Assessment of Internal Phosphorus Loading Following Iron Filings Treatment in Shoreview Commons Pond

Results of Post-Treatment Water Quality Monitoring

DRAFT Technical Memorandum

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Acknowledgments

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1 Introduction

Stormwater ponds are primarily designed to detain and treat urban stormwater runoff. Ponds act to contain phosphorus (P), a critical pollutant in runoff, that washes off from lawn fertilizers, degrading organic matter, animal wastes, and other non-point sources in the surrounding watershed area. However, under certain environmental conditions ponds can become a source of phosphorus due to the recycling of phosphorus accumulated in the bottom sediments. Laboratory incubation of pond sediment cores collected from several ponds in the Twin Cities metro area has demonstrated moderate to high rates of sediment phosphorus release under low dissolved oxygen (DO) or anoxic conditions (Taguchi et al. 2020, Janke et al. 2021, Natarajan and Gulliver 2022, Janke et al. 2023). Sediment oxygen demand measured in the laboratory sediment cores and in situ pond water column DO concentrations have confirmed that ponds are susceptible to developing anoxic conditions during dry periods between storm events. In fact, the monitoring of physiochemical conditions in many ponds in the Twin Cities metro area has indicated the presence of thermal stratification and low DO conditions during the warmer months (Taguchi et al. 2018, Taguchi et al. 2020, Janke et al. 2021, Natarajan and Gulliver 2022, Janke et al. 2023). The prolonged anoxia and associated risk of internal phosphorus loading that results in increased phosphorus concentrations in the pond negate the intended purpose and diminish the overall efficacy of ponds. Substantial internal loading will therefore affect not only the pond water quality but also the downstream lakes and streams that receive pond outflows, thereby increasing risks of harmful algal bloom occurrences and water quality degradation in the water bodies.

One of the recommended methods to reduce internal phosphorus loading is treatment of sediments with iron filings to bind the sediment phosphorus (Natarajan et al. 2021). Based on the results of a laboratory iron filings dosing study with lake sediments (Natarajan et al. 2017, Natarajan et al. 2021), iron filings treatment was implemented in four stormwater ponds in the Twin Cities metro area in 2020 and 2021 (Natarajan and Gulliver 2022), including a stormwater pond, Shoreview Commons, in the City of Shoreview, Ramsey County, MN. The Shoreview Commons Pond was investigated for internal phosphorus release in the laboratory and monitored for summertime water quality from 2018 to 2020 before it was recommended for treatment (Natarajan et al. 2020). The monitoring showed relatively high phosphorus concentrations and persistent anoxia in the pond water column during summer, and a high anoxic sediment phosphorus release rate measured in the laboratory, suggesting a potential for significant internal phosphorus loading in the pond (Natarajan et al. 2020). The pond was treated with iron filings in winter 2021. Monitoring performed in summer 2021 at the Shoreview Commons Pond (Janke et al. 2023) and at other iron-treated ponds (Natarajan and Gulliver 2022) seemed to indicate that the iron filings treatment was successful at reducing phosphate release from the sediments and total phosphorus concentrations in the pond during the first year of treatment.

The current study is a continuation of the 2018-2020 study (Natarajan et al. 2020) to assess the post-treatment phosphorus water quality in the Shoreview Commons Pond. The main objective of this study is to measure phosphorus concentrations in the Shoreview Commons Pond over two years to estimate the length of time that the iron filings treatment will be successful at reducing phosphate release from the sediments. The pond was monitored in 2022 and 2023 to verify the environmental conditions (DO, temperature, conductivity) and phosphorus concentrations in the pond water, and the data were used to assess the importance of internal phosphorus loading in the pond and whether the pond is returning to the large phosphate release present before iron filings treatment.

2 Methods

2.1 Site description and background

The Shoreview Commons Pond (area = 2.9 ac; mean depth = 0.61 m) is located north of Highway 96 and east of the City Hall in the Shoreview Commons Park, Shoreview, MN, in the Ramsey-Washington Metro Watershed District. The pond is managed by the City of Shoreview. The 0.583 km^2 drainage area to the pond consists of primarily residential and park/institutional land, 35% of which is impervious. Sources of inflow to the pond consist of a storm sewer outfall and overland flow from adjacent land. The pond outflow is routed downstream via a submerged outlet culvert into Snail Lake.

Historic monitoring of the pond has indicated odor problems, low water clarity, high total phosphorus and chl-*a* concentrations, and a heavy surface cover of duckweed and watermeal especially during summer (Stantec 2017). Field monitoring from 2018 to 2020 showed that the entire pond water column had low DO (< 1 mg/L) during much of the growing season (June to September), a condition that can trigger phosphorus (P) to release from the anoxic sediments (Natarajan et al. 2020). The laboratory-measured anoxic sediment P release rate was also high, suggesting the high potential for internal P loading that may significantly impact the pond water quality. Based on the results of the 2018-2020 study, iron filings treatment was implemented in the pond with the goal of sequestering phosphorus in the sediments and reducing re-release of phosphorus to the pond water column. In February 2021, the city maintenance crew used a mechanized spreader on the ice cover to apply iron filings (D_{50} = ~0.60 mm) at a design dosing rate of 500 g iron/m^2 sediment area (4461 lb/ac), which would settle to the sediments after ice-out. The first summer following the iron filings treatment appeared to have a positive impact since the total phosphorus concentrations were lower and the floating plant cover (FPC) of duckweed and watermeal was visibly less compared to previous years (Janke et al. 2023).

2.2 Field monitoring

2.2.1 Routine water quality sampling

The pond was sampled on a bi-weekly basis from May through October in 2022 and in 2023. The surface to bottom profiles of dissolved oxygen (DO), temperature, and specific conductivity were taken at 25-cm intervals using a Hach multi-parameter water quality meter. Cloud cover, air temperature and wind conditions were also recorded. Surface (epilimnion) water samples were collected from five locations and composited into a single sample in the field (Figure 1). The surface water samples were collected just below the floating plant cover, avoiding as much floating vegetation (duckweed and watermeal) as possible. One hypolimnion sample was collected (at least 0.25 m above the pond bottom) at the deepest location (sampling location #3 in Figure 1) using a Van Dorn sampler[1] or a pole sampler with a Nalgene bottle. When the pole sampler was used, the pole was extended to the greatest depth possible with the bottle in the 'upside down' position, before allowing it to flip, releasing air and collecting water at depth.

The pond water samples from the field were processed, stored, and analyzed at SAFL. The water samples were analyzed for soluble reactive phosphorus (PO_4-P), total dissolved phosphorus, and total phosphorus (TP) in a spectrophotometer (detection limit = 10 µg/L P) following the ascorbic acid colorimetric method (Standard Methods 4500-P, APHA 1995). One hypolimnion water sample from each month of the monitored period was analyzed for dissolved iron (Fe) concentration by the ICP analysis method.

Figure 1. Water sampling locations (red circles) in the Shoreview Commons Pond. Locations 1 to 5 were used for surface water (epilimnion) sample collection. Locations 6 and 7 were used only for duckweed and watermeal sampling.

Additionally, visual estimates of the extent (fraction of open water) of floating plant coverage (FPC) were made during each site visit. The floating plants, primarily a mix of duckweed and watermeal, were sampled at seven or less locations when present, using a 10-inch or 12-inch diameter mesh skimmer submerged and carefully pulled upwards out of the water to capture a sample. The plant samples were dried at 60 °C and weighed in the laboratory to obtain the dry biomass weight (g) and density (g/m^2; obtained by dividing biomass weight by mesh skimmer

[1] https://www.kc-denmark.dk/products/water-sampler/van-dorn-water-sampler.aspx

area). The mean areal density of floating plants (g/m^2) was calculated based on measurements at seven sampling locations in the pond, with a value of zero assigned to locations where floating plants were absent or sparse that prevented sample collection. The absence of FPC was encountered typically early in the season (May) and in late Fall when plants started to senesce.

