ST. ANTHONY
FALLS LABORATORY

Project Report No. 599

St. Cloud Pond 52: Assessment of Pond Sediments After Iron Filings Treatment

Final Report

Prepared by:

Poornima Natarajan
John S. Gulliver
St. Anthony Falls Laboratory
University of Minnesota
2 Third Avenue SE Minneapolis, MN 55455

Prepared for:

City of St. Cloud
525 60th Street South, St. Cloud, MN 56301

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1 Introduction and Purpose

Pond 52, also called Little George, is a stormwater treatment pond (surface area = 0.52 ac) located in the City of St. Cloud in Stearns County, MN. The pond was constructed in 1998 to capture sediments and other runoff constituents (drainage area = 58 ac) before the runoff is directly conveyed to Lake George, an impaired waterbody due to low water clarity and high phosphorus levels since 2012[1] (the lake is proposed to be removed from the Minnesota's Impaired Waters List in 2022).

The analysis of Pond 52 sediments in 2016 (Olsen 2017) showed a potential for anoxic sediment phosphorus (P) release (3.44 mg P/m^2/day), high sediment oxygen demand (4.21 g/m^2/day), and a high concentration of bioavailable P forms in the sediments, especially the labile organic P (0.48 mg P/g), indicating a risk for internal phosphorus loading in the pond under summertime anoxia. Also, the historic total phosphorus (TP) concentrations in the pond water have been relatively high during the growing season (mean = 0.49 mg/L; max = 1.30 mg/L for the 2014 to 2017 period; City of St. Cloud data), which means the pond may discharge a high phosphorus load to the downstream lake. There is evidence of internal P loading, including high pond phosphorus concentrations and prevalence of summertime anoxia, in several stormwater ponds in the Twin Cities Metro Area, an indication that such ponds can be potential sources of phosphorus to downstream waterbodies (Taguchi et al. 2020, Janke et al. 2021).

As part of the Lake George's Water Quality Improvement Implementation Plan, the City of St. Cloud performed non-routine maintenance by dredging Pond 52 in November 2018 to restore its treatment capacity. The City also applied iron filings to the pond sediments in Spring 2019, as a chemical treatment measure for capturing the phosphorus in the sediments and reducing its re-release into the pond water column and further downstream to the lake. About 0.05 g iron/cm^2 of sediment area (i.e., 4461 lb/ac) was spread over the pond area. The iron application dose was selected based on the results of a laboratory-scale experimental iron-dosing study conducted at SAFL that showed a decrease in phosphate release from lake sediments amended with iron filings, under both oxic and anoxic conditions (Natarajan et al. 2021).

The City has been conducting post-maintenance water quality monitoring of Pond 52 since Spring 2019. The in situ data collected during the 2019 and 2020 field seasons (April to October period) indicated that the pond stratifies during a portion of the summer with bottom DO levels nearing anoxia (< 1 mg/L), which also coincides with a small elevation in phosphorus levels (see memo[2] for detailed discussion). Nevertheless, the 2019 to 2021 phosphorus data indicate an overall improvement in the pond water quality after the pond maintenance; i.e., a lowering of total and ortho-phosphorus concentrations in the pond water since 2019 when compared to the pre-maintenance concentrations (Figure 1). It is, however, not clear if the observed response is

[1] https://coscgis.maps.arcgis.com/apps/MapSeries/index.html?appid=3d7e60cdb96d42a4b68e22cc7322d1b9
[2] https://ci.stcloud.mn.us/DocumentCenter/View/21983/Pond-52-Memo

the result of iron filings application, or dredging, or a combination of the two non-routine maintenance measures.

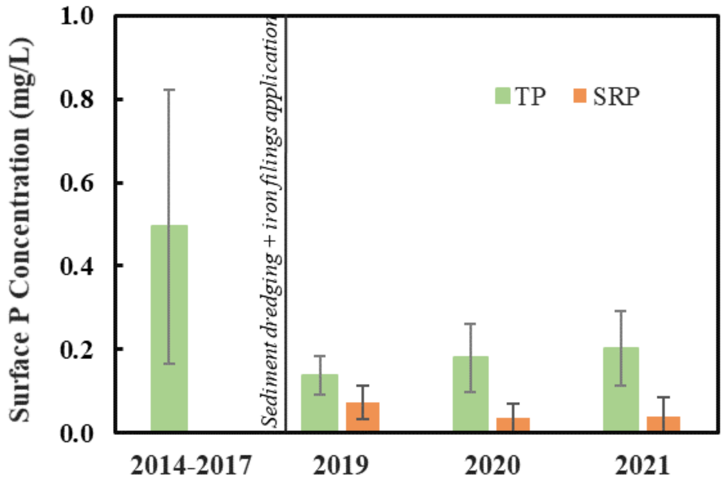

Figure 1. Historic (2014-2017) and post-maintenance (2019-2021) phosphorus water quality in Pond 52. The pond was dredged in November 2018 and then treated with iron filings in Spring 2019. The average total phosphorus (TP) and soluble reactive phosphorus (SRP, ortho-phosphorus) concentrations in the surface water of the pond during the April to October period are plotted. Error bars represent standard deviation of the mean. Data collected by the City of St. Cloud.

As part of the post-maintenance assessment of Pond 52, the City of St. Cloud partnered with the University of Minnesota (UMN) to perform a detailed analysis of the pond sediments. The goal of this work is to evaluate the impact of iron filings application on the pond sediment chemistry, especially the sedimentary phosphorus pool that can contribute to internal phosphorus loading. Sediment cores were collected from the pond for analysis and the findings are summarized in this report.

2 Methods

2.1 Sediment Core Collection

Five sediment cores were collected from Pond 52 in April 2021 (Figure 2). The upper 20-25 cm depth of sediments were collected into polycarbonate liner tubes (70 mm O.D.) using a surface corer. Visual examination indicated that the sediments were dark and blackish (i.e., mucky appearance) through the top 20 cm depth in four cores. One core (Core 2) showed the presence of lighter brown sediments (i.e., clayey appearance) beyond the 12 cm depth of sediments. The blackish appearance is likely organic material that remained after dredging of the pond.

