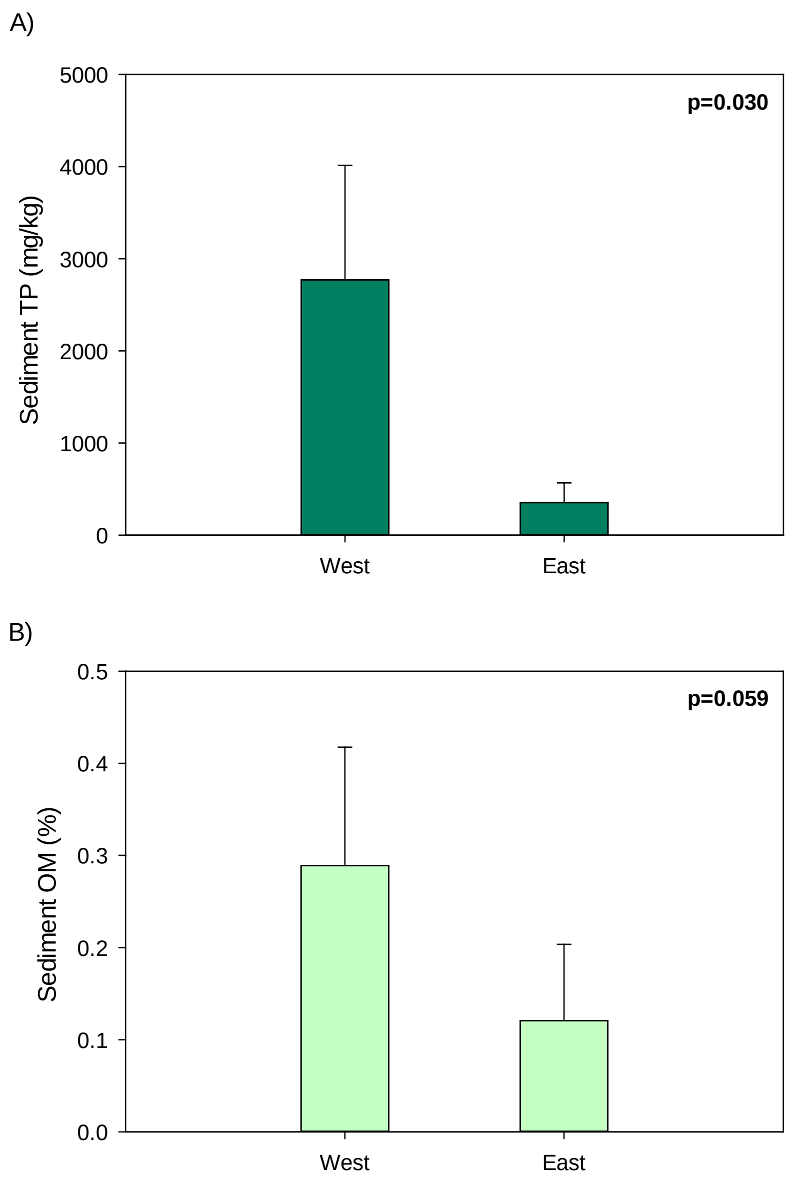

Figure 3. Mean (±SD) sediment TP (dry weight) (A) and organic matter (OM) (B) in the sediments of the west and east muck fields. P-values represent significance of west vs. east field comparisons using t-test.