2.2.2 Continuous monitoring

The Shoreview Commons Pond was instrumented to continuously monitor the water level, wind speed, and vertical temperature profile during the field season. A monitoring station was installed near the pond's deepest point and consisted of an anemometer (LaCrosse TX-23U) mounted roughly 0.91 m above the water surface, ultrasonic distance gauge for water level measurement, and a thermistor chain of 4 to 6 nodes spaced roughly 15 to 46 cm (6 to 18 inches) apart in the vertical direction (spacing determined by water depth) and a Luminescent DO probe. Data were logged at 10- or 15-minute intervals with an Arduino-type data logger connected to a solar panel. The discrete Onset Hobo data loggers were installed for conductivity at a depth of roughly 15 cm above the bottom to detect high chloride concentrations and DO was logged at a depth of roughly 30 cm below the surface at the pond.

3 Results

3.1 Data collection summary

We performed a total of 13 site visits between June and October in 2022, and 12 site visits between May and October in 2023. The weather was hot and dry for Twin Cities in 2022 and 2023; with May to October mean air temperature roughly 7.1 °C above average (~25 °C observed vs. 18.2 °C, the 1981-2010 normal at Minneapolis-St. Paul International Airport)[2]. The rainfall total observed over the same period was only 18 cm in 2022 and 40 cm in 2023 (vs. the 1981-2010 normal of 46 cm). In 2023, more than half (19 cm) of the total precipitation for this period fell between September 23 and October 31, which is normally a drier period at this location.

3.2 Phosphorus water quality

The sampled phosphorus concentrations in the pond water were generally in the low to moderate range during the 2022 and 2023 monitoring seasons (Figure 2). In 2022, the surface phosphorus concentrations ranged from 0.057 – 0.22 mg/L TP and 0.012 – 0.042 mg/L SRP during the June to October period. In 2023, 0.049 – 0.36 mg/L surface TP and 0.007 – 0.047 mg/L surface SRP were measured between May and October. In the hypolimnetic water, TP concentrations were typically higher than the surface water, ranging from 0.051 – 0.28 mg/L in 2022 and 0.064 – 0.33 mg/L in 2023. The hypolimnion and surface SRP concentrations were typically similar during both years (Figure 2). The surface TP and SRP concentrations in 2022 (year 2) and 2023 (year 3)

[2] https://www.dnr.state.mn.us/climate/twin_cities/listings.html

were somewhat higher than the concentrations measured in 2021(year 1 of treatment), but still lower than pre-treatment levels, as discussed in Section 3.4.

The dissolved iron (Fe) concentrations in the hypolimnion water samples were low (< 0.1 mg/L) and appeared to follow the trend of hypolimnion SRP concentrations with both iron and phosphate concentrations generally increasing during peak periods of low bottom DO (Figure 2). The reduction and dissolution of Fe (III)-phosphate minerals under low DO conditions can release a portion of phosphate and ferrous iron from the sediments. However, the release of phosphate is still controlled due to the formation of Fe(II)-phosphate minerals that retain phosphorus in the sediments (Natarajan et al. 2021). The laboratory studies on Shoreview Commons sediments support this hypothesis because anoxic phosphate release was lowered and smaller after iron dosing (see Figure 11 in Section 3.4.1).

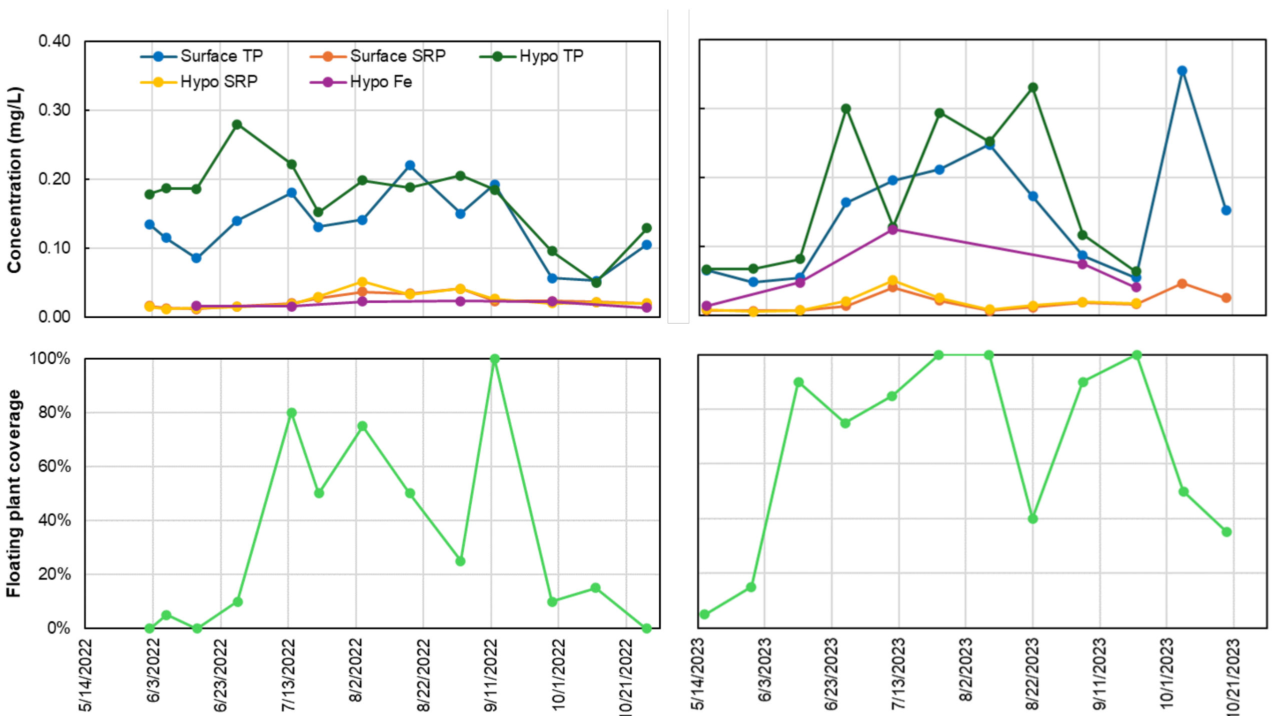

Figure 2. Time series of surface and hypolimnion TP and SRP, and hypolimnion dissolved iron (Fe) concentrations in the pond water column (mg/L), and floating plant cover (FPC) on pond surface (%) at the Shoreview Commons Pond during the May to October period of 2022 (left) and 2023 (right). Average concentrations plotted are based on surface water samples collected under the FPC at five locations in the pond. Hypolimnion (hypo) samples were collected from the deepest location in the pond. Visual assessment of FPC by the field crew represents duckweed and watermeal coverage as a percentage of pond surface area and does not portray biomass density.

The surface TP levels in the pond, however, exceeded the MPCA's 0.06 mg/L TP standard for aquatic life and recreation in shallow lakes in the North Central Hardwood Forests region during the two monitored seasons [Minn. R. § 7050.0222; MPCA)]. Also, the measured concentrations mostly exclude the phosphorus contained in the floating plant material in the pond, which can be substantial and was not quantified in this study. Duckweed and watermeal covered most of the pond surface during the summer season (Figure 2), with peak biomass density (plotted in Figure 10 in Section 3.4) typically observed in the July to August period. The floating plants were established only around mid-July in the 2022 season but were observed earlier with a more pervasive coverage in the 2023 season. Even though the floating plant cover (FPC) was close to 100% until September 2023, the FPC was characterized as thin (i.e., less dense) by the field crew. The presence of floating plants likely affected the oxygen dynamics in the pond, especially during the peak cover period (discussed in Section 3.3).