Figure 2. Map of sediment coring locations (1-5) and photograph of the five sediment cores collected from Pond 52 in April 2021 for the post-iron treatment sediment analysis.

2.2 Sediment Analysis

The pond sediments were analyzed for the different types of phosphorus (P) fractions contained in the total sedimentary P pool (Table 1), which consist of the biologically-available P fractions (i.e., loosely-bound P, iron-bound P, and labile organic-P) that contribute to internal phosphorus loading, and other P forms that are not generally available or sensitive to changes in DO conditions in the pond (i.e., aluminum-bound P, mineral-bound P, and other refractory P).

The top 20 cm sediments in the five sediment cores were sectioned (1-cm sections for upper 6 cm depth, 2-cm sections for the 6 to 12 cm depth, and 3- and 5-cm section up to the 20 cm depth) and analyzed following the sequential extraction method using the extractants summarized in Table 1 (method adapted from Psenner and Puckso 1988 and SCWRS 2010). The labile organic-P fraction was determined by subtracting the aluminum-bound P from the nonreactive NaOH-extractable P (Al-P + labile organic-P determined by persulfate digestion of NaOH extract). The extracts from each step were centrifuged at 3000 RPM for 10 minutes and analyzed for orthophosphate (soluble reactive phosphorus, SRP) concentrations in a Lachat autoanalyzer using ascorbic acid colorimetry (APHA 1995). The extracts from the iron-bound P analysis step were bubbled with oxygen for 20 minutes before the SRP analysis.

Table 1. Sediment phosphorus (P) fractions in the pond sediments determined using the sequential phosphorus extraction method. Descriptions of the phosphorus fractions and their biological availability are included. Details of the chemical extractant solutions (concentrations expressed in molarity (M) or normality (N)) used in each extraction step are provided. The sum of the six P fractions provides the total P in the sediments.

Sediment P fraction	Description	Biological availability and mobility conditions	Extractant for sequential extraction method
Loosely-bound P	Porewater-soluble and adsorbed to calcium carbonate	Biologically available when released under oxic and anoxic conditions	1 M ammonium chloride
Iron-bound P (Fe-P)	Adsorbed to iron oxyhydroxides	Biologically available when released under anoxic conditions	0.11 M sodium bicarbonate and 0.1 M sodium dithionite
Aluminum-bound P (Al-P)	P bound to amorphous aluminum hydroxide	Biologically unavailable; can release under high pH conditions	0.1 M sodium hydroxide (NaOH)
Labile organic-P	Organic P that can be mineralized by bacteria to soluble P	Biologically available after mineralization and released under oxic and anoxic conditions	Persulfate digestion of the extract from the Al-P extraction step
Mineral-bound P	Calcite- and apatite-bound P	Biologically unavailable; can release under low pH conditions	2 N hydrochloric acid (HCl)
Residual organic- P	Presumed organic and refractory	Biologically unavailable	30% hydrogen peroxide and 2 N HCl

Water content analysis (drying at 105 °C) and organic matter content analysis (loss on ignition at 550 °C) of the sediments were also performed. The total metal concentration in the pond sediments was determined at the UMN Research Analytical Laboratory, using the acid digestion and ICP-OES method (EPA 3051). Sub-samples from the upper 15 cm sediment sections were combined into 2-cm depth sections, dried, and sieved through a 2-mm sieve prior to metal analysis.

3 Results

3.1 Sediment Phosphorus Characterization

The physical characteristics and the phosphorus fractionation results for the five sediment cores from Pond 52 are summarized in the Appendix Table A-1.

The analysis of the moisture content and organic matter content in the upper 20 cm depth of sediments revealed both spatial and vertical variation in the physical characteristics of the sediments in the pond area (Figure 3). The moisture content in the upper 8 cm sediments in four cores (Cores 1 to 4) ranged from 70 to 92%, which indicates a relatively high solids content and thus dense sediments. The sediment organic content was relatively high in these cores, varying between 19 and 39% over the 0 to 8 cm depth (mean = 27%). Beyond the 8 cm depth, sediment moisture content decreased further down to 50% near the 20 cm depth. Sediments collected at one location (Core 5; Figure 3) contained a lower moisture content, higher bulk density, and the lowest organic matter content when compared to other sediments locations in the pond (Cores 1 to 4); it is probable that the Core 5 location receives and accumulates the least amount of incoming debris due to the runoff flow pattern and pond configuration.