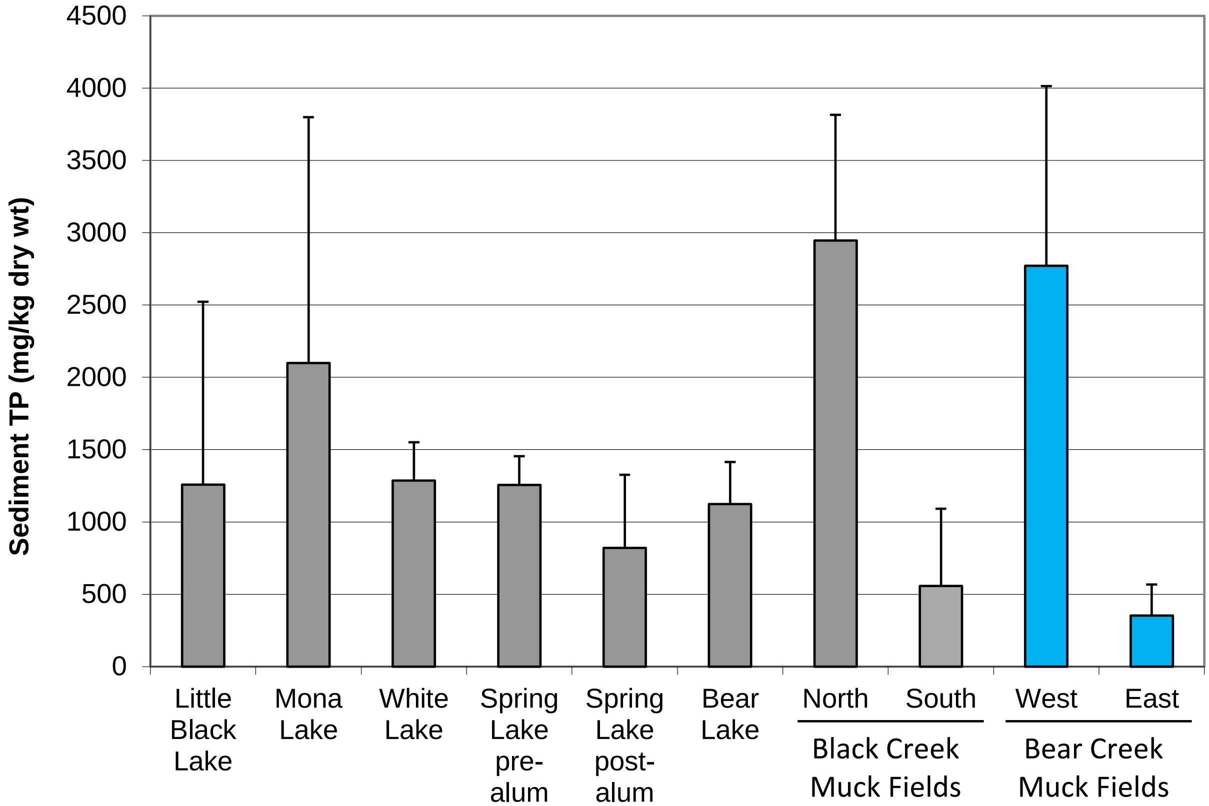

Figure 4. Comparison of mean (±SD) sediment TP (dry weight) measured in the Bear Creek muck fields (blue bars) and other west Michigan waterbodies (gray bars). Sources: Little Black Lake: Steinman et al. 2011; Mona Lake: Steinman et al. 2009; White Lake: Steinman et al. 2008a; Spring Lake pre-alum: Steinman et al. 2004; Spring Lake post-alum: Steinman and Ogdahl 2008; Bear Lake: unpublished data; Black Creek muck fields: Steinman and Ogdahl 2011.

P sorption

Mean EPC_0 values ranged from 0.055 to 0.453 mg/L in the west field; at all sites, the mean EPC_0 values were lower than the associated water column SRP concentration (Figure 5). When EPC_0 values are lower than the SRP concentration in the overlying water column, the sediments can serve as a sink for P, as the concentration gradient helps drive the P from higher (water column) to lower (sediment) concentrations. The situation was reversed in the east field, where mean EPC_0 values ranged from 0.007 to 0.029 mg/L, which were higher than the corresponding water column SRP concentrations at each site (Figure 5). Hence, in the east field, the sediments can serve as a potential source of dissolved phosphorus to the water column. The difference in EPC_0 values among the fields was statistically significant (Table 2), further evidence the fields have very different characteristics and may require separate management strategies.

The mean P sorption maximum (S_{max}) also was significantly different between the two fields (Table 2). The much greater mean S_{max} value in the west field suggests these sediments have a greater overall potential for P sorption than sediments in the east field. However, regardless of the absolute S_{max} value in each field, it is important to compare those values with the corresponding sediment TP values. This allows one to determine if the P sorption capacity of the sediment has been reached and if so, recognize that the sediment has either very limited or no additional ability to sorb more P (i.e., S_{max} > sediment TP); conversely, if S_{max} < sediment TP, then the sorption capacity has not been reached. Our data (Table 3) indicate that in the west field, P saturation of sediment has already occurred in 2 sites (1 and 2) and is near saturation in one other (site 5); in the east field, P saturation of sediment has not yet occurred at any of the 4 sampling sites, but is approaching saturation at two sites (6 and 7; Table 3).