3.3 Stratification and dissolved oxygen dynamics

Figure 3 and Figure 4 show contour plots (isopleths) that were generated from the routine bi-weekly profile measurements at the pond, with linear interpolation used to fill the gaps between sample times. The contour plots are intended to show general, seasonal patterns of stratification and mixing in the pond.

In general, the Shoreview Commons Pond was often well mixed, with small top-to-bottom gradients in temperature and conductivity throughout much of both the 2022 and 2023 field seasons. Conductivity was elevated (> 600 uS/cm) at the start of the season (June) in both years, likely from road salt inputs. Specific conductivity measurements greater than 500 µS/cm are likely due to runoff containing road salt applied during the winter months (Granato and Smith 1999), and such high conductivity values can make water denser and more resistant to vertical mixing (Novotny et al. 2009). Road salt appeared to flush from the pond by late summer as indicated by the decrease in conductivity levels, although due to drought conditions in both years, the pond stayed at slightly elevated conductivity (above 350-400 uS/cm) throughout the season, indicating that it did not completely flush out. The return of elevated conductivity in late fall may suggest longer-term storage of salt in pond sediment or groundwater inputs.

Dissolved oxygen was generally low in both seasons, particularly at the bottom of the pond, likely the result of high oxygen demand by the organic sediments. During 2022, anoxia (DO < 1 mg/L) was not persistent, showing some periods of oxygenation with the upper water column usually oxygenated (Figure 3). In summer 2023, anoxia was also cyclical but more persistent at the pond bottom, and included periods in late summer and fall during which the entire water column was anoxic (Figure 4). This may have been due to greater FPC in 2023 than in 2022 (Figure 2), which if dense enough could promote anoxia by preventing mixing and re-aeration (Janke et al. 2023).

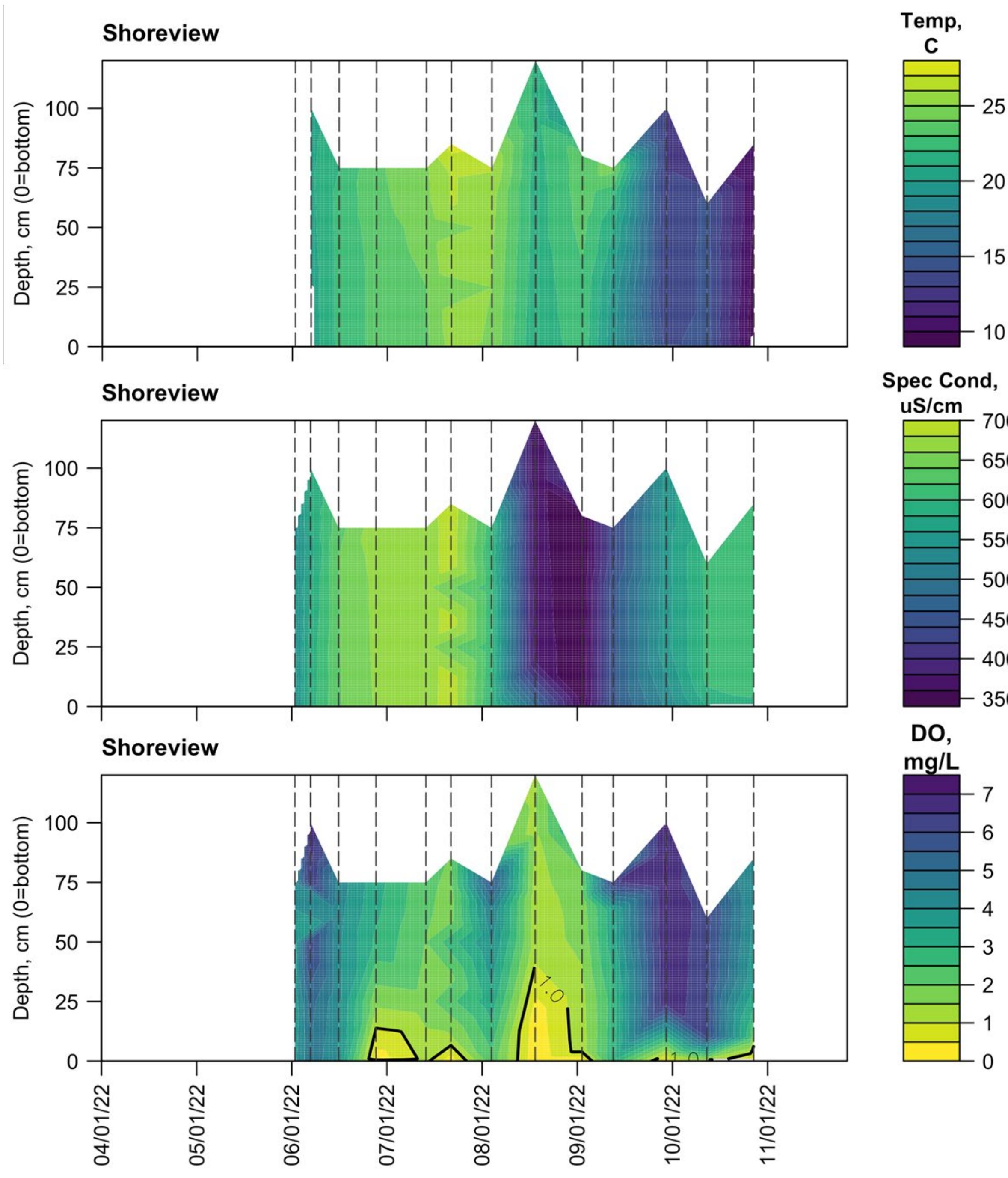

Figure 3. Time series contour plots of (a) temperature, (b) specific conductivity, and (c) dissolved oxygen (DO) concentrations in the Shoreview Commons Pond from the May to October periods in 2022. Color indicates values per the scale at right (note difference in scales among plots), with water depth relative to the pond bottom on the y-axis, and time along the x-axis. Vertical dashed lines show times when profiles were taken at the pond; linear interpolation is used to fill the time series between pond visits. On the DO plot, a contour for 1.0 mg/L indicates levels below which the pond is considered anoxic.