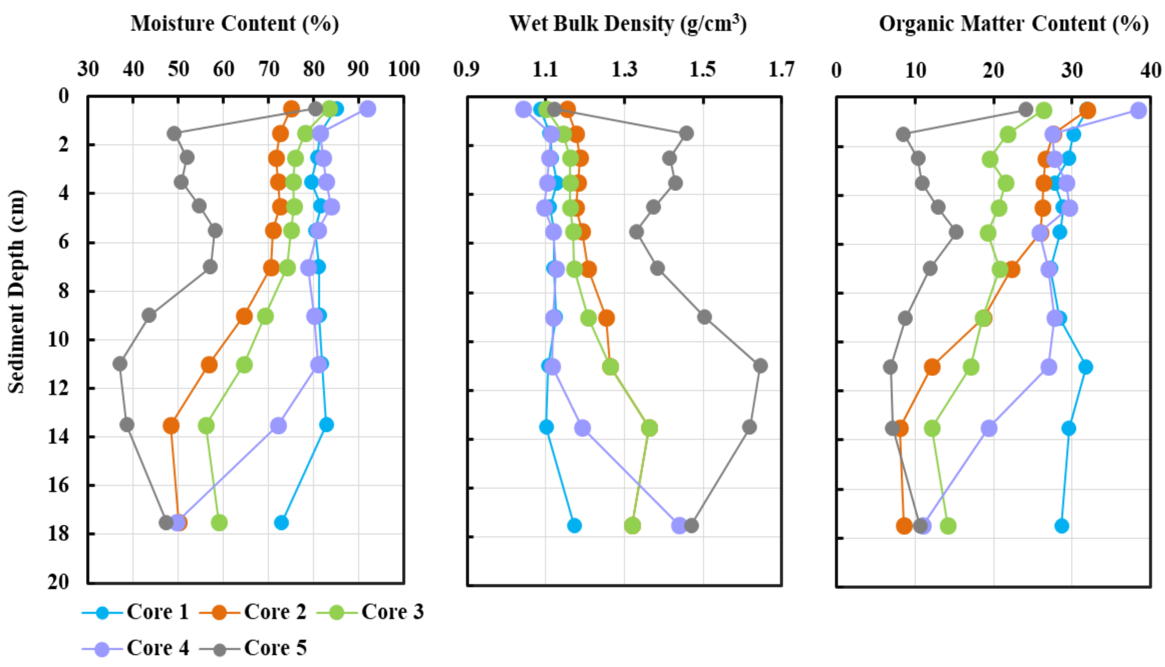

Figure 3. Vertical variations in the sediment moisture content, wet bulk density, and organic matter content in Pond 52. The 0 cm sediment depth represents the sediment-water interface. Values are plotted in the mid-point of a given sediment depth interval (for example, concentration for 0-2 cm depth is plotted at 1 cm).

Spatial and vertical variability was observed in the concentrations of P fractions in the sediments (Figure 4). The loosely-bound P was low (< 0.005 mg P/g) in the sediments. The iron-bound P concentrations were high in the sediments, especially in Core 1 (Figure 4); the high concentrations are attributed to the adsorption of phosphorus to iron oxide/hydroxides formed from the iron filings added to the sediments (Natarajan et al. 2021). Not surprisingly, iron-bound P was the predominant P fraction in the upper sediment layers, except for Core 4. Concentration peaks for iron-bound P was found to be in the top 3 or 6 cm sediment depth in Cores 1-4. Given the sediment moisture contents at these locations, it is likely that the iron filings pieces deposited across the top 6 cm depth during the iron filings application and produced a higher P mass sorption within that depth.

As expected, the iron-bound P decreased beyond the 6 cm sediment depth. The sediments at coring location 5 contained the lowest amount of iron-bound P, even in the top 2 cm of sediments, and these concentrations were similar to the iron-bound P found below the 6 cm depths at the locations. The spatial and vertical variability in iron-bound P are likely a result of differences in iron concentrations in these sediments (see discussion in Section 3.2 and Figure 5a). As discussed earlier, the low P and iron in Core 5 could also be due to the dense nature of sediments at this location (Figure 3) that may prevent deeper penetration of iron filings into the sediments.

Labile organic-P concentrations were moderately high in the upper 8 cm depth in three cores (Cores 1, 2, 4), but were present at much lower levels in Core 5. The labile organic-P also decreased with sediment depth, representing microbial degradation of organic material. These observations are in agreement with their respective sediment organic content profiles (Figure 3). Together, the iron-bound P and labile organic P constitute a relatively high concentration of mobile (bioavailable) P in the upper 6 cm depth of the existing sediments in Pond 52, composed of 57% iron-bound P and 43% labile organic-P mass.

Concentrations of the unavailable P fractions, i.e., aluminum-bound P, mineral-bound, and residual-P, were generally low and presented minimal vertical variability in most of the sampled sediments; vertical variation was visible only in Cores 2 and 3. The concentrations of these P fractions are not expected to be impacted by iron filings as these P forms are not mobilized under low redox conditions in the sediments. The average total P composition in the top 6 cm of the existing sediments is 34% redox-P (loosely-bound P + iron-bound P), 26% labile organic-P, 17% Al-P, 12% mineral-P, and 11% residual-P (total P data provided in the Appendix Table A-1).

