Investigating the Water Quality Impacts of Floating Treatment Wetlands in a Stormwater Retention Pond and Lake: An Environmental Monitoring Approach

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Abstract

Floating treatment wetlands (FTWs) are a best management practice (BMP) applied in aquatic environments to improve water quality by mitigating nutrient pollution. This paper evaluates the efficacy of FTWs installed in natural environments as a tool for the removal of excess nutrients and enhancement of water quality. To this end, regular measurements of key water quality indicators as well as qualitative observations were made at two sites in Minnesota where FTWs have been installed. The results show that there were measurable changes in several water quality parameters over the study period. Statistically significant changes were observed in ortho-phosphate concentration, dissolved oxygen concentration, and pH for one of the study sites. Changes observed in other parameters were inconclusive, and further work is required to understand how FTWs may affect water quality in natural environments when deployed at low coverage rates, as well as how much of the observed changes are attributable to the FTWs and to natural changes in the environment.

Introduction

A floating treatment wetland (FTW), also referred to in literature as constructed floating islands, floating beds, or suds, are water quality improvement best management practice (BMP) consisting of a buoyant mat planted with wetland vegetation (Deering, 2016; Zhang et al., 2014). The primary purpose of a floating treatment wetland is typically controlling eutrophication through the reduction of nutrient pollutants such as nitrates (NO_3), and phosphates, particularly ortho-phosphate (PO_4) (Ortega, 2018; Zhang et al., 2014). High levels of these nutrients, which can be caused by runoff from agricultural operations or urban impervious surfaces entering bodies of water, lead to algal blooms, which reduce the dissolved oxygen available to aquatic life, creating hypoxic 'dead zones' (Díaz & Rosenberg, 2011; Wurtsbaugh, Paerl, & Dodds, 2019). The ideal solution is naturally to address the source of the pollution, but this can in some cases be prohibitively difficult. Nonpoint sources of pollution such as agricultural runoff, which are distributed over a wide area and lack a single origin, contribute approximately 82-84% of P and N that flow into waterways in North America (Wurtsbaugh et al., 2019). There are some existing methods and best management practices for controlling nonpoint source nutrient pollution, such as nutrient management, conservation tillage, and filter strips (Deering, 2016). The difficulty inherent in regulating nonpoint sources of pollution mean that an *in-situ* method that directly cleans waterways is a desirable and viable alternative method of controlling nutrient pollution.

There are several means by which a FTW operates to improve water quality. First, a FTW facilitates the growth of macrophytes, and this vegetation growing on the treatment wetland uptake nitrates, phosphates, and other nutrients as they grow (Marimon, Xuan, & Chang, 2013; Zhang et al., 2014). Second, the main body of the FTW and the roots of the vegetation provide growing space for a microbial biofilm consisting of phosphorus and nitrogen fixing bacteria, which accounts for a large portion of nutrient uptake and sequestration (Zhang et al., 2014). The uptake and sequestration of nutrients by macrophytes and microorganisms are the primary task of FTWs in most contexts. A FTW also acts as a physical filter through the interactions of plant roots with the water, gathering sediment and suspended solids (Nichols, Lucke, Drapper, & Walker, 2016).

Prior literature (Jones, Willis, Gough, & Freeman, 2017),(Liu et al., 2016) has investigated the nutrient removal ability of FTWs in controlled environments through mesocosm studies, but there is an acknowledged shortage of field studies regarding their effectiveness once deployed in natural systems, particularly in the context of urban stormwater retention ponds (Nichols et al., 2016; Wang et al., 2013). This study applied environmental monitoring principles in an attempt to provide a baseline for qualitative and quantitative evaluation of the performance of FTWs at two sites in Minnesota. This is a novel approach to studying FTWs, measuring changes over time in natural water bodies rather than the difference between treatment groups in controlled mesocosms, as has been done in many prior studies (Garcia Chanc, Van Brunt, Majsztrik, & White, 2019). Data was collected over a period of 13 weeks at two sites where FTWs are in use to control eutrophication and improve water quality. There are key differences between evaluating FTW performance in a mesocosm versus in a natural environment. First, in mesocosms, conditions can be precisely controlled, something that is impossible once experiments are scaled up to natural lakes and ponds. Second, in most mesocosm studies of FTWs, FTWs cover a large percentage of the water's surface, frequently ranging from 36-65% (Deering, 2016). However, in the context of actual commercial use in lakes and ponds, FTWs may cover a far smaller percentage; in one sample site – a pond in Vadnais Heights, Minnesota - FTWs cover 0.57% of the surface area, and in the other - Fleming lake, Minnesota - FTWs cover only 0.08% (Ortega, 2018). The essential question is then whether consistent measurements of FTW effectiveness are possible in the context of low coverage rates in uncontrolled environments.