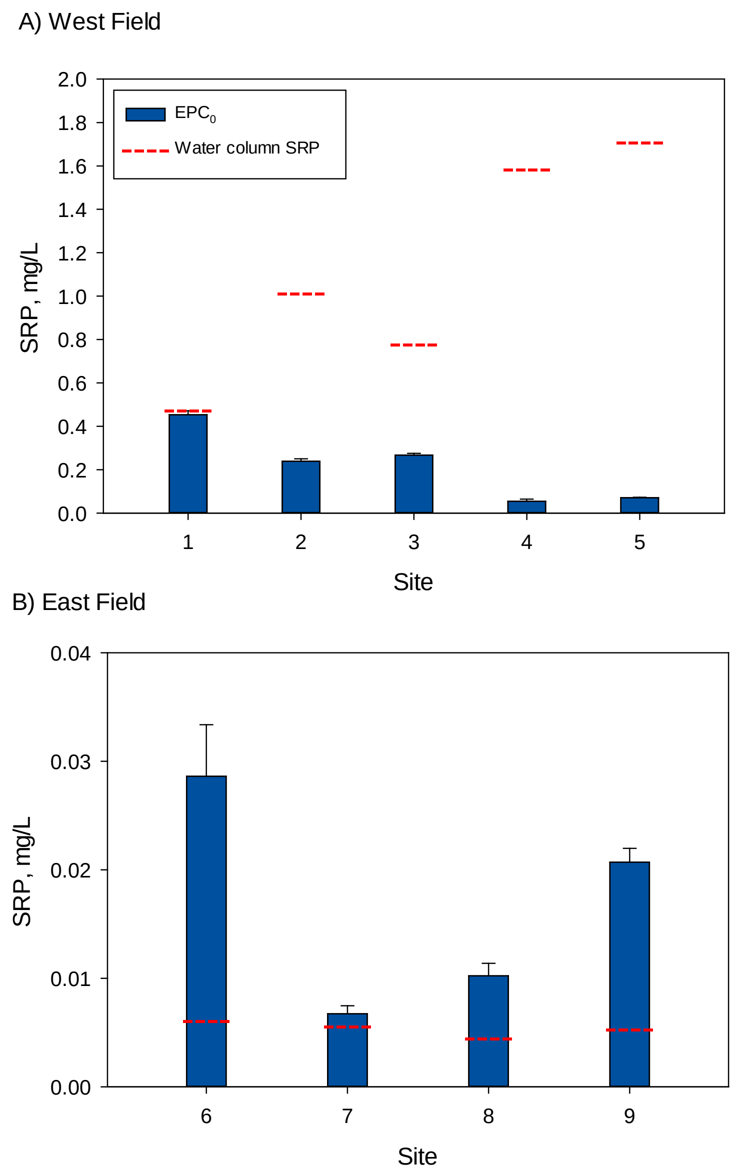

Figure 5. Mean (±SD) equilibrium phosphorus concentrations (EPC_0; blue bars) and water column SRP concentrations (n=1; red lines) at sampling sites in the west (A) and east (B) muck fields. Note different y-axis ranges for panels A and B.

Table 2. Isotherm summary data. EPC_0 = equilibrium phosphorus concentration, S_{max} = P sorption maximum. n=15 for west field means; n=12 for east field means. P-values represent significance of west vs. east field comparisons using t-test (t) or Mann-Whitney Rank Sum Test (r).

	West		East			
	Mean	SD	Mean	SD	Test	P-value
EPC_0, mg/L	0.217	0.151	0.017	0.009	r	<0.001
S_{max}, mg/kg	3413	2868	832	475	t	<0.001

Table 3. Mean S_{max} (n=3) and sediment TP (dry weight) values for sampling sites in the west and east muck fields.

Field	Site	Smax, mg/kg		Sediment TP (dry), mg/kg
		Mean	SD	
West	1	1310	103	1914
West	2	2500	0	3924
West	3	3333	0	2506
West	4	8333	2887	4179
West	5	1587	137	1334
East	6	763	128	527
East	7	268	50	135
East	8	1508	137	549
East	9	602	40	201

Sediment pore water

Pore water SRP was extremely high in both muck fields; consistent with the sediment TP data (Table 3), pore water SRP concentrations were much greater in the west field than in the east field (Figure 6, Table 4). There was a steep SRP gradient from the overlying water column to the sediment pore water in both fields (Figure 6). Mean SRP concentrations at the sediment-water interface were significantly greater in the west field (0.735 mg/L) than in the east field (0.009 mg/L); this difference was even more extreme in the deeper sediment pore water, where the mean concentration in the west field was 5.506 mg/L compared to 0.222 mg/L in the east field (Table 4).