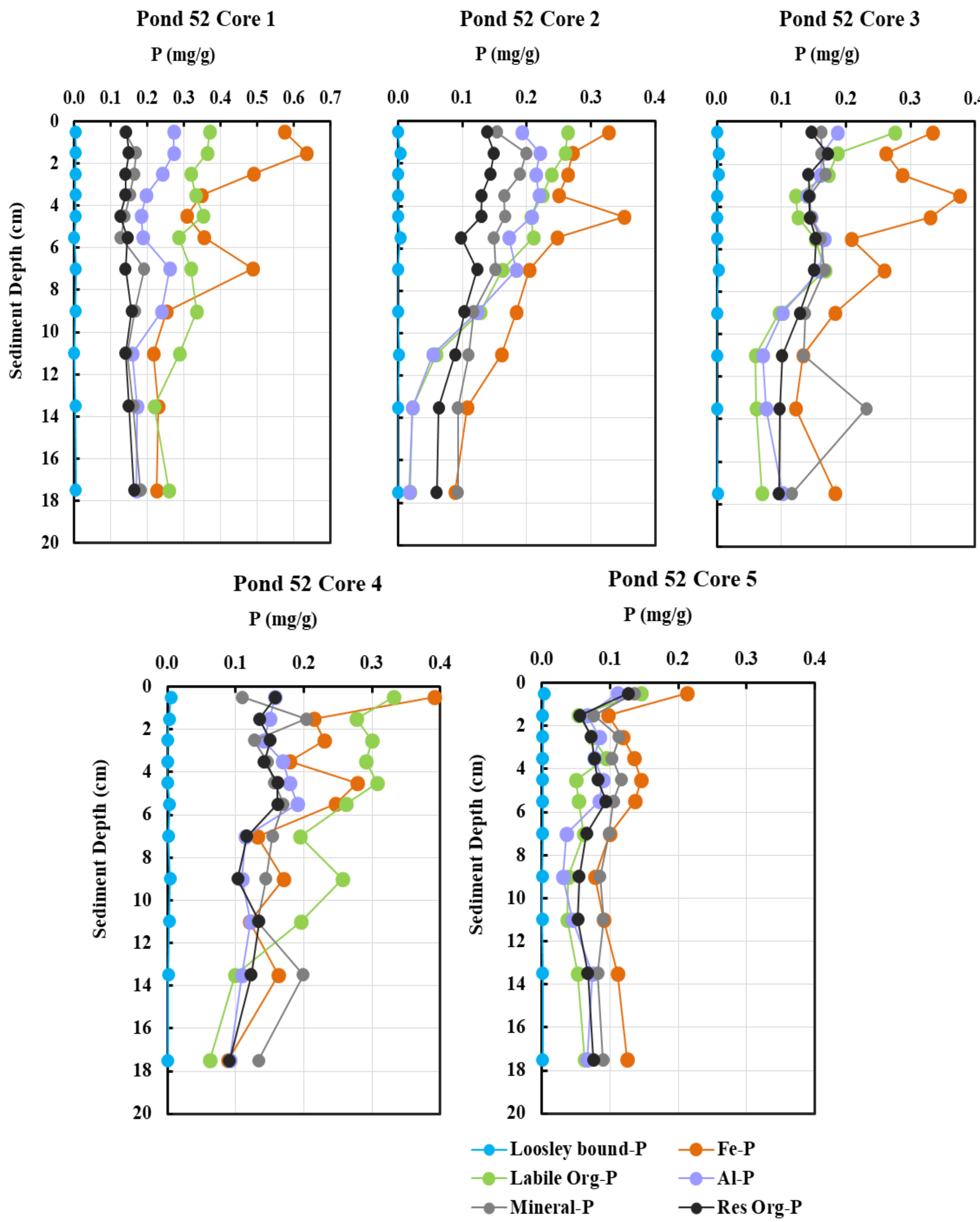

Figure 4. Vertical profiles of the sediment phosphorus (P) fractions in the five sediment cores collected from Pond 52. The loosely-bound P, iron-bound P (Fe-P) and labile organic-P are the bioavailable or mobile forms of sediment P. Total P is the sum of the six P fractions as provided in the Appendix Table A-1. The sediment depth 0 cm represents the sediment-water interface. Concentrations are expressed on a dry sediment weight basis and are plotted in the mid-point of a given sediment depth interval (for example, concentration for 0-2 cm depth is plotted at 1 cm). Note difference in X-axis scale for the Core 1 plot.

3.2 Sediment Iron Concentrations

The results of metal analysis of the five sediment cores are summarized in the Appendix Table A-2. The total iron (Fe) concentrations in the top 15 cm depth of sediments varied across the pond area, with lowest Fe concentrations at coring location 5 (Figure 5a). These differences are expected because a perfectly uniform distribution of iron filings is difficult to achieve. The vertical profiles indicated that the Fe concentrations were more or less uniform throughout the upper 8 cm depth of sediments, except for in Core 5 that exhibited a vertical variation and a peak in concentration the 5 cm depth. In Cores 1 to 4, the upper 8 cm sediments have 92 to 70% moisture content and the bulk density is higher in the deeper sediments (Figure 3). The vertical changes in sediment physical characteristics is reflected in the vertical profiles of sediment Fe beyond the 8 cm depth. The sediments at coring location 5, that had the lowest Fe levels, also had high density throughout the 0 to 15 cm depth (<50% moisture content). As discussed earlier, vertical variability in the sediment's physical characteristics influenced not only the vertical deposition of the iron filings pieces into the sediments, but also the corresponding availability of iron to bind P. Additionally, the processes of chemical dissolution and movement of dissolved iron will slowly continue to change the vertical distribution of iron over time.

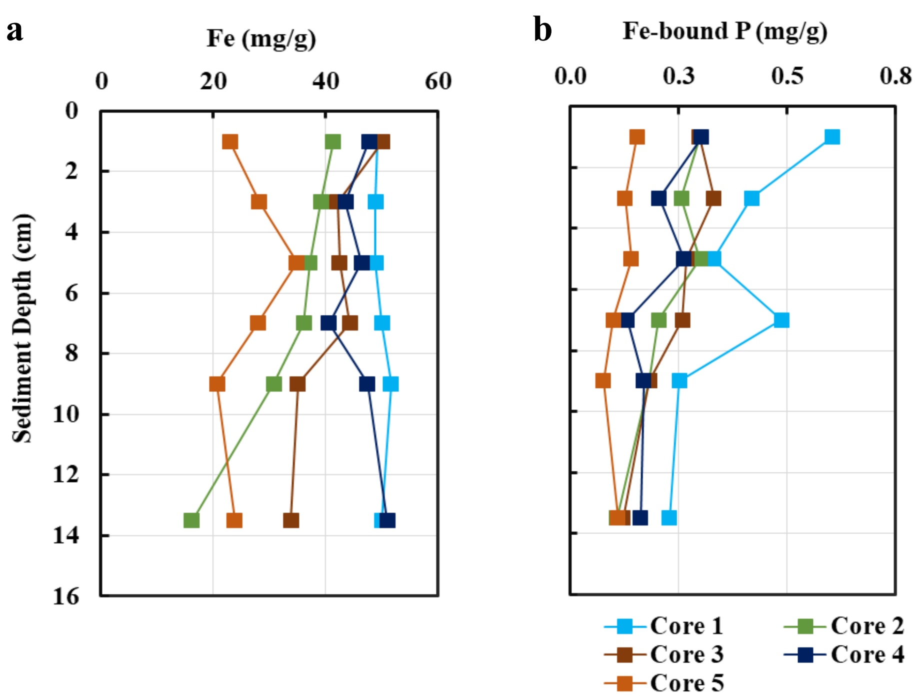

Figure 5. Vertical profiles of total iron (Fe) and iron-bound phosphorus (P) fraction in the upper 15 cm sediments of Pond 52. The sediment depth 0 cm represents the sediment-water interface. Concentrations are expressed on a dry sediment weight basis and are plotted in the mid-point of a given sediment depth interval (for example, concentration for 0-2 cm depth is plotted at 1 cm).

Figure 5b shows the vertical profiles of iron-bound P in the sediments that largely appear to follow the total sediment Fe profiles; i.e., higher iron-bound P was formed at the locations with high Fe concentrations, which means the availability of reactive iron corresponded with P sorption onto iron. The scatter plot in Figure 6 further illustrates the correlation between Fe and iron-bound P concentrations determined in the upper 15 cm depth of sediments. The linear correlation coefficient improved to a $R^2 = 0.54$ if only the upper 8 cm depth was considered.