Methods

The study sites were two locations in Minnesota where FTWs have been installed in an effort to improve water quality These are a wet stormwater retention pond in Vadnais Heights, Minnesota, and Fleming Lake, in Fleming township, Minnesota. Both have been the subject of prior projects carried out at the University of Minnesota, some of which are cited in this report (Ortega, 2018). The stormwater pond studied has three FTWs installed, and Fleming Lake has twelve, all of which are BioHaven® Floating Treatment Wetlands produced by Midwest Floating Island. The FTWs were installed in 2016 for both locations.

The Vadnais Heights pond is located at 45.068048N, 93.093557W latitude and longitude. It has previously been determined that the pond has a surface area of 2433 m^2 and a maximum depth of 0.81m (Ortega, 2018). The pond falls within the Sucker Lake catchment, which has land cover of 69.83% developed land, 15.72% forest, 6.25% water, and 8.21% wetland according to the national land cover database (Minnesota Department of Natural Resources, 2018). The pond itself has a narrow riparian buffer of trees to the South, and planted wildflowers to the East, but otherwise primarily borders suburban lawn.

Fig. 1: The sample site in Vadnais Heights. Picture taken on June 5th, 2019.

Fleming Lake is a 297-acre shallow lake (maximum depth 15 ft) located in Aitkin county, Minnesota. Land cover in the surrounding catchment (within 1000' of the shoreline) is 62.7% wetland, 14.8% planted land, 11.3% forest, and 10.3% developed as of 2016 according to data from the Minnesota LakeBrowser and National Land Cover Database (Minnesota Department of Natural Resources, 2018; University of Minnesota, 2018). It is considered an impaired lake by the Minnesota DNR due to excess nutrient levels and eutrophication.

Fig. 2: A floating treatment wetland in Fleming Lake. Picture taken on July 26th, 2019. This image depicts sample site number 4 in the results.

Baseline samples were taken on June 4th for the sampling site at Vadnais Heights, and every week after July 3rd. No sampling was performed for a period of four weeks between the initial, baseline samples and the rest of the study period. A discussion of the potential implications of this missing data, as well as other sources of error and uncertainty, is included in the discussion portion of this paper. Ortho-phosphorus measurements and other data from the Vadnais sample site has been collected and modeled over the past few years by researchers at the environmental and ecological engineering water quality lab at the University of Minnesota (Ortega, 2018). All sampling at the Vadnais pond was performed at the same point on the Northeast shore of the pond.

Comprehensive sampling at Fleming Lake was performed twice: once on July 17th and again on August 29th. The five sample sites were arrayed at points of interest around the lake; the two inlets, the outlet, the approximate center of the lake, and near a well-established FTW. This data was supplemented with data collected by the residents of Fleming Lake on July 1st and July 23rd. In addition to the data collected through monitoring in this project, past data was also compiled and reviewed from several sources to provide a meaningful comparison over time. Turbidity data for Fleming Lake as well as land cover data was sourced from the Minnesota LakeBrowser developed by the University of Minnesota's Remote Sensing and Geospatial Analysis Laboratory in collaboration with the Water Resources Center (University of Minnesota, 2018).

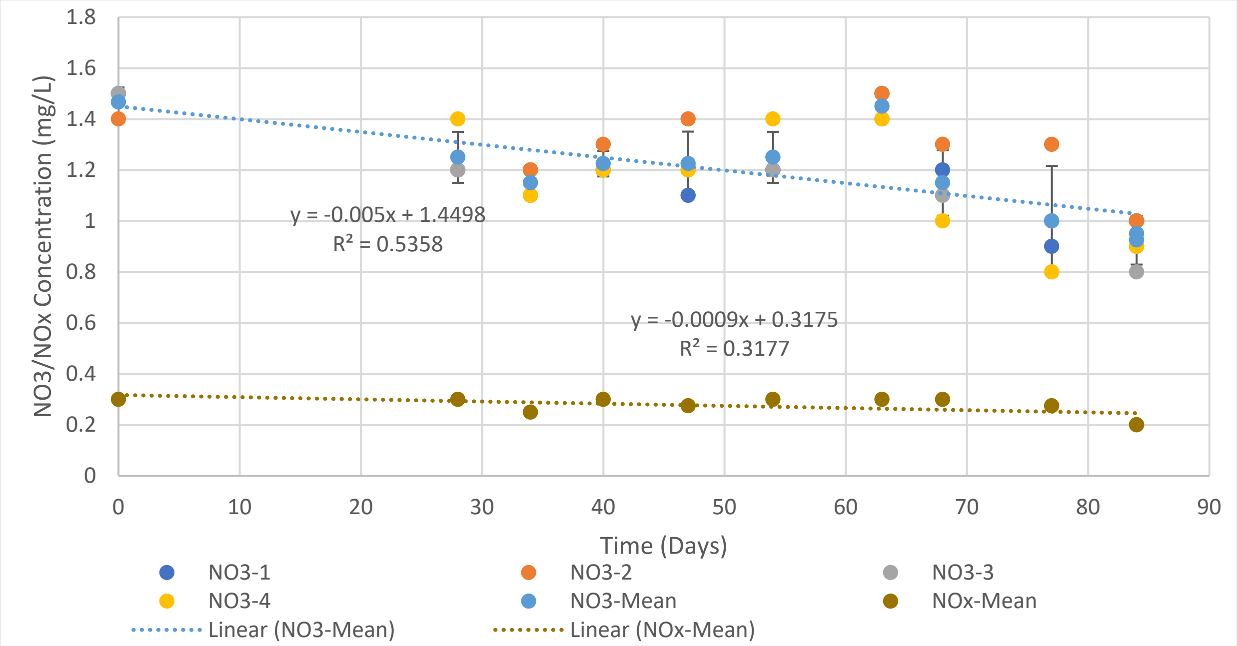
Fig. 3: Sampling locations at Fleming lake, marked by blue points on the map. Image source: (Minnesota Department of Natural Resources, 2018)