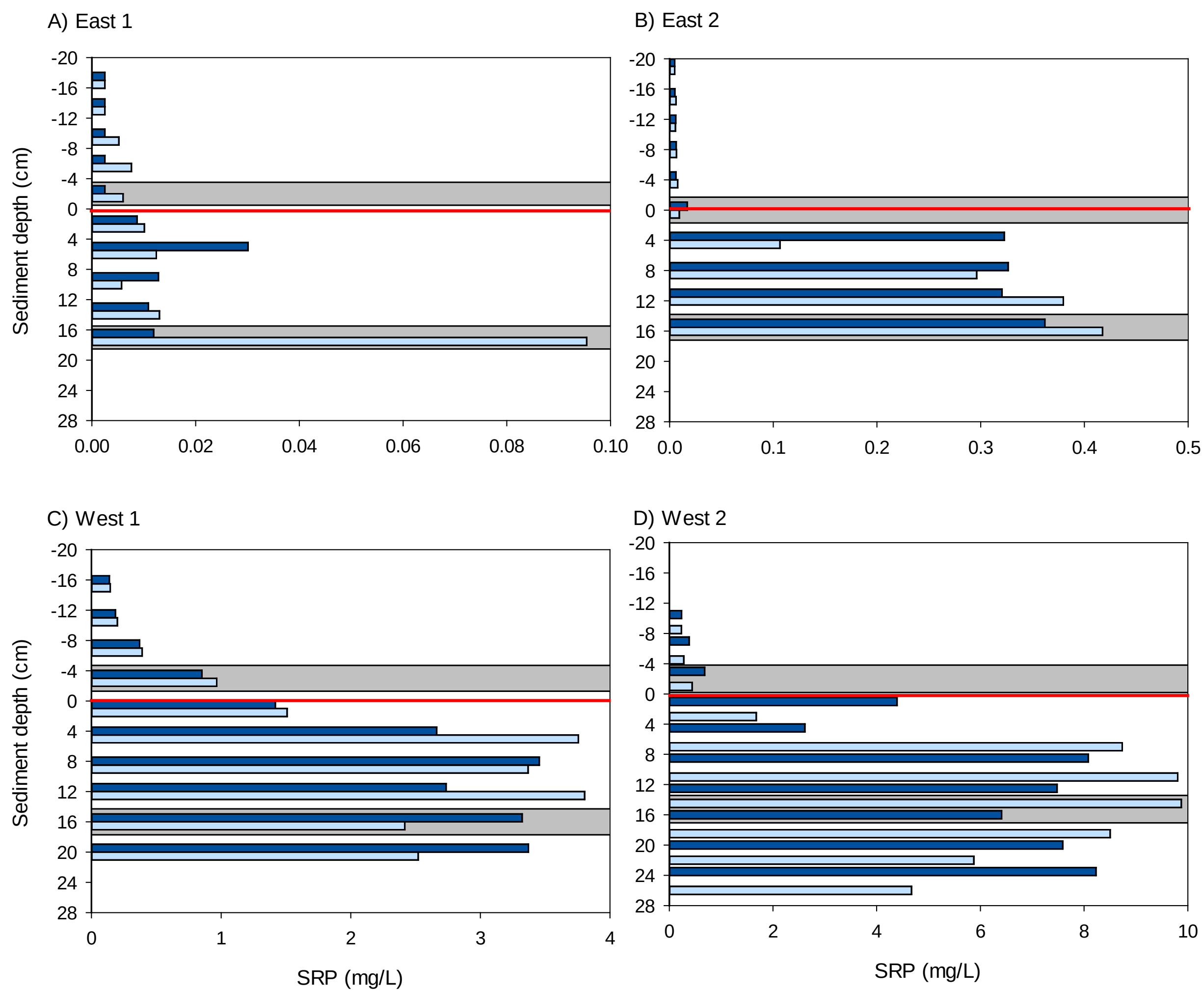

Figure 6. SRP profiles from peepers placed in the east and west muck fields. The red line on each panel indicates the sediment surface. The dark blue and light blue bars at each depth represent samples from duplicate peepers. The duplicate peepers at West 2 (panel D) were unintentionally offset from each other by ~2 cm. Gray shaded areas identify samples used to calculate average SRP at the sediment-water interface (above red line) and in the sediment pore water (below red line). Note different x-axis scales among panels.