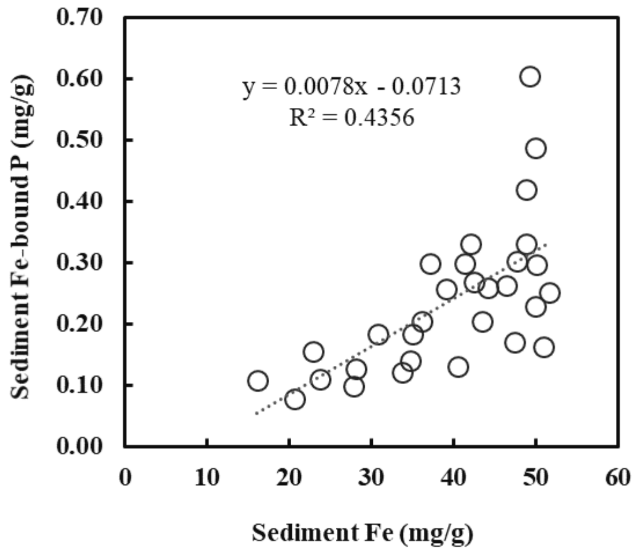

Figure 6. Correlation plot showing the sediment concentrations of total iron (Fe) and iron-bound phosphorus (P) fraction in Pond 52. Data are plotted for the 0 to 15 cm sediment depth of the five sediment cores collected in 2021.

3.3 Comparison of Sediment Characteristics Before and After Pond Maintenance

The current characteristics of the Pond 52 sediments were compared with the sediment data from 2016 (Olsen 2017) to evaluate the changes in the sediment chemistry after the 2018-2019 pond maintenance project (i.e., dredging followed by iron filings application). For this comparison, it is assumed that the new/existing sediment surface in 2021 was more than 10 cm below the old sediment surface in 2016. Accordingly, the vertical profiles of the sediment phosphorus fractions and organic content for the 2021 sediments are plotted below the 2016 sediments in Figure 7.

Removal of the older "muckier" sediments (i.e., considered rich in organic matter) decreased the organic matter content and the labile organic-P concentrations in the new sediments. The aluminum-bound, mineral-bound, and residual organic-P profiles in the new sediments largely follow their profiles in the older sediments. Following dredging, the addition of iron filings to the pond resulted in a marked increase in the iron-bound P fraction, especially in the upper 8 cm depth of the new sediments.