The primary method of data collection for this study was monitoring over time of key water quality parameters at the sites discussed above. The water quality parameters measured are: temperature, specific conductivity, pH, turbidity, dissolved oxygen (DO) content, nitrate, nitrate-nitrogen, and orthophosphate. These values were measured using three different instruments. A Hach Nitratax® probe for nitrate and nitrate-nitrogen, a Hach DR890 colorimeter with PhosVer® reagent for orthophosphate, and a YSI 6820 multiparameter water quality sonde for all other measurements. Each day sampling was performed, four measurements of each parameter were taken, with the first being a test run to check instrument calibration. Each run came from a separate sample, and samples were bottled in 1L plastic Nalgene sample bottles. Between sample runs, the bottles were rinsed with deionized water and dried to prevent disruption to the results. For samples taken from Fleming lake, the water samples were stored in a cooler and refrigerated immediately upon returning to the lab to minimize changes to the results due to travel time.

Results

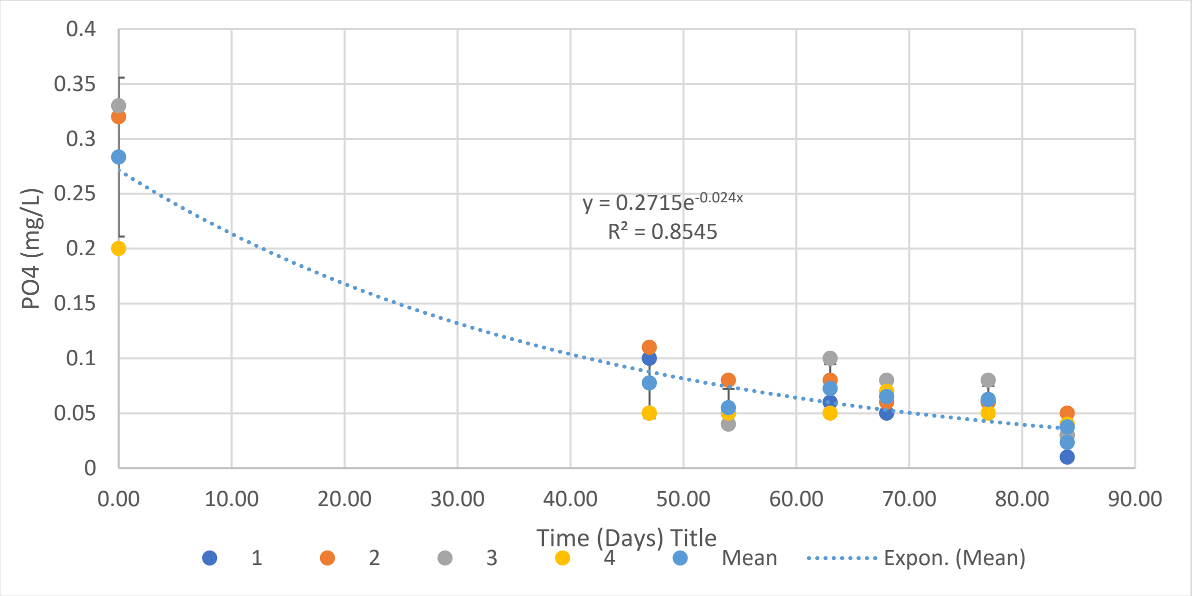
Section 1: Vadnais Sample Site

Figure 3: Measurements of nitrate and nitrate-nitrogen over time in milligrams per liter for the Vadnais Heights sample site.