Table 4. Sediment pore water summary data, characterizing mean SRP concentrations at the sediment-water interface (-3 to 0 cm above the sediment surface) and in the sediment pore water, at 14.5-17 cm sediment depth (see Figure 6). n=4 for each mean value. P-values represent significance of west vs. east field comparisons using t-test.

	West		East		
	Mean	SD	Mean	SD	P-value
Water column (-3 - 0 cm) SRP (mg/L)	0.735	0.228	0.009	0.006	0.006
Sediment porewater (14.5-17 cm) SRP (mg/L)	5.506	3.377	0.222	0.198	<0.001

Discussion

Ecological implications

Despite their close geographic proximity to one another, the Bear Creek muck fields had very different ecological characteristics. This is undoubtedly related to their prior history, as the east field was dredged whereas the west field was not. The dredging removed a considerable amount of muck soil, and its associated phosphorus. Indeed, the mean sediment TP concentration in the dredged east field was the lowest we have measured among 9 different systems in west Michigan (Steinman et al. 2004, 2008a, 2009, 2004; Steinman and Ogdahl 2008, 2011). Although the sediment TP concentration in the east field was low, there was still sufficient phosphorus in this field's water column to stimulate a very substantial algal bloom, which we assume was responsible for the low dissolved P concentration in the water column (due to biological uptake of P). This low SRP concentration in the water column was far below the EPC_0 values in the east field, creating conditions whereby the sediment could serve as a source of P to the water column. Two key questions that emerged from our study and need to be answered are: 1) how frequent are these bloom conditions in the east field; and 2) do the SRP concentrations increase when there are no blooms (with a reduced biological demand for P)? If SRP concentrations are higher in non-bloom conditions, the EPC_0 values may be closer to water column SRP concentrations, resulting in little or no sediment P release to the water column. Hence, it is important to know bloom dynamics in this field, and if the data we obtained are representative of typical conditions.

In contrast to the east field, the undredged west field had very high sediment TP concentrations. These high concentrations presumably result from a combination of naturally high P levels associated with these histosol soils and the fertilizer applications made when the fields were in celery production. Although we did not measure biota as part of this study, it was evident from our sampling that the submerged aquatic vegetation (SAV) in the west field was extensive and dense, in contrast to the east field. These vascular autotrophs in the west field likely meet most of their phosphorus demand from sediment P (Barko and Smart 1980), so the dissolved inorganic phosphorus concentration is not drawn down in this field to the degree we measured in the east field due to phytoplankton uptake. In addition, the annual dieback and mineralization of organic P from the SAV, coupled with the high sediment TP, contribute to the very high P concentrations in the water column, despite the EPC_0 values that suggest the sediments in this field act as a P sink.

While the high sediment P concentrations certainly are cause for concern, the relationship between sediment TP and P release to the water column is not straightforward (Nürnberg 1988). It is the mobile P (cf. Pilgrim et al. 2007), consisting of the loosely sorbed and Fe-P redox sensitive fractions, that are most likely to contribute to internal P loading. Inclusion of sediment P fractions in the TP measurement that are not mobile, such as aluminum, calcium, and magnesium-bound P, can result in an inaccurate estimate of potential P release. We did not fractionate the sediment P in these sediments, so it is unknown how much of the sediment P is mobile.

Comparison to Black Creek muck fields

The Black Creek (Mona Lake) muck fields also were used for celery production until being flooded in the mid-1980s for conservation and recreation value (Steinman and Ogdahl 2011). Similar to the Bear Creek muck fields, one of the Black Creek muck fields (north) had high sediment organic matter and sediment TP concentrations; the other field had much lower concentrations of OM and sediment TP, although to our knowledge neither field has been dredged.

Unlike the Bear Creek muck fields, the Black Creek muck fields' surface water is hydrologically connected to the adjacent creek through single breaches in the levee. The cuts allowed some exchange with the lower-P-concentration creek water, but also allowed fish passage. Bioturbation by carp likely contributed to the high P concentrations in both of the Black Creek fields (cf. Søndergaard et al. 2003). Restoration projects have been proposed for these muck fields, including an initial closing of the breaches to prevent P-rich water from reaching Black Creek and Mona Lake, and a longer-term strategy involving drawdowns and alum treatment. The Black Creek muck fields are estimated to be the source of approximately 30% of the external load reaching Mona Lake (Steinman and Ogdahl 2011).