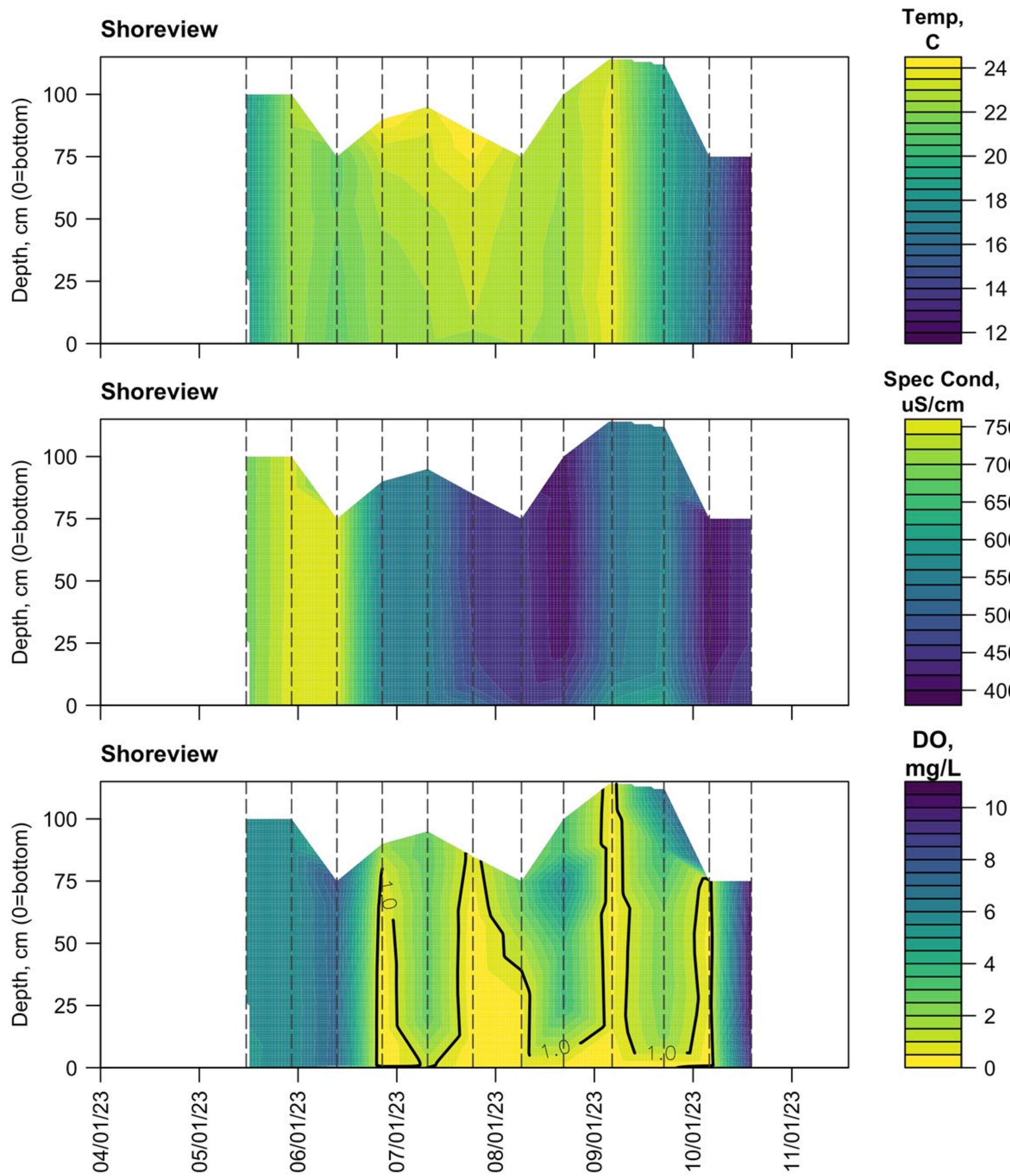

Figure 4. Time series contour plots of (a) temperature, (b) specific conductivity, and (c) dissolved oxygen (DO) concentrations in the Shoreview Commons Pond from the May to October periods in 2023. Color indicates values per the scale at right (note difference in scales among plots), with water depth relative to the pond bottom on the y-axis, and time along the x-axis. Vertical dashed lines show times when profiles were taken at the pond; linear interpolation is used to fill the time series between pond visits. On the DO plot, a contour for 1.0 mg/L indicates levels below which the pond is considered anoxic.

Figure 5 shows a time series of the continuous monitoring station data (wind speed in 2022; water level in 2022 and 2023; vertical temperature profiles in 2022 and 2023), plotted as measured wind speed 0.91 m above the pond water surface, water depth relative to sediment, and stratification strength as relative thermal resistance to mixing (RTRM), which is a measure of the density difference between the top and bottom temperature nodes.

Both 2022 and 2023 were marked by long periods of drought and generally few storm events, as shown in the water level time series, where rainfall events are indicated by a rapid increase in water level. In particular, during the persistent dry period between mid-August and late September in 2023, the pond was largely stagnant, as illustrated by the highest values of RTRM and generally high anoxia during this period. It is notable that the daily minimum RTRM values were close to zero (indicating a destratified water column) in 2023 and negative in 2022 during much of this period, which indicates that the pond mixed to the bottom or close to the bottom most days. The low wind speeds in general at this pond (see 2022 data in Figure 5), and the lack of runoff to provide mixing, suggests that nighttime cooling is providing some water column mixing. The high water column anoxia, which was observed in the profile data collected during daytime site visits (Figure 3 and Figure 4), suggests that the pond quickly re-stratifies during the day and sediment oxygen demand is high enough to quickly consume any oxygen made available during nighttime mixing.

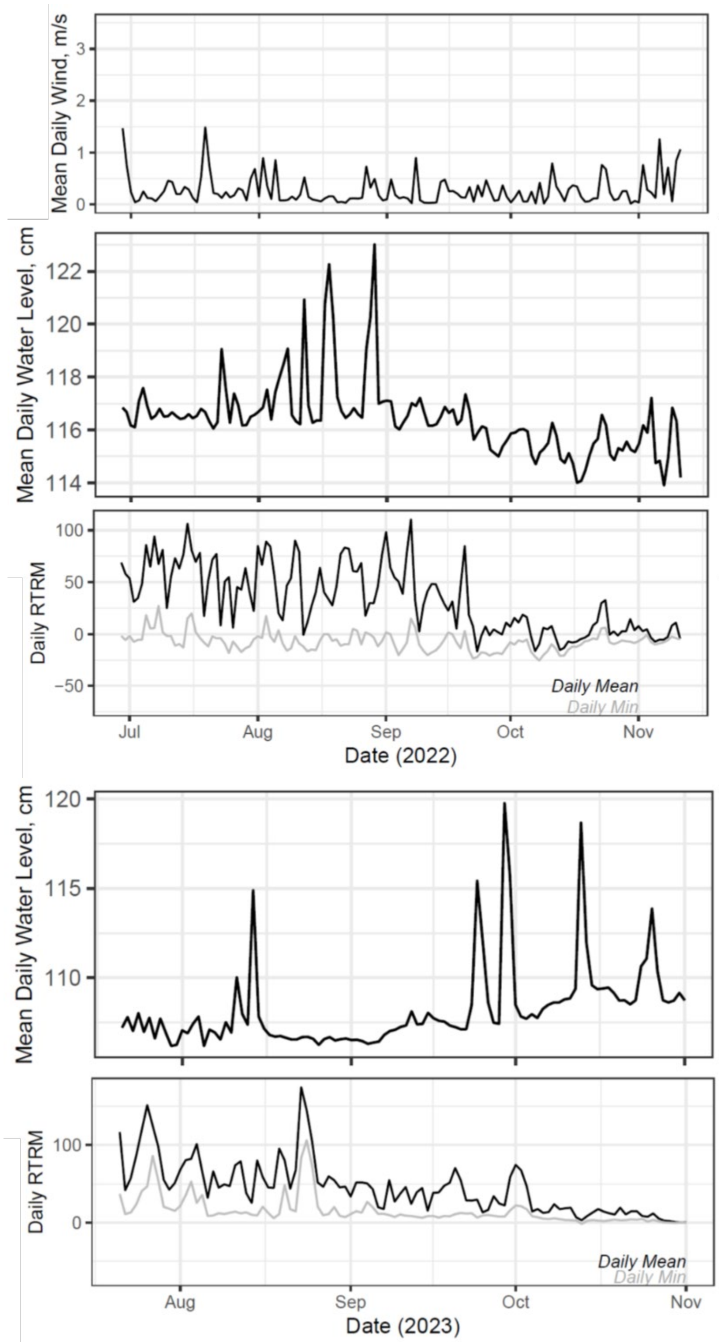

Figure 5. Time series of mean daily wind speed (km/h; 2022 only), water level (cm), and RTRM at the Shoreview Commons Pond in 2022 and 2023. Measurements were done by the continuous monitoring station installed in the pond and data were averaged into daily values.