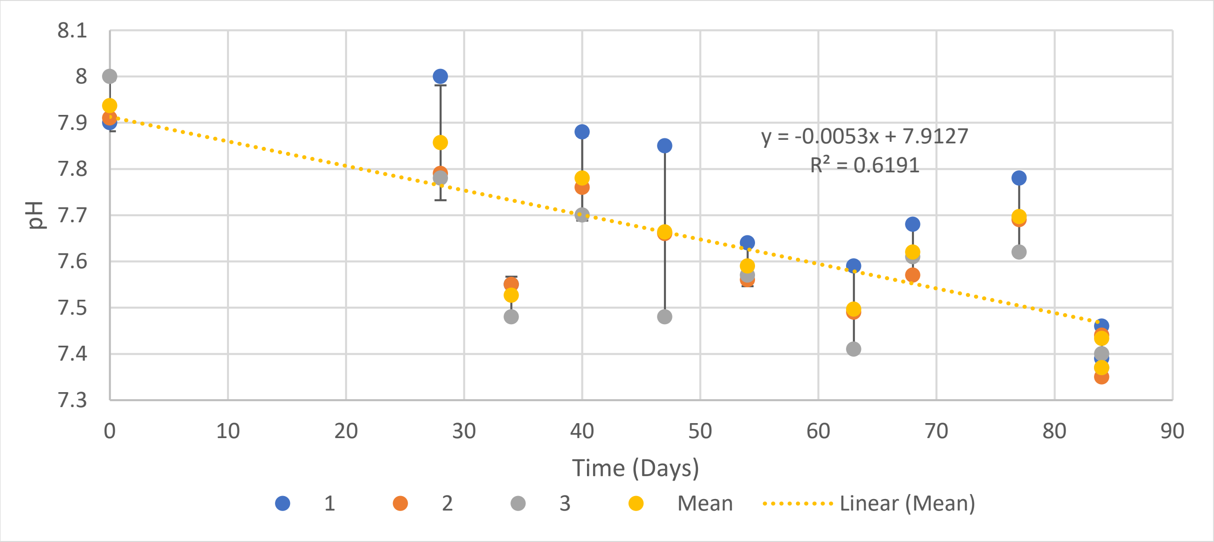
A linear regression was performed on the mean values of each sample set to evaluate the data over time and presence of a trend. The regression indicates that from an initial value of approximately 1.5 mg/L NO3 on June 5th, nitrate concentrations declined at a rate of 0.005 mg/L per day, with an R^2 value of 0.5358. For this graph, as with all others on which a regression has been performed, the date on the x-axis was replaced by a count of days since the first sample to facilitate the regression. Similar procedure was followed for the nitrate-nitrogen data; a standard linear regression was performed on the mean of all data points collected (however, due to substantial overlap between the data points, only the mean is plotted for NOx-N). The resulting regression showed a marginal decline, with an R^2 value for the linear model of 0.3177. Error depicted for the nitrate data is the standard deviation calculated about the mean. For the nitrate-nitrogen data, there was sufficient overlap between the measured values that the standard deviation was zero or negligible for all points.

Figure 4: Measurements of ortho-phosphorus over time in milligrams per liter for the Vadnais Heights sample site.



An exponential regression was performed using the means of each set of samples in order to quantify the trends on the graph. The regression equation is shown in fig. 4, and the R^2 value was found to be 0.8545. Based on the regression equation, PO_4 concentrations underwent exponential decay over the study period. As with the previous figures, error bars show values within one standard deviation of the mean.