Restoration implications

The Bear Creek muck fields provide a unique opportunity, if restored appropriately, to retain nutrients by serving as a flow-through marsh; however, they also may serve as a major source of nutrients to a lake that is already P-rich and subject to cyanobacterial blooms (Steinman et al. 2006b, Xie et al. 2011). Similar to the Black Creek muck fields, the Bear Creek fields have very high water column P concentrations and are located in very close proximity to their receiving water body. Hence, there would be very little time or space for P assimilation before the phosphorus from the muck fields reached Bear Lake.

Given the very high water column SRP and TP concentrations in the west field, it is critical that a considerable amount of phosphorus be retained in the field or removed from the system (e.g., dredged) before this field is hydrologically reconnected to Bear Creek, given its close proximity to Bear Lake. This caution applies also to the east field, as the water columnTP concentrations are still approximately double the maximum summer concentrations measured in Bear Lake (Xie et al. 2011, Steinman and Ogdahl, unpubl. data). Furthermore, it is unclear if the low SRP concentrations we measured in the east field are typical of year-round conditions, or are ephemerally associated with phytoplankton bloom-induced phosphorus uptake.

These results help inform possible restoration options. We identify three possibilities for consideration in a hydrologic reconnection/wetland restoration design:

1) Hydrologic reconnection with treatment and polishing cells

   The three most obvious hydrologic reconnection schemes include: a) flow from Bear Creek entering the upper end of the east field, being directed through different treatment cells throughout the field (cf. Guardo et al. 1995), and exiting at the lower end (near Witham Road) into Bear Creek; b) flow from Bear Creek entering the upper end of the east field, again being exposed to treatment cells before moving through a culvert or series of culverts under Witham Road into the west field, and then exiting through a cut in the west field berm into Bear Creek; and c) flow from Bear Creek entering the upper end of the west field, being directed through different treatment cells throughout the field, and exiting at the lower end into Bear Creek.

   None of the three schemes is ideal. The east field design has the benefits of lower sediment P and lower saturation of sediment P, but the area is relatively small, thereby limiting the overall treatment capacity, and still has high TP concentrations in the surface water. The scenario using both fields has the advantages of a longer hydrologic residence time, which enhances sediment deposition and phosphorus retention (Kadlec and Wallace 2009), and more area with which to work. However, flow directed through the west field in its current condition is potentially problematic given the very high P levels in the sediment and saturated condition of sediment, especially near the berm. The use of just the west field has the dual challenge of small size and sediment saturated with P.

   While treatment wetlands have been shown to be very effective at removing nutrients (Chen 2011, Juston and DeBusk 2011), their initial conditions play a significant role in their efficacy. It is likely that hydrologically reconnecting the fields with Bear Creek and routing flow through various treatment trains consisting of treatment cells would not effectively reduce nutrient loads without some type of sediment processing. This is discussed in more detail below.

2) Dredge the west field

   Dredging is a highly effective, but expensive, option for sediment P mitigation (Cooke et al. 2005). It is a long-term solution provided external nutrient loads are controlled. However, for many projects the benefits are not substantially greater than for chemical inactivation to justify the additional cost. Several factors should be considered before undertaking dredging in the muck fields: a) A disposal area would have to be identified and associated costs figured into the costs of dredging; b) Nutrient-rich sediment can have productive uses, such as soil amendments or potting soil. The sale of dredged sediment can significantly help to offset the overall costs of a dredging project (Cooke et al. 2005); and c) Preliminary studies are necessary to determine whether the muck field sediment is contaminated beyond nutrients. Such a condition would likely make dredging a cost-prohibitive option.

3) Coupled chemical inactivation/drawdown

Another alternative would be a coupled chemical inactivation and water drawdown project. In this case, a chemical such as alum, which binds to phosphorus, would be added to each field to strip phosphorus from the water column. Then, the water would be drawn down, the sediment exposed to air and naturally consolidated, and re-inundated. The different phases and details are below:

<u>Phase 1:</u> The first phase requires the installment of a multi-directional pump structure to allow both de-watering (i.e., "drawdown") and re-flooding of the fields. This would provide additional water level management and also facilitate drawdown, which provides three important functions: a) consolidation and oxidation of the muck soils; b) creation of favorable conditions for plant growth; and 3) elimination of any bioturbating fish, such as common carp, which can stir up the P-laden sediments and out-compete preferred native fish species.