3.4 Comparison of pre-treatment and post-treatment water quality

The field observations from the 2022 and 2023 monitoring seasons contrast with the seasonal trends largely observed at the pond before iron filings treatment, specifically for surface DO and TP concentrations. In the pre-treatment period, i.e., 2020 and before (Figure 6 and Figure 7), the pond had a primarily anoxic water column (DO < 1 mg/L) from June to October, with periodic but only a brief increase in surface DO. Low DO concentrations (< 1 mg/L) were measured within a few cm below the water surface during the peak FPC period of June to August. Runoff input from storm events did not appear to completely mix the water column or disrupt the observed stratification lasting much of the summer during most years. Thermal stratification typically weakened by the end of September and the pond appeared to be at least partially mixed in October, although the DO concentrations continued to be low in the entire water column. Floating plant cover was typically dense and at 100% coverage from June to August and decreased to less than 50% only after September and the plants senesced by October.

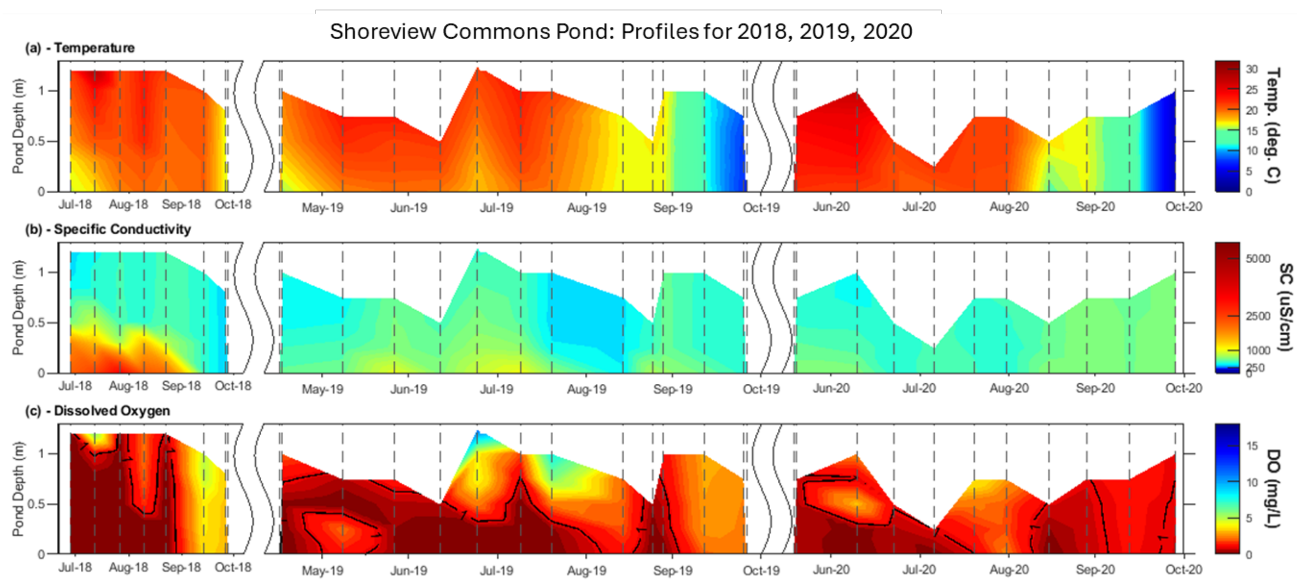

Figure 6. Time series contour plots of (a) temperature, (b) specific conductivity, and (d) dissolved oxygen (DO) concentrations in the Shoreview Commons Pond from the May to October periods in 2018, 2019, and 2020. Vertical lines show times when profiles were taken at the pond; linear interpolation is used to fill the time series between pond visits. The 1 mg/L DO anoxic threshold is shown in plot (c). Data and plots extracted from Natarajan et al. (2020).

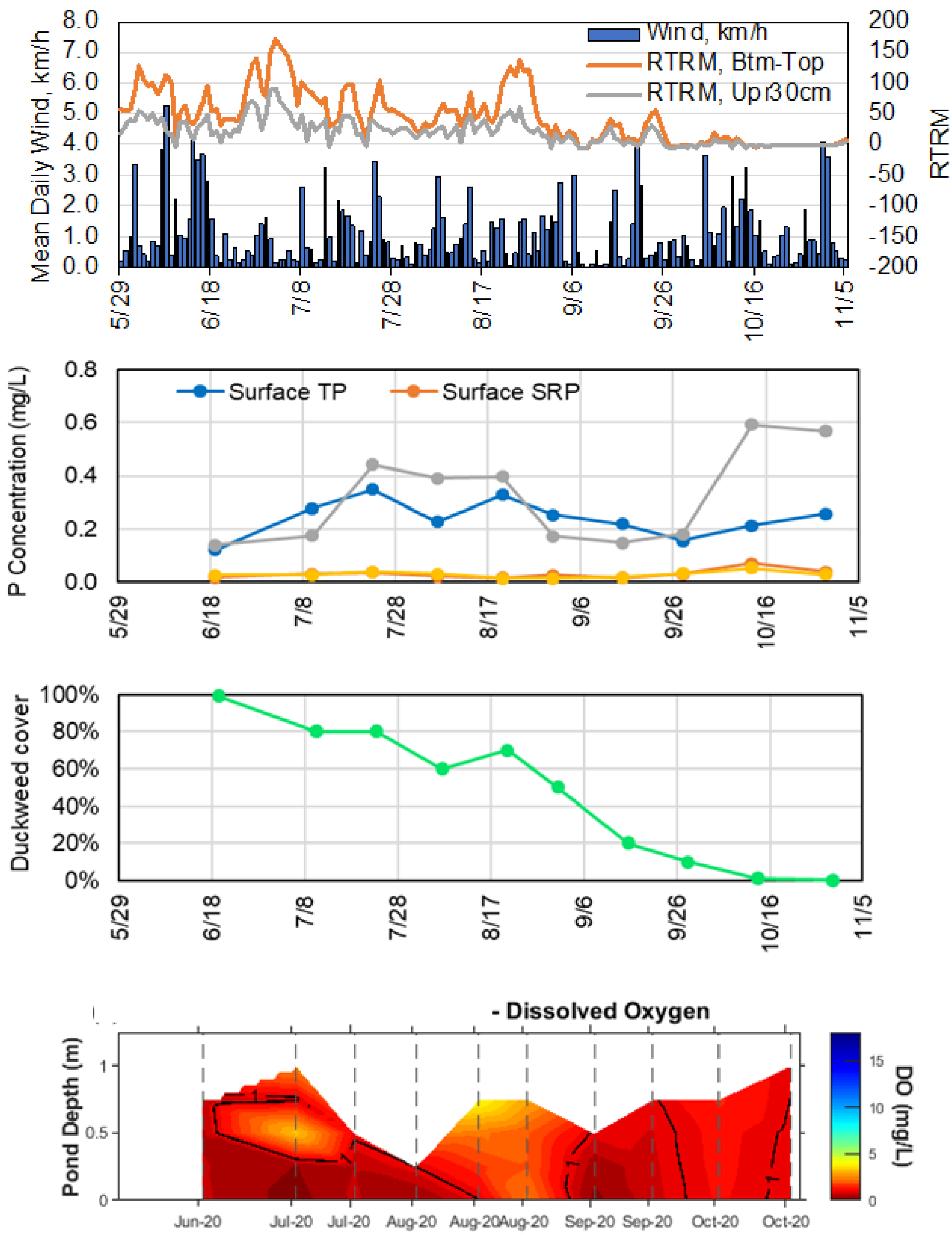

Figure 7. Shoreview Commons Pond's 2020 time series of RTRM (for upper water column and for whole water column 'top-btm'), surface and hypolimnion TP and SRP (mg/L), floating plant cover (FPC or duckweed cover %), DO profiles (mg/L; as contours). RTRM measured by the monitoring stations and averaged into daily values. Other data collected on site visits. Data and plots extracted from Janke et al. (2023).