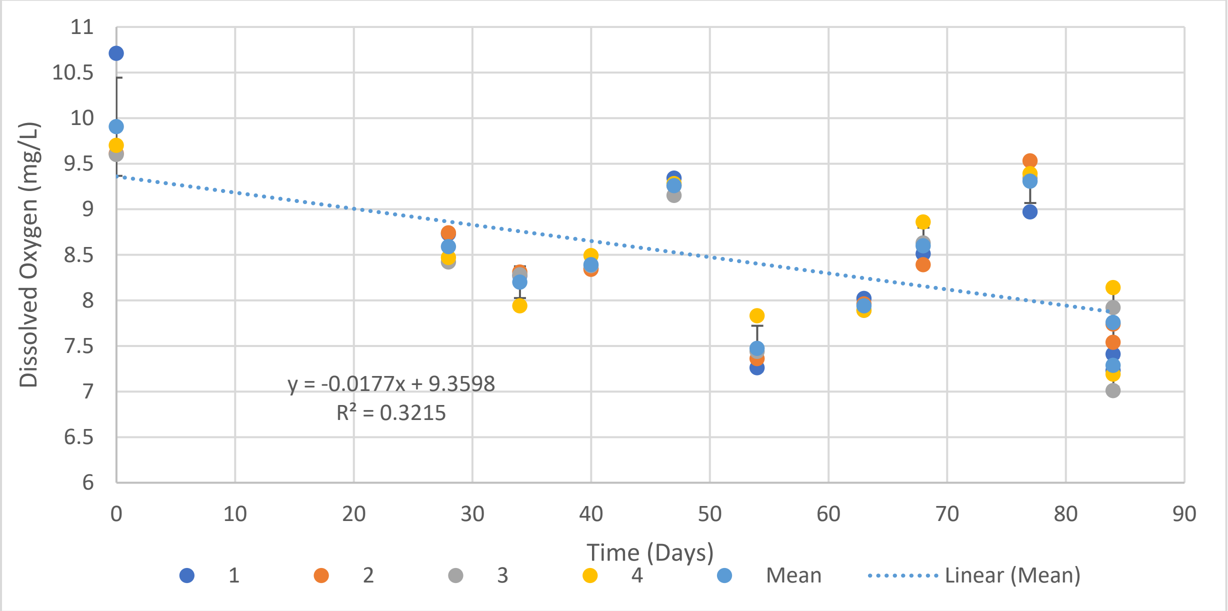
Figure 5: pH measurements conducted over time at the Vadnais Heights sample site.



A linear regression was performed on the mean pH measurements collected at the Vadnais sample site. The results show a clear decline in pH over the study period, with pH declining by approximately 0.0053 per day from an initial value of approximately 7.91. The R^2

value for the linear model is 0.6191. Error bars are representative of the standard deviation calculated about the mean.

Figure 6: Dissolved oxygen (DO) measurements over time at the Vadnais Heights site.



A linear regression was performed on the mean dissolved oxygen concentration over time for the Vadnais sample site. A measurable decline occurred over the study period, approximated in the linear model as a decline of 0.0177 mg/L dissolved oxygen per week, with an R^2 value of 0.3215. The error bars on the plot are the standard deviation calculated about the mean.

Section 2: Fleming Lake Sample Site

Table 1: Data for water quality metrics and physiochemical properties collected from Fleming Lake during the two comprehensive sampling runs.

7/17/2019									
Location	Temp (°C)	SC (mS/cm)	pH	Turbidity (NTU)	DO (% saturation)	DO (mg/L)	Nox - N (mg/L)	NO3 (mg/L)	PO4 (mg/L)
1	25.4	0.109	8.72	5.1	118.2	9.7	0.3	1.3	0.03
2	24.77	0.117	8.27	2.8	88	7.2	0.3	1.2	0.04
3	25.32	0.109	8.32	4.2	11.4	9.69	0.3	1.2	0.07
4	25.55	0.109	8.26	2.8	96.3	9.63	0.3	1.2	0
5	25.62	0.109	8.54	3.7	120.1	9.81	0.3	1.2	0.15
8/29/2019									
1	17.91	0.111	7.64	15	80.6	7.75	0.3	1.2	0.01
2	16.11	0.15	7.17	25	57.5	5.6	0.4	1.6	0.1
3	17.96	0.111	7.01	12.7	95.6	9.06	0.2	1	0.04
4	17.9	0.11	7.62	13	93.9	8.91	0.1	0.4	0.03
5	17.84	0.11	6.62	11.4	94.7	8.99	0.2	0.8	0.03

Fig. 8: Measurements of dissolved oxygen over time for the five sample sites at Fleming Lake.