<u>Phase 2:</u> Following the installation of pumps, the fields would be treated with aluminum sulfate (alum) or similar P inactivation agent to strip out the P in the water column and inactivate the P in the sediment (Cooke et al. 2005). The alum treatment ideally would reduce P concentrations in the water to the point where it could be discharged into Bear Creek without creating any water quality violations. The alum treatment also will facilitate the establishment of rooted wetland vegetation in the fields by reducing sediment P release and competition for light from phytoplankton.

<u>Phase 3:</u> Utilizing the pumps, both fields will be completely drawn down one at a time to consolidate the soils, facilitate establishment of native wetland vegetation, and eliminate common carp, thereby providing ideal conditions for the return of productive and functioning wetlands.

<u>Phase 4:</u> Upon wetland vegetation establishment (approximately one growing season) and soil consolidation, the fields would be re-flooded to complete the hydrological restoration of these wetlands. In the event that monitoring indicates that a second drawdown is needed to promote wetland vegetation establishment and reduce P concentrations to a lower level, another drawdown would occur in the following year.

<u>Phase 5:</u> Following the attainment of safe and acceptable P levels, the water control structure would be completely opened to allow water from Bear Creek to freely flow into the fields to re-create the coastal flow-through marshes that existed historically.

This design option would restore valuable wetland habitat, eliminate the need (and expense) of sediment dredging, promote biotic uptake and the physic-chemical settling and entrapment of P (i.e., phytoremediation), and attenuate P-loading to Bear Lake.

Summary

The results from this study show that the phosphorus concentrations, both in the sediments and the water column, in the Bear Creek muck fields require remediation before hydrologic reconnection to Bear Creek. The fields have different sediment phosphorus characteristics, likely attributable to one field being dredged, but water column P is high in both. In addition, isotherm data indicate P saturation is occurring in some sediments, so there is limited capacity to sorb additional phosphorus in the future. Three possible restoration scenarios are presented, which can be evaluated separately or in combination with one another, to address the phosphorus issue before hydrologic reconnection.

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References

Aldous A., P. McCormick, C. Ferguson, S. Graham, and C. Craft. 2005. Hydrologic regime controls soil phosphorus fluxes in restoration and undisturbed wetlands. Restoration Ecology 13: 341–347.

APHA. 1992. Standard Methods for the Examination of Water and Wastewater. 18th Edition. American Public Health Association.

Barko, J.W. and R.M. Smart. 1980. Mobilization of sediment phosphorus by submersed freshwater macrophytes. Freshwater Biology 10: 229-238.

Bhagat, Y. and C.R. Ruetz III. 2011. Temporal and fine-scale spatial variation in fish assemblage structure in a drowned river mouth system of Lake Michigan. Transactions of the American Fisheries Society 140: 1429-1440.

Carter, G.S, T.F. Nalepa, and R.R. Rediske. 2006. Status and trends of benthic populations in a coastal drowned river mouth lake of Lake Michigan. Journal of Great Lakes Research 32: 578-595.

Chen, H. 2011. Surface-flow constructed treatment wetlands for pollutant removal: applications and perspectives. Wetlands 31: 805-814.

Cooke, G.D., E.B. Welch, S.A. Peterson, and S.A. Nichols. 2005. Restoration and management of lakes and reservoirs. 3rd edition. CRC Press, Boca Raton, FL.

Davis, W.P. and A.D. Steinman. 1998. A lightweight, inexpensive benthic core sampler for use in shallow water. Journal of Freshwater Ecology 13: 475-479.

Graetz, D.A. and V.D. Nair. 2000. Phosphorus sorption isotherm determination. *In* G.M. Pierzynski (ed.) Methods of phosphorus analysis for soils, sediments, residuals, and waters. Southern Coop. Ser. Bull. 396. Kansas State Univ., Manhattan.

Guardo, M., L. Fink, T.D. Fontaine, S. Newman, M. Chimney, R. Bearzotti, and G. Goforth. 1995. Large-scale constructed wetlands for nutrient removal from stormwater runoff: an Everglades restoration project. Environmental Management 19: 879-889.

Juston, J.M. and T.A. DeBusk. 2011. Evidence and implications of the background phosphorus concentration of submerged aquatic vegetation wetlands in Stormwater Treatment Areas for Everglades restoration. Water Resources Research 47: W01511.

Kadlec, R.H. and S.D. Wallace. 2009. Treatment Wetlands. 2nd Edition. Taylor and Francis, Boca Raton, FL.