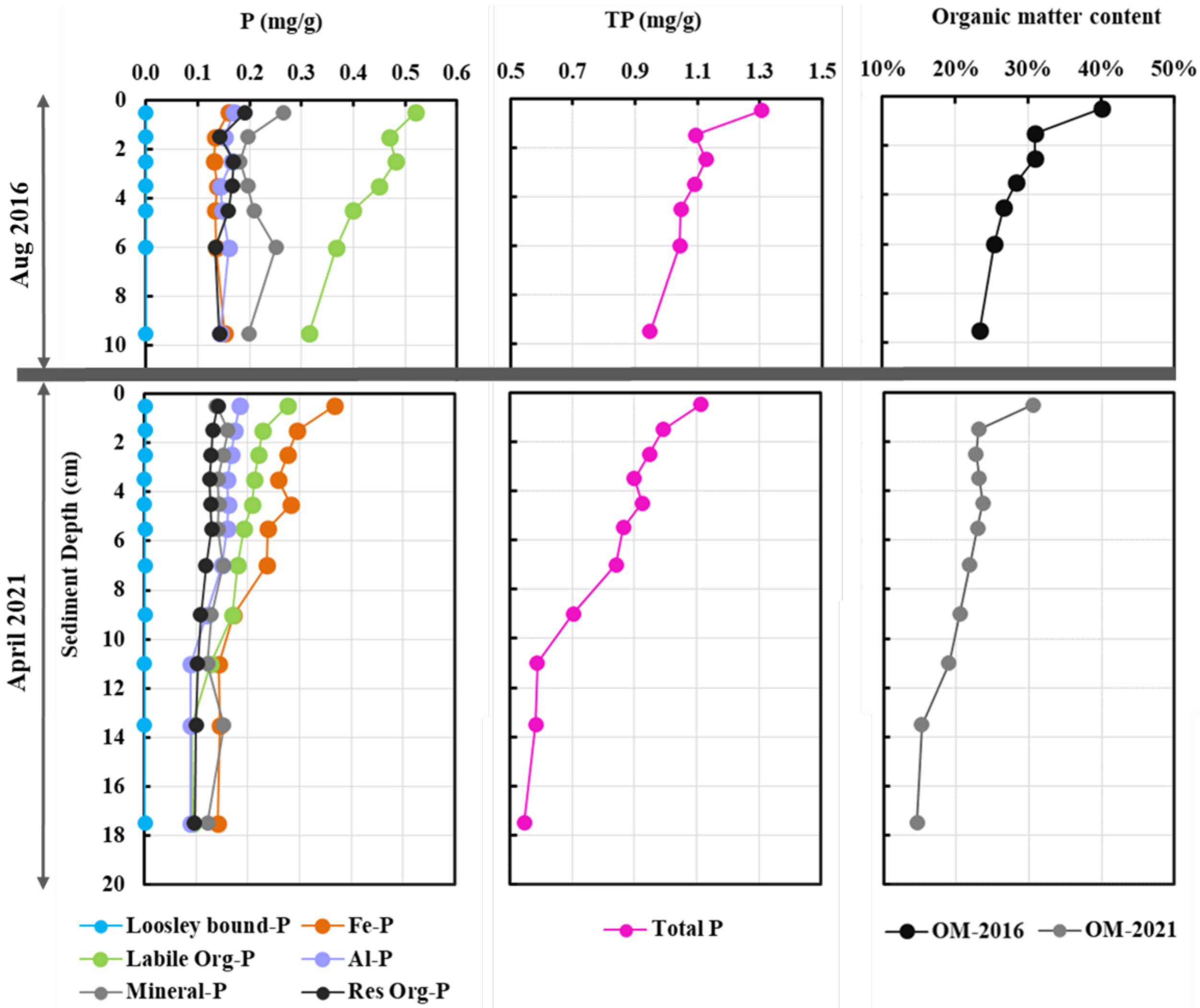

Figure 7. Sediment quality in Pond 52 before and after the 2018-2019 pond maintenance by dredging and iron filings treatment. Vertical profiles of the sediment phosphorus (P) fractions, total sediment P (TP), and sediment organic matter (OM) are plotted for the August 2016 sediments (upper panel) and the April 2021 sediments (lower panel). The concentrations shown are average calculated for six cores from the 2016 sampling (Olsen 2017) and five cores from the 2021 sampling. The sediment depth 0 cm represents the sediment-water interface in the pond; the 0 cm depth in the 2021 plot is the current sediment surface in the pond. Concentrations are expressed on a dry sediment weight basis and are plotted in the mid-point of a given sediment depth interval (for example, concentration for 0-2 cm depth is plotted at 1 cm).

The total iron (Fe) concentration in the 2016 sediments was previously determined only for the 0-4 cm depth and found to be 44.4 mg Fe/kg on average. In the iron-filings treated sediments, the average Fe concentration in the 0-4 cm sediment depth is 45.2 mg Fe/kg. Although similar, it is possible that the iron minerals present in the 2016 sediments were not reactive since the iron-bound P were also lower in those sediments. The application of iron filings provides a supply of reactive iron in the sediments to bind phosphate mobilized from the sediments.

4 Summary of Findings and Interpretations

This study evaluated the Pond 52 sediments two years after the pond was treated with iron filings. The chemical composition of the sediment phosphorus and metals were determined in the upper 20 cm depth of the existing iron-treated sediments.

a) The addition of iron filings manifested the formation of a significant mass of iron-bound P in the sediments due to the binding of phosphate with the iron in sediments. The peak iron-bound P concentration was found to be within the upper 2 to 6 cm depth of sediments in different locations in the pond. The iron-bound P constituted 57% of the mobile P form and 34% of the total sedimentary P in the top 6 cm of sediments.

b) Some spatial heterogeneity in the physical characteristics of the sediments, i.e., moisture content, solids content and wet bulk density, was detected in the pond along with vertical variations from the surface to 20 cm depth of sediments. Spatial and vertical variabilities were found in both iron-bound P and iron concentration profiles in the sediments. The non-uniform distribution of iron filings over the pond area and deposition of iron pieces into the sediments were identified as the reasons for the observed variabilities. Still, a correlation was found between the sediment iron and iron-bound P concentrations.

c) Labile organic-P, which can be mobilized by bacterial mineralization, was present in moderately high concentrations in the upper 6 cm depth of sediments. The labile organic-P mass constituted 43% of the mobile P and 26% of the total sediment P.

d) The comparison of vertical profiles of the sediment P fractions before and after the pond maintenance and treatment yielded interesting results. The pond dredging removed the upper organic-rich sediments, which lowered the organic matter and labile organic-P in the existing surficial sediments. The upper 15 cm of sediment depth still had a relatively high organic content. The following iron filings application enhanced the iron content and thus the formation of iron-P minerals in the existing sediments. The other forms of P (mineral-P, residual P) were not affected by iron addition, and their concentrations lined up with the concentrations seen in the deepest layers of the old sediments.

e) It is hypothesized that the augmented presence of iron will facilitate the formation of iron corrosion products (such as iron hydroxides) and dissolved iron that bind phosphorus by chemical sorption and precipitation mechanisms (Natarajan et al. 2021). By capturing the mobile P in the sediments, the diffusion of phosphate across the sediment-water interface should be reduced. The cycle of iron dissolution and iron oxidation can be expected to generate new sorption sites on the iron filings. Phosphate and dissolved (ferrous) iron released under anoxic conditions can coprecipitate once oxic conditions are re-established in the water column (Kleeberg et al. 2012, Kleeberg et al. 2013). Although these hypotheses suggest the possibility of an increase in overall sorption capacity, the longevity of the iron filings cannot currently be predicted.

f) The post-maintenance water quality monitoring of Pond 52 offers some support to the positive impact of iron filings treatment on the pond phosphorus levels. When compared to historic conditions, the low TP and SRP concentrations in the first year after iron filings treatment (2019) and thereafter (2020 and 2021) suggest a reduction in the overall pond phosphorus levels. Assuming P mass input to the pond has not changed, a low P concentration will be maintained in the pond water if the iron filings are effectively binding P and reducing the internal release from the sediments.

g) The TP concentration in Pond 52 appears to be gradually increasing. Continued monitoring of the pond will address the issue of the length of effectiveness (longevity) of iron filings treatment. In addition, sediment core collection and analysis after 3 – 5 years and comparison with the analysis provided herein will demonstrate the impact of iron filings upon internal phosphorus loading. These two actions will help inform the City of St. Cloud about the longevity of iron filings treatment for other applications to ponds and lakes.

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Appendix

Appendix A: Sediment Analysis Results for the Pond 52 Sediments After Iron Filings Treatment

Table A- 1. Sediment physical characteristics and sediment phosphorus (P) fractions in the sediment cores collected from Pond 52 in April 2021. Total P is the sum of the P fractions. The P fractionation results are on a dry-weight basis. The 0 cm depth represents the sediment-water interface. Figure 1 in the main text shows the coring locations (1-5) in the pond. The pond was dredged in November 2018 and iron filings were applied to the sediments in April 2019.