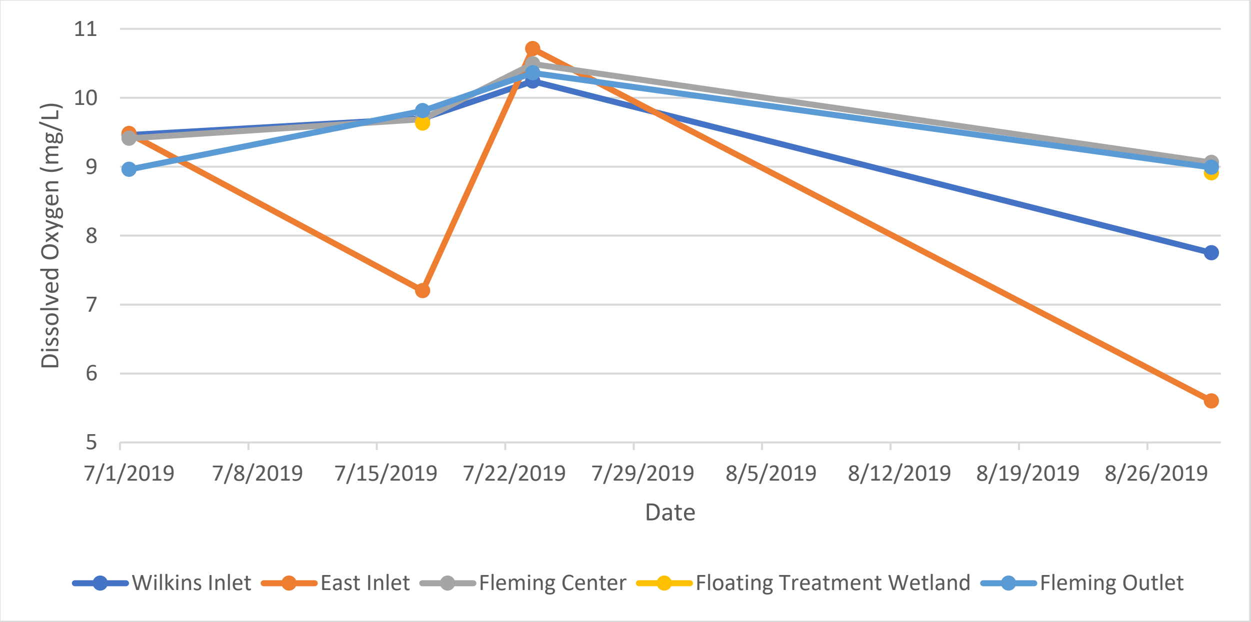
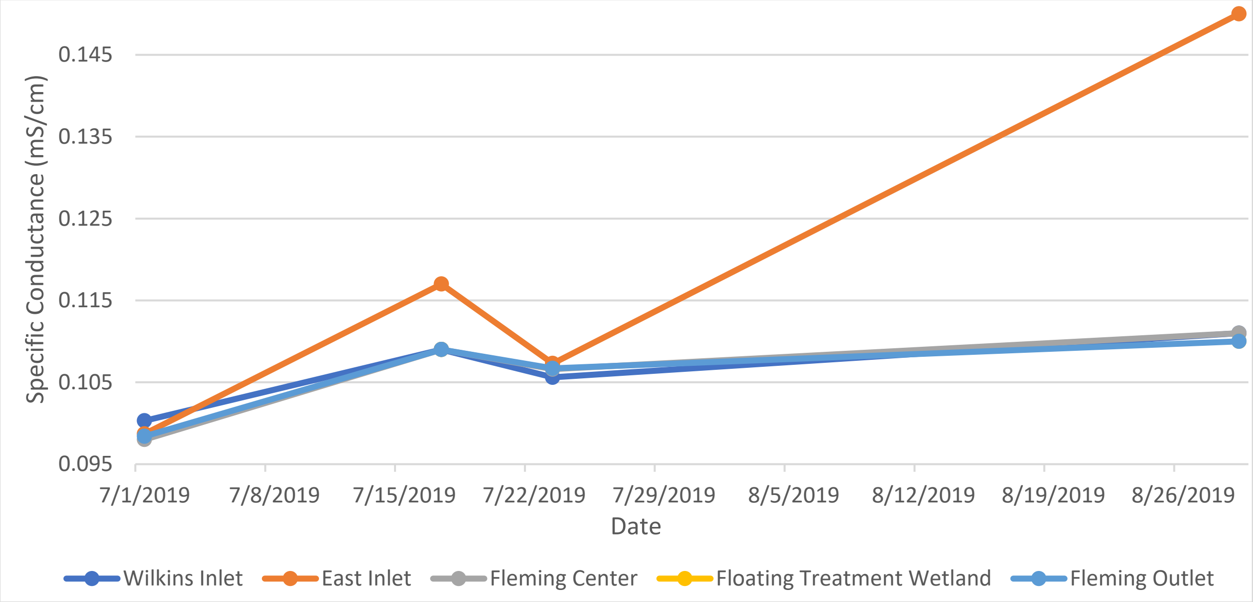


Fig. 9: Specific conductance measurements over time at the five sites in Fleming Lake.



Discussion

Section 1: Vadnais Sample Site

One method of determining whether the FTWs in this study produced a demonstrable improvement in water quality is whether there was a statistically significant decline in nutrient concentrations. It should be noted that eutrophic lakes and bodies of water tend to show seasonal variations in nutrient loading patterns. In the particular case of phosphorus, the tendency is for nutrient loading to peak over the summer (Jeppesen et al., 2005; Søndergaard, Bjerring, &

Jeppesen, 2013). However, there is great variation in patterns between bodies of water based on local and regional factors. To accurately evaluate whether there was a significant difference, data at the watershed and catchment level must be considered. Drawing from past evaluation of these same FTWs and prior literature, it becomes possible to draw some meaningful conclusions.