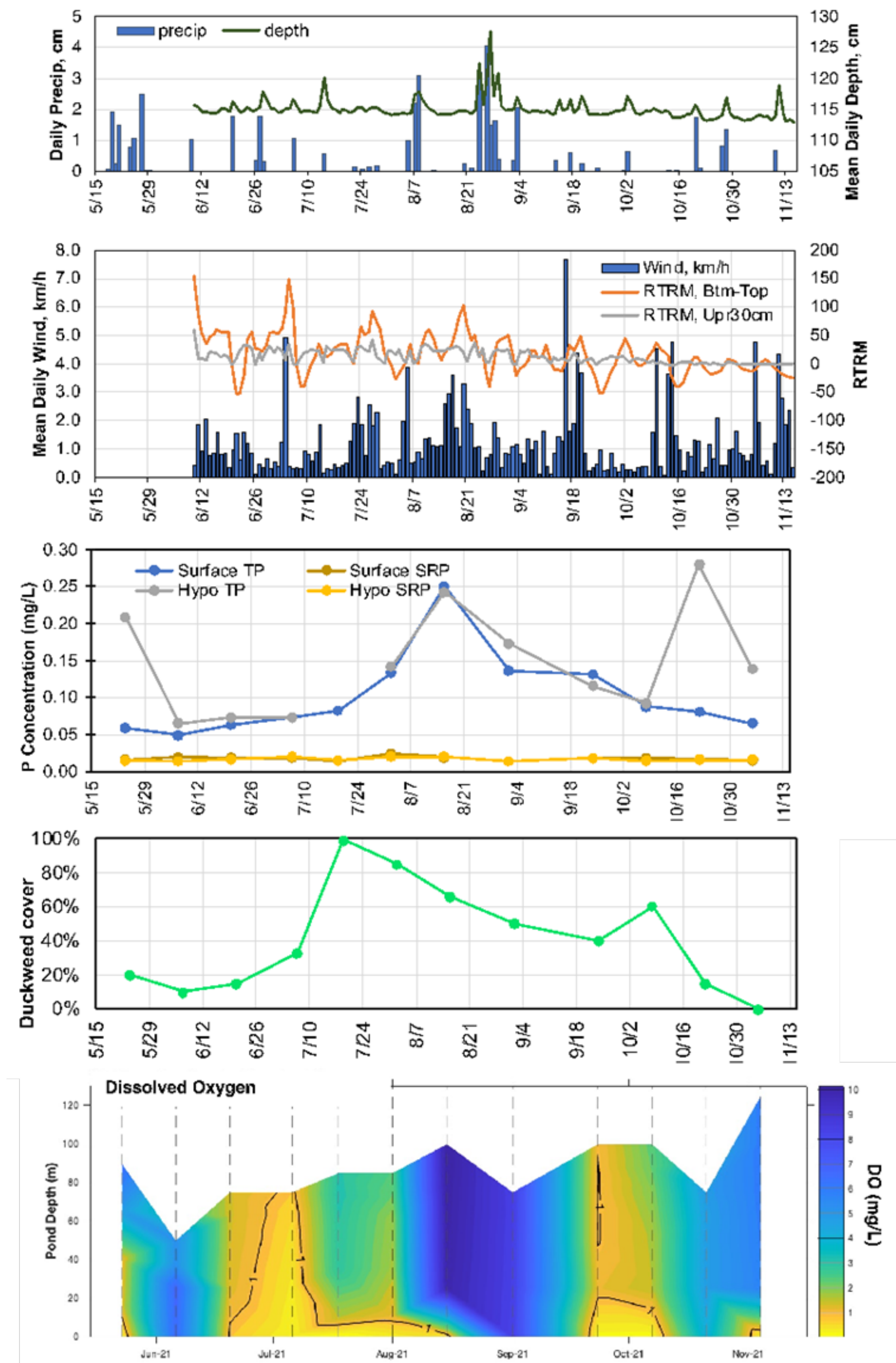

Figure 8. Shoreview Commons Pond's 2021 time series of rain (cm; from MSP Airport), water depth (cm), wind speed (km/h), RTRM (for upper water column and for whole water column 'top-btm'), surface and hypolimnion TP and SRP (mg/L), floating plant cover (FPC or% duckweed cover), DO profiles (mg/L; as contours. RTRM, wind, and water level measured by the monitoring stations and averaged into daily values). Other data collected on site visits. Data and plots extracted from Janke et al. (2023).

In summer 2021, the first year following iron filings treatment, the pond did not maintain temperature stratification (also indicated by fluctuating RTRM values; Figure 8), had lower top-bottom density difference, less persistent FPC, and low DO only at peak FPC in July 2021 (Janke et al. 2023). Water column DO and FPC showed roughly opposite trends, with DO increasing after FPC senescence started in fall. A strong correlation between pond water column DO and FPC has been established based on a dataset of more than 20 ponds (Janke et al. 2023). The lower FPC and an increased surface DO in 2021 were likely due to low overall availability of phosphorus that resulted from the iron filings treatment. In summer 2022, the second year following treatment, the pond had low DO periodically and FPC was less pervasive and thin. Low DO conditions in the entire water column were observed more frequently in summer 2023, the third year following treatment, and there was more FPC present than the previous year.

Figure 9, showing the mean phosphorus concentrations in the pond during each monitoring season from 2018 to 2023, illustrates the direct response to the iron filings treatment that lowered internal phosphorus release in the pond. The pond had a reduced average surface TP and SRP in all three years after iron filings application. The hypolimnetic phosphorus levels were also reduced post treatment. Overall, the mean pre-treatment surface TP was reduced by 43% after treatment (0.23 mg/L mean for 2018-2020 vs. 0.13 mg/L mean for 2021-2023). Water quality in Alameda Pond, with no iron filings addition, is shown for comparison in Figure 9. Long-term monitoring at the Alameda (area = 2.9 ac), which is heavily sheltered, has shown a predominantly stratified and fully anoxic water column with heavy FPC during each entire summer (Janke et al. 2023). Alameda had similar TP levels as Shoreview Commons in the years before 2021. Alameda pond water quality has not changed over the years, unlike the TP and SRP reduction observed after the iron filings treatment at the Shoreview Commons Pond.

The FPC in Shoreview Commons was observed to be sparse and thinner in the first year after treatment although gradual increases in areal coverage and biomass density were noted in the following two years (Figure 2 and Figure 10). Still, the FPC during post-treatment years can be characterized as less dense when compared to the pre-treatment period. The overall reduction in pond phosphorus levels post treatment is hypothesized to have contributed to the lower floating plant prevalence in the pond.