Sediment Core ID	Depth interval (cm)	Water content (by mass)	Organic matter content (by mass)	Wet bulk density (g/cm^3)	Sediment Phosphorus (P) Fractions					
					Redox-P (Loose-P + Iron-P)	Labile organic-P	Aluminum-P	Mineral-P	Residual organic- P	Total P
					mg P/g dry sediment					
1	0-1	85.0%	31.9%	1.09	0.575	0.369	0.273	0.139	0.143	1.37
	1-2	81.5%	30.2%	1.11	0.634	0.363	0.271	0.169	0.149	1.47
	2-3	80.8%	29.5%	1.12	0.490	0.318	0.242	0.164	0.140	1.24
	3-4	79.5%	27.8%	1.13	0.349	0.333	0.197	0.153	0.140	1.08
	4-5	81.6%	28.8%	1.11	0.308	0.353	0.183	0.138	0.126	1.03
	5-6	80.4%	28.5%	1.12	0.354	0.286	0.187	0.127	0.145	1.02
	6-8	81.2%	27.2%	1.11	0.488	0.319	0.261	0.191	0.140	1.33
	8-10	81.3%	28.4%	1.13	0.252	0.334	0.240	0.166	0.157	1.09
	10-12	81.8%	31.8%	1.12	0.217	0.287	0.158	0.144	0.140	0.887
	12-15	82.8%	29.6%	1.12	0.229	0.220	0.172	0.162	0.149	0.896
	15-20	73.0%	28.6%	1.11	0.225	0.258	0.171	0.181	0.164	0.943
2	0-1	75.0%	32.0%	1.15	0.328	0.264	0.192	0.153	0.138	0.998
	1-2	72.5%	27.6%	1.18	0.271	0.259	0.221	0.199	0.149	1.05
	2-3	71.7%	26.6%	1.19	0.264	0.238	0.214	0.190	0.143	1.00
	3-4	72.1%	26.4%	1.18	0.250	0.224	0.220	0.165	0.130	0.933
	4-5	72.5%	26.2%	1.18	0.352	0.207	0.207	0.166	0.129	1.00
	5-6	71.1%	25.9%	1.19	0.467	0.211	0.173	0.149	0.099	1.05
	6-8	70.5%	22.3%	1.20	0.205	0.162	0.184	0.152	0.123	0.794
	8-10	64.7%	18.7%	1.22	0.267	0.127	0.123	0.117	0.103	0.695
	10-12	56.7%	12.1%	1.22	0.161	0.059	0.054	0.110	0.089	0.443

Sediment Core ID	Depth interval (cm)	Water content (by mass)	Organic matter content (by mass)	Wet bulk density (g/cm^3)	Sediment Phosphorus (P) Fractions					
					Redox-P (Loose-P + Iron-P)	Labile organic-P	Aluminum-P	Mineral-P	Residual organic- P	Total P
					mg P/g dry sediment					
	12-15	48.4%	8.1%	1.28	0.108	0.023	0.022	0.093	0.063	0.290
	15-20	50.2%	8.5%	1.35	0.089	0.019	0.017	0.093	0.060	0.260
3	0-1	83.6%	26.4%	1.47	0.334	0.276	0.186	0.161	0.146	1.05
	1-2	78.1%	21.7%	1.44	0.262	0.187	0.163	0.163	0.172	0.893
	2-3	75.9%	19.5%	1.10	0.287	0.172	0.160	0.168	0.142	0.880
	3-4	75.5%	21.5%	1.14	0.377	0.122	0.139	0.144	0.143	0.870
	4-5	75.7%	20.6%	1.16	0.330	0.126	0.147	0.146	0.144	0.834
	5-6	75.0%	19.3%	1.16	0.385	0.152	0.166	0.161	0.154	0.970
	6-8	74.0%	20.8%	1.16	0.259	0.167	0.159	0.166	0.151	0.846
	8-10	69.3%	18.6%	1.17	0.183	0.096	0.101	0.137	0.129	0.609
	10-12	64.6%	17.0%	1.17	0.134	0.060	0.071	0.134	0.101	0.476
	12-15	56.0%	12.1%	1.18	0.122	0.061	0.077	0.232	0.098	0.563
	15-20	58.9%	14.2%	1.20	0.183	0.070	0.101	0.117	0.096	0.541
4	0-1	92.0%	38.5%	1.22	0.391	0.332	0.158	0.110	0.158	1.08
	1-2	81.5%	27.5%	1.26	0.215	0.277	0.150	0.203	0.135	0.930
	2-3	82.1%	27.7%	1.36	0.231	0.300	0.141	0.127	0.151	0.896
	3-4	82.7%	29.3%	1.32	0.433	0.291	0.169	0.146	0.142	1.13
	4-5	84.0%	29.7%	1.04	0.378	0.307	0.180	0.157	0.162	1.11
	5-6	80.9%	25.8%	1.11	0.247	0.261	0.191	0.170	0.162	0.979
	6-8	78.7%	27.0%	1.11	0.132	0.195	0.114	0.154	0.116	0.682
	8-10	80.1%	27.8%	1.10	0.170	0.256	0.109	0.145	0.103	0.746
	10-12	81.0%	27.0%	1.10	0.121	0.196	0.122	0.133	0.134	0.671
	12-15	72.0%	19.3%	1.12	0.163	0.099	0.109	0.199	0.123	0.657
	15-20	49.6%	10.9%	1.12	0.089	0.063	0.092	0.134	0.092	0.443
5	0-1	80.5%	24.1%	1.13	0.213	0.146	0.111	0.135	0.126	0.686
	1-2	49.2%	8.5%	1.13	0.097	0.053	0.067	0.076	0.056	0.327
	2-3	51.9%	10.3%	1.11	0.119	0.074	0.084	0.113	0.073	0.434
	3-4	50.7%	10.9%	1.12	0.135	0.094	0.077	0.103	0.077	0.450
	4-5	54.7%	12.9%	1.19	0.145	0.050	0.090	0.116	0.082	0.445
	5-6	58.1%	15.2%	1.44	0.137	0.053	0.084	0.105	0.094	0.434