Nitrate and nitrate-nitrogen has not previously been evaluated for the areas studied in the context of FTW efficacy. With little data available for comparison, it can only be determined whether there was a significant decline over this study period. An ANOVA for repeated measures was performed on the nitrate measurements, and there was not a statistically significant change in concentration between dates at $p<0.05$. While there was a decline, it did not reach the threshold for significance. This is not necessarily surprising, as it has been found that the optimal area coverage for FTWs to remove nitrogen is around 25% (Marimon et al., 2013). With the FTWs in the Vadnais pond covering only 0.57% of the total area, any significant impact on nitrogen would likely be localized to the immediate area around and under the FTWs.

The overall trend in phosphate concentration is far more apparent than that of nitrate. The relative decline from the initial baseline value to the final measurement was far greater – 0.28±0.072 to 0.02±0.011 - than nitrate. Furthermore, the R^2 value for the fitted model was far higher; 0.8545 compared to 0.5358 for the NO_3 regression. A single-factor ANOVA for repeated measures was performed on the data points to establish the statistical significance of the observed trend, and the results show that there was a statistically significant difference over time in orthophosphate concentration, with $p=0.002583$. Ortega (2018) used the relationship between chlorophyll *a* concentration and phosphorus as determined by Dillon & Rigler to estimate phosphorus concentrations (Dillon & Rigler, 1974; Ortega, 2018). However, there is an issue with the phosphate measurements, and that is that there are missing measurements for several days when data was otherwise collected. These missing data points are from the period July 3rd to July 15th, and were due to a shortage of reagent necessary to operate the colorimeter. Based on the exponential decay model fitted to the data, this period is when some of the largest changes in concentration would be expected, but with no actual measurements of phosphate made, this cannot be confirmed.

The pH data obtained from the measurements at the Vadnais site show a downward trend throughout the study period. To determine the significance of this trend, a single-factor ANOVA for repeated measurements was performed on the data. The observed decline in pH over time was statistically significant, with $p=0.001148$. Ortega (2018), when studying these same sites, observed an increase in pH readings adjacent to the recently installed FTWs relative to other points in the pond, contradicting these observations. However, for this study, all samples for the Vadnais site were taken from the same point near the shoreline, so this localized effect should not have significantly impacted the results. One potential cause of this decline in pH is precipitation. Rainwater has a lower pH than the typical lake or pond, so it is possible that large volumes of precipitation could have this effect. The results found by Ortega (2018), suggest that this is unlikely under ordinary conditions. However, the summer of 2019 had the most precipitation since 1892 for parts of Minnesota, lending credence to the hypothesis that heavy rains were a significant factor in the decline in pH (Minnesota Department of Natural Resources, n.d.).

Dissolved oxygen measurements over time also showed a clear downward trend. This is somewhat expected, as increasing algal blooms over the course of the summer intensified eutrophication and reduced available oxygen in the water. This decline was statistically significant, as verified by an ANOVA for repeated measurements, which found significance at $p<0.05$. FTWs are often implemented in an effort to reduce eutrophication and by extent improve available DO. Prior literature indicates that FTWs can have mixed effects; it has been observed that directly underneath FTWs, lower dissolved oxygen conditions may occur (Wang et al., 2013). However, mesocosm studies, when looking at overall conditions, found higher DO values in an FTW treatment when compared to a control (Wang et al., 2013).

It must be noted that while statistically significant changes in some parameters were observed, fully understanding the cause of the observed changes is not possible with the data at hand. With the FTWs covering only 0.57% of the available surface area, the most significant impacts on water quality are expected to be small and localized.

Section 2: Fleming Sample Site

Substantially less data was collected from Fleming Lake, making it difficult to accurately determine statistical significance. However, it is still possible to draw some conclusions.

During the course of the study period, Fleming lake underwent a substantial increase in algal blooms, particularly towards late August. This is likely due to the dieback of curly-leaf pondweed and other aquatic plants temporarily increasing available nutrients, allowing an algal bloom to occur. Observed changed in water quality parameters coincide with the increasingly eutrophic conditions observed at the end of August. An increase in nutrient concentrations near one of the inlets, and a decrease nearer the outlets, a decrease in dissolved oxygen. In addition, an increase in specific conductance was observed from one of the inlets, indicating an increase in ion and sediment loads.