Mozaffari, M. and J.T. Sims. 1994. Phosphorus availability and sorption in an Atlantic Coastal Plain watershed dominated by animal-based agriculture. Soil Science 157: 97-107.

Nelson, W.A. and A.D. Steinman. 2013. Changes in the benthic communities of Muskegon Lake, a Great Lakes Area of Concern. Journal of Great Lakes Research 39: 7-18.

Newman S. and K. Pietro. 2001. Phosphorus storage and release in response to flooding: implications for Everglades stormwater treatment areas. Ecological Engineering 18: 23-38.

Novak, J.M., K.C. Stone, A.A. Szogi, D.W. Watts, and M.H. Johnson. 2004. Dissolved phosphorus retention and release from a coastal plain in-stream wetland. Journal of Environmental Quality 33: 394-401.

Nürnberg, G.K. 1988. Prediction of phosphorus release rates from total and reductant-soluble phosphorus in anoxic lake sediments. Canadian Journal of Fisheries and Aquatic Sciences 45: 453-462.

Pant, H.K. and K.R. Reddy. 2001. Phosphorus sorption characteristics of estuarine sediments under different redox conditions. Journal of Environmental Quality 30: 1474-1480.

Pilgrim, K.M., B.J. Huser, and P.L, Brezonik. 2007. A method for comparative evaluation of whole-lake and inflow alum treatment. Water Research 41: 1215-1224.

Reddy, K.R., R.H. Kadlec, E. Flaig, and P.M. Gale. 1999. Phosphorus retention in streams and wetlands: a review. Critical Reviews in Environmental Science and Technology 29: 83-146.

Richardson, C.J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. Science 228: 1424-1427.

Søndergaard, M., J.P. Jensen, and E. Jeppesen. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506–509: 135–145.

Steinman, A.D., R. Rediske, and K.R. Reddy. 2004. The reduction of internal phosphorus loading using alum in Spring Lake, Michigan. Journal of Environmental Quality 33: 2040-2048.

Steinman, A.D., G.A. Lamberti, P. Leavitt. 2006a. Biomass and pigments of benthic algae. Pages 357-379. In: Methods in Stream Ecology, R. Hauer and G. Lamberti (editors). Academic Press, NY.

Steinman, A.D., R. Rediske, X. Chu, R. Denning, L. Nemeth, D. Uzarski, B. Biddanda, and M. Luttenton. 2006b. An environmental assessment of an impacted, urbanized watershed: the Mona Lake Watershed, Michigan. Archiv für Hydrobiologie 166: 117-144.

Steinman, A.D. and M. Ogdahl. 2008. Ecological effects after an alum treatment in Spring Lake, Michigan. Journal of Environmental Quality 37:22-29.

Steinman, A.D., M. Ogdahl, and M. Luttenton. 2008a. An analysis of internal phosphorus loading in White Lake, Michigan. Pages 311-325. F.R. Miranda and L.M. Bernard (editors). Lake Pollution Research Progress. Nova Science Publishers, NY.

Steinman, A.D., M. Ogdahl, R. Rediske, C.R. Ruetz III, B.A. Biddanda, and L. Nemeth. 2008b. Current status and trends in Muskegon Lake, Michigan. Journal of Great Lakes Research 34: 169-188.

Steinman, A.D., X. Chu, and M. Ogdahl. 2009. Spatial and temporal variability of internal and external phosphorus loads in an urbanizing watershed. Aquatic Ecology 43: 1-18.

Steinman, A.D., and M.E. Ogdahl. 2011. Does converting agricultural fields to wetlands retain or release phosphorus? Journal of the North American Benthological Society 30: 820-830.

Steinman, A.D., M.E. Ogdahl, and C.R. Ruetz III. 2011. An environmental assessment of a small shallow lake (Little Black Lake, MI) threatened by urbanization. Environmental Monitoring and Assessment 173: 193-209.

U.S. EPA. 1993. Methods for Chemical Analysis of Inorganic Substances in Environmental Samples. Method 365.31; EPA-600/4-79R-93-020/100.

Xie, L., J. Hagar, R.R. Rediske, J. O'Keefe, J. Dyble, Y. Hong, and A.D. Steinman. 2011. The influence of environmental conditions and hydrologic connectivity on cyanobacteria assemblages in two drowned river mouth lakes. Journal of Great Lakes Research 37: 470-479.