Sediment Core ID	Depth interval (cm)	Water content (by mass)	Organic matter content (by mass)	Wet bulk density (g/cm^3)	Sediment Phosphorus (P) Fractions					
					Redox-P (Loose-P + Iron-P)	Labile organic-P	Aluminum-P	Mineral-P	Residual organic- P	Total P
					mg P/g dry sediment					
	6-8	57.1%	11.9%	1.12	0.100	0.062	0.036	0.099	0.066	0.342
	8-10	43.5%	8.8%	1.46	0.078	0.038	0.031	0.085	0.055	0.270
	10-12	37.0%	6.8%	1.42	0.090	0.037	0.045	0.090	0.053	0.297
	12-15	38.5%	7.1%	1.43	0.110	0.052	0.074	0.082	0.067	0.362
	15-20	47.4%	10.6%	1.37	0.125	0.062	0.067	0.090	0.076	0.396

Table A- 2. Total metal concentrations in the sediments cores collected from Pond 52 in April 2021. The results provided are on dry sediment weight basis (mg/kg). The 0 cm depth represents the sediment-water interface. Concentrations below the laboratory detection limit (LOD) are indicated as < LOD. Figure 1 in the main text shows the coring locations (1-5) in the pond. The pond was dredged in November 2018 and iron filings were applied to the sediments in April 2019. The average metal concentrations in the 0-4 cm depth of the pond sediments collected in 2016 are also included in the table.

Sediment Core ID	**Depth interval (cm)**	**Al (mg/kg)**	**B (mg/kg)**	**Ca (mg/kg)**	**Cd (mg/kg)**	**Cr (mg/kg)**	**Cu (mg/kg)**	**Fe (mg/kg)**	**K (mg/kg)**	**Mg (mg/kg)**	**Mn (mg/kg)**	**Na (mg/kg)**	**Ni (mg/kg)**	**P (mg/kg)**	**Pb (mg/kg)**	**Zn (mg/kg)**
1	0-2	13623	3.63	30364	0.598	60.6	107	49222	2879	14213	487	1177	41.8	1922	103	473
	2-4	12533	6.10	28116	0.559	63.2	108	48830	2723	13466	445	1089	41.9	1587	103	453
	4-6	12281	4.80	27148	0.561	59.9	107	48873	2654	13158	415	1222	42.0	1452	109	433
	6-8	12831	5.00	29034	0.642	61.7	105	49965	2762	13437	454	1311	43.9	1764	113	468
	8-10	13061	4.07	27283	0.566	64.8	107	51625	2819	13306	431	1430	44.0	1480	107	461
	12-15	15180	3.18	26073	0.796	56.6	83.9	49959	3135	13241	410	1873	37.1	1339	118	483
2	0-2	14075	6.14	41638	0.676	51.2	75.8	41306	2877	13211	484	3257	36.2	1423	117	459
	2-4	12728	5.73	46788	0.598	46.4	70.5	39130	2675	12054	499	2968	35.0	1395	109	386
	4-6	12393	6.64	42925	0.697	61.6	62.2	37105	2510	12039	714	2549	42.2	1468	111	347
	6-8	11474	4.96	52024	0.493	41.1	64.6	36090	2344	11628	493	2451	30.2	1188	87.6	325
	8-10	10199	5.04	58458	0.358	35.6	50.4	30757	2038	10463	491	1988	26.9	1057	75.8	255
	12-15	4605	4.76	73706	<0.001	14.7	17.8	16135	833	6385	424	847	13.4	641	35.3	67.8
3	0-2	11250	<0.003	72720	0.480	44.8	74.6	50048	2454	9953	542	6784	31.6	1219	118	347
	2-4	12786	6.75	99162	0.707	34.3	57.8	42060	2549	9936	629	5274	26.4	1262	138	311
	4-6	11778	5.88	90141	0.692	33.0	61.4	42425	2300	10014	604	4851	26.1	1249	139	316
	6-8	13014	7.59	81238	0.703	36.1	55.9	44229	2559	10195	580	4286	26.4	1198	137	320
	8-10	9468	5.53	102300	0.366	28.5	41.3	35018	1973	8418	499	3038	20.8	983	110	215
	12-15	6308	3.70	54431	<0.001	21.0	28.3	33811	1318	6399	368	1453	14.9	811	84.0	150
4	0-2	9837	6.41	28646	0.656	63.2	123	47676	2089	8351	416	917	40.0	1354	127	397
	2-4	9750	7.99	24160	0.600	62.9	99.0	43497	2035	8284	352	790	37.9	1369	121	373
	4-6	10600	8.10	27659	0.585	57.0	97.0	46373	2174	8828	375	763	36.4	1374	130	402
	6-8	8768	7.63	34572	0.583	45.3	75.0	40573	1804	7735	334	593	30.6	1263	144	366
	8-10	9560	7.49	33274	0.612	46.0	93.4	47398	2036	8134	350	666	31.1	1090	122	391
	12-15	8319	5.74	35808	0.518	51.8	79.9	50912	1636	6814	329	415	33.1	1090	145	323
5	0-2	4920	1.73	49343	<0.001	16.3	29.4	22920	1031	6435	379	2367	13.4	623	73.4	141

Sediment Core ID	**Depth interval (cm)**	**Al (mg/kg)**	**B (mg/kg)**	**Ca (mg/kg)**	**Cd (mg/kg)**	**Cr (mg/kg)**	**Cu (mg/kg)**	**Fe (mg/kg)**	**K (mg/kg)**	**Mg (mg/kg)**	**Mn (mg/kg)**	**Na (mg/kg)**	**Ni (mg/kg)**	**P (mg/kg)**	**Pb (mg/kg)**	**Zn (mg/kg)**
	2-4	5945	1.61	49486	<0.001	20.7	30.0	28178	1112	8861	403	2206	15.9	679	78.7	138
	4-6	6508	1.64	53827	<0.001	23.4	28.4	34796	1278	5921	434	2521	17.4	898	89.7	157
	6-8	4644	1.27	63029	<0.001	17.5	31.8	27839	939	6180	439	1969	12.3	598	84.6	104
	8-10	2838	<0.003	49374	<0.001	12.9	18.8	20641	631	6235	319	1198	12.4	475	67.0	66.1
	12-15	4052	2.97	46388	<0.001	18.7	33.8	23799	772	6936	371	941	13.5	614	56	101
Average in 2016	0-4	20426	20.98	49001	1.240	60.1	138	44353	4543	15936	861	1769	46.2	2897	142	475