Nutrient loading of N and P is the main driver of eutrophication (Wurtsbaugh et al., 2019). Therefore, evaluating the statistical significance of changes in nitrate and phosphate concentration is important to evaluate the severity of the observed eutrophication. An ANOVA for repeated measures was run for both nitrate and phosphate concentrations, and found that there was not a statistically significant change in either case. With only two measurements to draw from, this only shows that there was no significant change from July to late August. It gives no information about what may have happened to nutrient concentrations in between these points, which is when the algal bloom began. Improving the consistency of measurements is a necessary next step in future work of this kind, as the existing data is insufficient for interpolation.

Dissolved oxygen measurements peaked in midsummer and then declined substantially by the end of August. This trend is consistent with other observed changes in the lake, namely an increase in algae and eutrophic conditions at the end of the summer. An ANOVA for repeated measurements found that the observed changes were statistically significant at $p<0.05$. The algal blooms and eutrophication reducing available DO is clearly concerning. However, while this effect was present across sample sites, it was most pronounced at the inlets, meaning that water flowing in to Fleming lake was less oxygenated than water flowing out, a positive sign for the health of the lake and its ability to resist further eutrophication.

Specific conductance (SC), as a measure of the ability of a substance to conduct electricity, indicates the concentration of ions in water in the context of water quality monitoring. As such, it is useful for indicating the concentration of substances such as dissolved salts, chlorides, and other inorganic ionic compounds. Changes in SC over time were observed at Fleming lake, particularly at the East inlet. However, an ANOVA for repeated measures found that the changes were not statistically significant for the lake as a whole.

Section 3: Experimental Flaws and Sources of Error

Observations of natural systems are, unlike studies in controlled mesocosms, are fundamentally inconsistent. The observed decline in nutrient concentration over the study period corroborated with an improvement in other water quality metrics from previous years suggests that the FTWs deployed may indeed producing measurable improvement in water quality. However, the essential issue with this study is that it cannot be known how much of the observed changes are due to the FTWs versus changes in the environment, i.e., precipitation, temperature, or land use. In light of this, there are numerous improvements that could be made to this study and flaws in the methodology that ought to be addressed in future work.

First and foremost, the measurements in this study for the Vadnais site lack a control for comparison purposes. There are several methods that could be used in future work to rectify this. Samples could be taken from multiple locations in the pond, as was done in some previous studies to provide a sort of control group and determine to what degree water quality improvements were localized around the FTWs (Ortega, 2018). Another possibility is the use of measurements from a pond located in the same catchment with similar characteristics that does not have FTWs. Second, there are numerous water quality parameters that are useful for evaluating FTW performance that were not considered in this study, such as chlorophyll *a* concentration as a measurement of algae and aquatic plant activity, and alkalinity to evaluate resistance to pH changes, since statistically significant changes in pH were observed in this study.

Methodological flaws aside, there were several sources of error in the measurements. First, instrumentation error disrupted some of the readings. Specific conductance measurements for the Vadnais site were done incorrectly for the first four measurements, resulting in unusable data. Second, weather and other uncontrollable events may have altered measurements. Precipitation leads to runoff, which increases turbidity, suspended solids, and nutrient loads, all of which may have impacted measurements taken within a short timeframe after rainstorms.

Conclusion

In light of the consequences of global climate change, applying knowledge of the natural world to devise new methods of pollution control is an important task for environmental/ecological engineers and scientists. Many climate models predict an increase in precipitation across temperate regions, a natural result of which is increased runoff and therefore nutrient pollution (Marimon et al., 2013; Solomon et al., 2004). FTWs are one potential method of mitigating this significant issue.

If FTWs are to be utilized as a BMP for water quality improvement, it is necessary to understand the optimal conditions for their use. The results of this study show that at very low surface area coverage, it is difficult to measure statistically significant changes in water quality directly attributable to FTWs. Even at low coverages, FTWs may offer other benefits, such as habitat for native plant and animal species (if plants are selected appropriately), or aesthetic appeal. However, in order to produce measurable, significant improvements in water quality, it is important to position FTWs in locations where they can be deployed at optimal coverage rates (optimal being approximately 25% coverage for most efficient nitrogen uptake according to Marimon et. al, 2013).

Future work in this area will continue to evaluate how key measures of water quality change over the lifetime of the treatment wetlands and with changing natural conditions. It should therefore be noted that this study acts primarily as a pilot, an early effort to extend the study of FTWs from laboratory mesocosms to natural bodies of water. By itself, the data acquired in this study is insufficient to precisely quantify the impact of FTWs on the study areas, though it is possible to draw some conclusions about their efficacy when known information from prior work is considered. Hence, a major goal of any future work will be to build on the data collected in this study, creating a dataset of water quality information spanning multiple years to investigate FTW dynamics and efficacy over the long term.

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