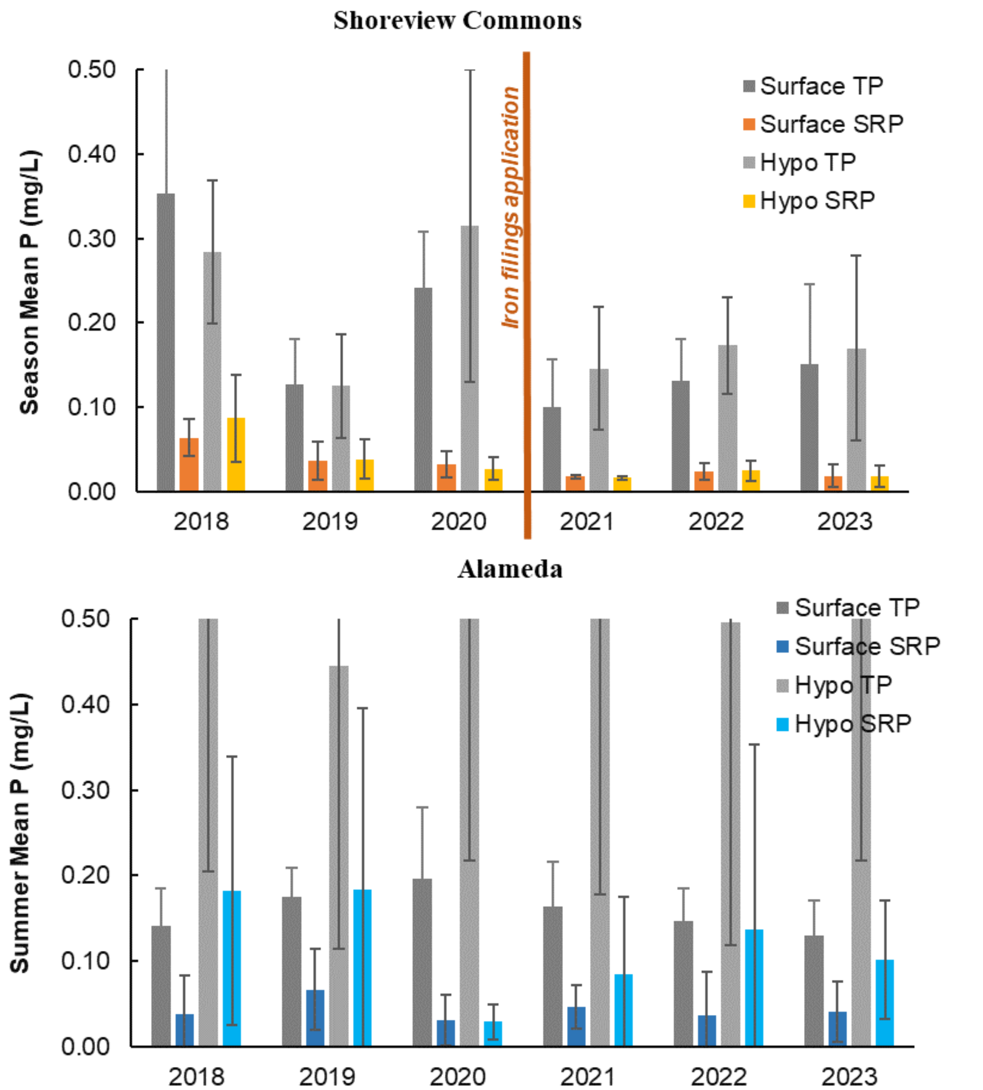

Figure 9. Phosphorus (P) water quality in the Shoreview Commons Pond (top) and Alameda Pond (bottom) from 2018 to 2023. Mean water column total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations in the surface and hypolimnion during the May to October period are plotted. Error bars represent standard deviation of the mean. The number of water samples collected were 7 in 2018, 11 in 2019, 10 in 2020, 12 in 2021, 13 in 2022, and 12 in 2023. Iron filings treatment was performed in Shoreview Commons in February 2021. Alameda was not treated and is shown for comparison of water quality during the same period. Hypolimnion concentrations in Alameda were 0.53 mg/L in 2018, 0.72 mg/L in 2020, 0.97 mg/L in 2021, 0.60 mg/L in 2023.

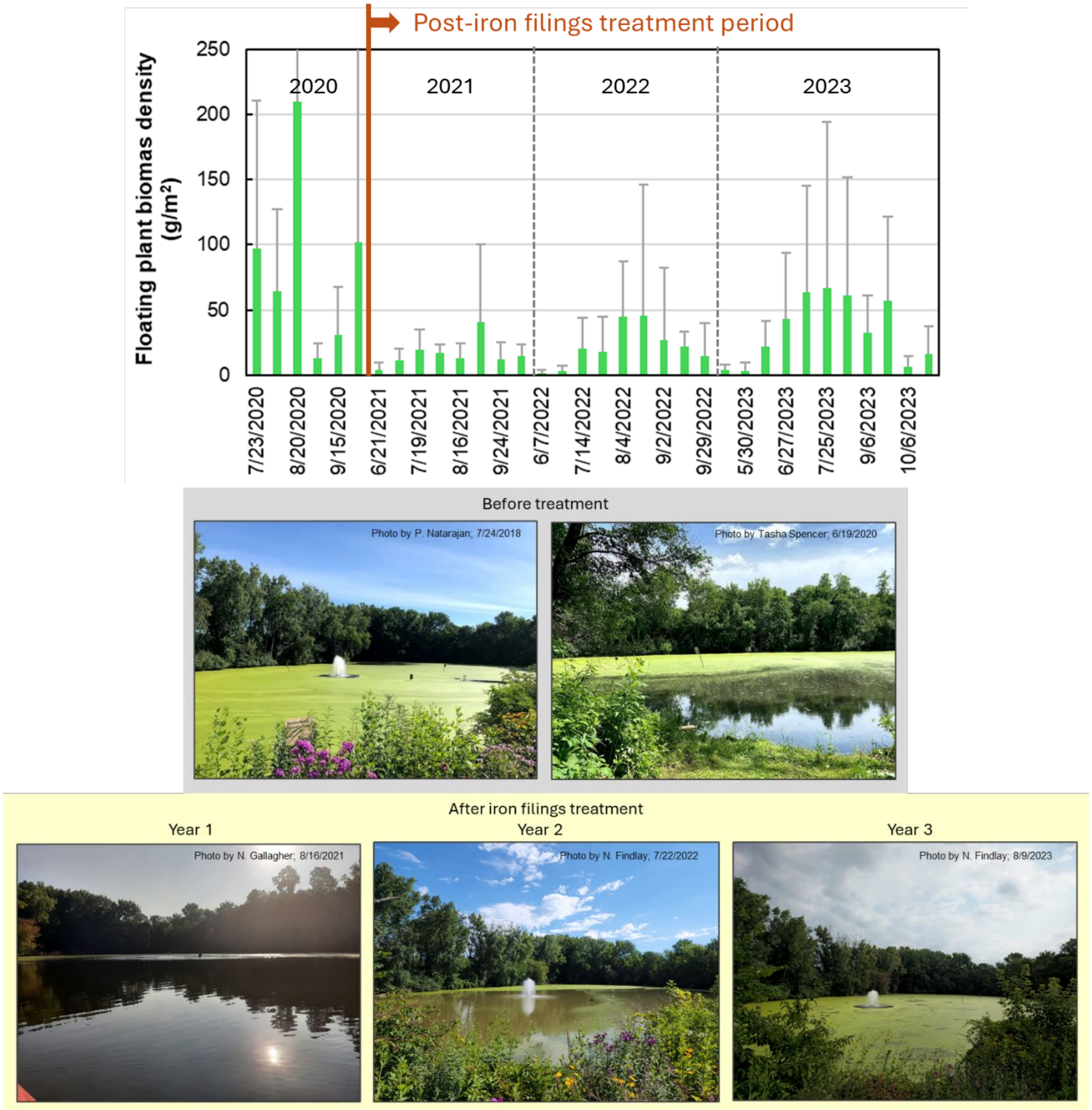

Figure 10. Areal density of floating plant biomass (duckweed and watermeal; g/m^2) in the Shoreview Commons Pond before iron filings treatment (2020) and after treatment (2021, 2022, 2023). Mean biomass density at seven sampled locations is plotted for each sampling date, where density at a location with no FPC was assigned zero value. Error bars show standard deviation of the mean. Photographs show the floating plant cover (FPC) at the pond during peak summer period (June to August) from 2018 to 2023

3.4.1 Effect of iron filings treatment on pond sediments

As part of other concurrent projects focused on assessing effectiveness of iron filings treatment in reducing pond phosphorus, the iron-treated sediments from the Shoreview Commons Pond were evaluated for their potential to re-release phosphorus into the water column. Laboratory column studies to determine sediment phosphorus release were conducted on sediment cores collected nine months (November 2021; Janke et al. 2023) and 27 months (June 2023; Gulliver et al. 2023-2026 in progress) after the pond was treated with iron filings in February 2021. The results of the laboratory studies, illustrated in Figure 11, confirm the positive impact of iron filings addition on sediment phosphorus flux that is evident more than two years after treatment. Both oxic and anoxic sediment phosphorus releases were effectively controlled from the iron-amended sediments. Anoxic phosphorus flux was substantially reduced due to the enhanced iron concentrations in the sediments immediately after the iron filings application in 2021. An increase in the anoxic sediment phosphorus flux was detected in 2023, but the flux is still small and substantially lower than the flux measured in 2018 for untreated sediments. Shoreview Commons also had a notably high oxic release of phosphorus before iron filings treatment. No release was observed under oxic conditions for the treated sediments, which indicates that the oxidized iron was adsorbing phosphorus released by the microbial degradation of organic material. The mean sediment oxygen demand (SOD) was also lower for the iron-treated sediments. The reason for lower SOD is not clear, since the sediment organic content was similar in the sediments collected before and after iron filings treatment (mean organic content in upper 2 cm depth of sediments was 34% before and 31% after treatment).

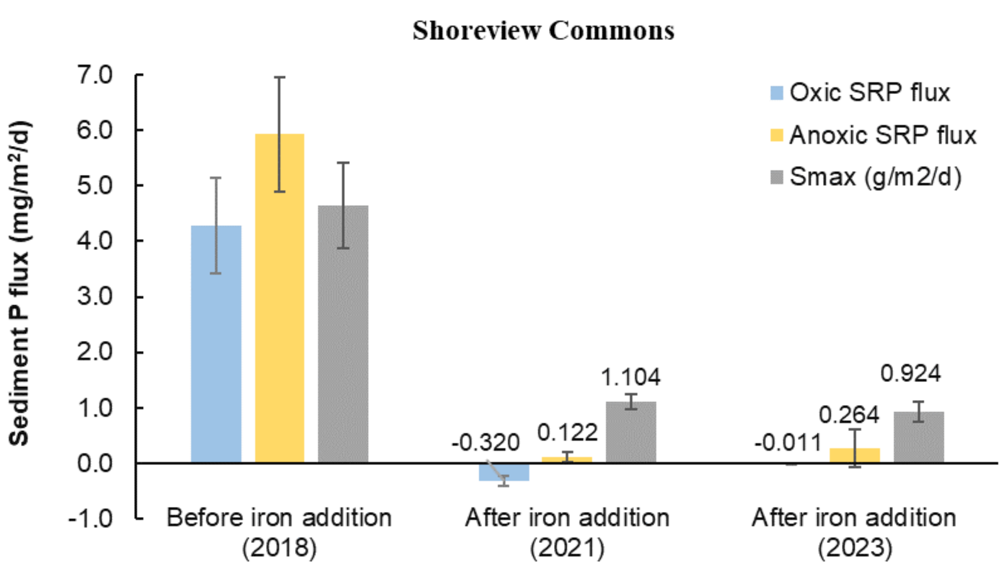

Figure 11. Oxic and anoxic sediment phosphate (SRP) release rates measured before and after iron filings application in Shoreview Commons Pond. The mean SRP flux at 20 °C and sediment oxygen demand (Smax) for five sediment cores are plotted. Error bars represent 67% confidence interval of the mean. Sediment cores were collected before iron treatment in July 2018 and after iron treatment in October 2021 and June 2023.

3.4.2 Estimated internal phosphorus loading in the pond

The in situ monitoring from 2018 to 2020 revealed a primarily anoxic and stratified pond water column during much of the growing season. About 72% of the pond area had low DO (DO < 2 mg/L) on average during the June to August period of those three years (Janke et al. 2021, Janke et al. 2023). Using the lab-measured anoxic sediment phosphate flux of 5.9 mg/m^2/day (at 20 °C), the summertime (June to August) internal phosphorus loading in the pond was estimated to be approximately 4.6 kg (~10 lb) during the pretreatment period. After the application of iron filings, a less pervasive anoxic water column was observed in summer, with an average 13% of pond area under anoxia during this period from 2021 to 2023. Using the anoxic phosphate flux of 0.22 mg/m^2/day measured from iron-amended sediments in 2023, the anoxic pond area in summer 2023 is estimated to have released about 0.08 kg (0.17 lb) of phosphorus. The calculations suggest a significant reduction in internal loading in the pond because of iron filings treatment. Under current conditions, it appears that the iron filings treatment is still successful after 2.5 years.

3.5 Summary and Recommendations

a) Monitoring of the physiochemical conditions in the pond showed a weakly-stratified water column with low DO occurring near pond bottom periodically in summer. The 2023 season showed more extensive anoxia than the 2022 season.
b) Floating plants (duckweed and watermeal) covering the pond surface were observed in peak summer, with 2023 season showing relatively denser cover than that observed in 2022.
c) The post-treatment TP and SRP concentrations were in the low to moderate range during the May to October period of 2022 and 2023. The sampled concentrations, however, exclude the phosphorus trapped in the floating plant biomass on the pond surface during the growing season.
d) Comparison of the post-treatment and pre-treatment pond water quality are largely indicative of improved conditions immediately after the iron filing application. The reduction in pond phosphorus concentrations after treatment likely resulted in reduced floating plant growth due to lower availability of phosphorus for plant uptake. The thinner FPC likely had a positive effect on the oxygenation of the pond water column. After the first year of treatment, however, gradual increases in pond phosphorus and floating plant biomass and frequent anoxia have been observed in the second and third year after treatment.
e) Investigation of phosphorus release from iron-treated sediments from the pond showed very low phosphorus release rates under both oxic and anoxic conditions. This means internal loading under summertime anoxia and due to the mineralization of labile organic P in the sediments under oxygenated conditions was substantially reduced after iron filings treatment and is currently a small load.
f) While the low internal P load estimate suggests that iron filings treatment was still successful as of the 2023 season, the somewhat high phosphorus concentrations (> 0.06 mg/L) sampled

in the pond suggest the continued impact of external phosphorus loading from the watershed on the pond water quality. This cannot be remediated by treating the sediments.

g) Based on the existing conditions in the pond, control of watershed phosphorus loading may be necessary to further reduce pond phosphorus levels. Watershed-based methods (reducing inflow concentrations and volumes) are an effective means of reducing TP exports for all ponds because the runoff inflow TP are a major component of the overall TP mass balance in each pond (Taguchi et al. 2022). Reducing inflow volumes (through the installation of infiltration practices) can lead to increased TP concentrations in ponds since constituents in the pond water will not be as diluted by inflow volumes. This approach would result in low TP export but would not reduce TP concentration for ponds that are treated as amenities where pond water quality is also a priority. Reducing inflow TP concentrations, by implementing practices such as street sweeping, without modifying inflow volumes can reduce both in-pond concentrations and overall pond TP export in a more predictable way.

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