# Floating Treatment Wetlands: Inter-Relationships between Engineered Solutions for Nutrient Pollution and their Bodies of Water

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## Dedication

I dedicate this thesis to my family, for always supporting my pursuit of science, and to my husband, who has been an incredible source of mental and emotional support throughout this process.

## Abstract

Floating treatment wetlands (FTWs) are a best management practice (BMP) currently used in several countries worldwide to reduce nutrient concentrations in bodies of water. This study examines the chlorophyll-*a* reduction potential of FTWs in two bodies of water within Minnesota. Field measurements were taken to determine the physical and chemical characteristics of the water affected by the FTWs. Results indicate that the FTWs influence the water close to them but impacts on the entire body of water depend on the percent of the surface area covered by FTWs. FTWs were examined in two additional field sites to determine possible accumulation of periphyton mass on the FTW matrix over time. In both field sites, periphyton was found to accumulate at a relatively constant rate. In addition, the resilience of the FTWs to harsh winter conditions, as they would experience in Minnesota, was tested in a laboratory study. This study put the FTWs through repeated freeze-thaw cycles to estimate degradation of the FTW matrix material due to ice stress. A mathematical model was created to estimate the loss of material from the FTWs after a given number of freeze-thaw cycles, and the majority of the losses were found to occur during the freeze-thaw cycles. Further research on these subjects is recommended based on the findings from these experiments.

**Table of Contents**

**List of Tables**

**List of Figures**

**List of Equations**

## Introduction and Research Overview

According to the 2010 US EPA Water Quality Assessment Report, which surveyed over twenty million acres of lakes across the US, about 25% (nearly five million acres) of the lake area surveyed had some nutrient-related impairment. About 84% of the lakes in Minnesota were surveyed, and of those, 14% were identified as having a nutrient-related impairment (US EPA, 2010). A more recent report by the Minnesota Pollution Control Agency (MPCA) estimated that 40% of the waters in Minnesota are impaired by some conventional pollutant. 42% of the lakes on its impaired waters list were identified as having some nutrient or eutrophication biological indicators (Minnesota Pollution Control Agency, 2018).

In the context of surface waters, nutrient pollution typically refers to excess concentrations of Nitrate-N and Phosphate-P. High levels of these nutrients can cause increased growth of algae, which can in turn reduce the amount of available dissolved oxygen and create “dead zones” of extremely low oxygen levels that stress and kill aquatic life (Burns, 1976; Conroy, Boegman, Zhang, Edwards, & Culver, 2011; Smith, Tilman, & Nekola, 1999). These nutrients come from a variety of sources, which can be divided into two major categories: point sources, or easily-identifiable points from which specific pollutants originate; and nonpoint sources, which are sources of pollution spread out over broad areas that cannot be narrowed down to a single source (US EPA, 2012). Nonpoint sources are typically associated with particular land uses, such as agricultural operations and urban runoff. The MPCA estimated that about 86% of the water pollution statewide is due to nonpoint sources, representing the largest combined threat to Minnesota’s waters (Minnesota Pollution Control Agency, 2017a). The MPCA recently

developed a nonpoint source management plan in order to reduce nutrient loading from nonpoint sources (Minnesota Pollution Control Agency, 2013). However, nonpoint sources are notoriously difficult to locate and manage. This occasionally necessitates solutions to be put in place to treat the pollution in situ. This allows the effects of the pollution in the body of water to be reduced, even if the source of the pollution cannot be identified.

Floating treatment wetlands (FTWs) are a possible best management practice (BMP) for reducing nutrient loading in ponds and lakes. FTWs were created based on the idea of bio-mimicry, engineered solutions that aim to imitate natural systems – in this case, filtration of water by natural wetlands. This study focuses on FTWs constructed by Midwest Floating Island, which are constructed from a matrix of recycled polyethylene terephthalate (PET) fibers injected with two-part polyurethane foam to provide buoyancy (Borne, Fassman, & Tanner, 2013; Floating Islands West, 2016). The PET fibers are made from recycled plastic bottles, a process that is marketed as environmentally-friendly "upcycling." This process takes waste plastic and turns it into a new product, preventing it from ending up in a landfill. The FTWs also have holes drilled partially through them to allow the matrix to be planted with aquatic plants. The FTWs are anchored in place to keep them in an optimal location within the body of water (Floating Islands West, 2016).

FTWs function as an in-situ solution for mitigating nutrient loading through two proposed mechanisms. First, the PET fibers have a high surface area on which biofilms and microbes may grow. As biofilms grow, they take up nitrate-N, ammonium-N, and phosphate-P from the water and reduce the nutrients available for growth of harmful algae (Van de Moortel, Meers, De Pauw, & Tack, 2010). As the biofilms accumulate on

the FTWs over time, they may increase the surface area available for further growth (Borne et al., 2013; Vymazal, 2007). Second, the plant roots provide an additional surface area for microbe and biofilm growth. The plants themselves take up nutrients from the water as well, providing increased denitrification at rates of 20 to 30 percent and phosphate removal rates of 40 to 50 percent (Martin Ecosystems, 2014; Sundaravadivel & Vigneswaran, 2001; Winston et al., 2013). The plants also assist with denitrification, although the rate and efficiency of denitrification depends on the specific plants on the FTW (Bachand & Horne, 1999; Moshiri, 1993). The plant roots can reduce the amount of suspended sediments by slowing water movement and allowing sediments to settle out of the water column (Lynch, Fox, Owen, & Sample, 2015; Wang & Sample, 2014) and the FTWs themselves provide a habitat for ducks, turtles, and other wildlife (Floating Islands West, 2016).

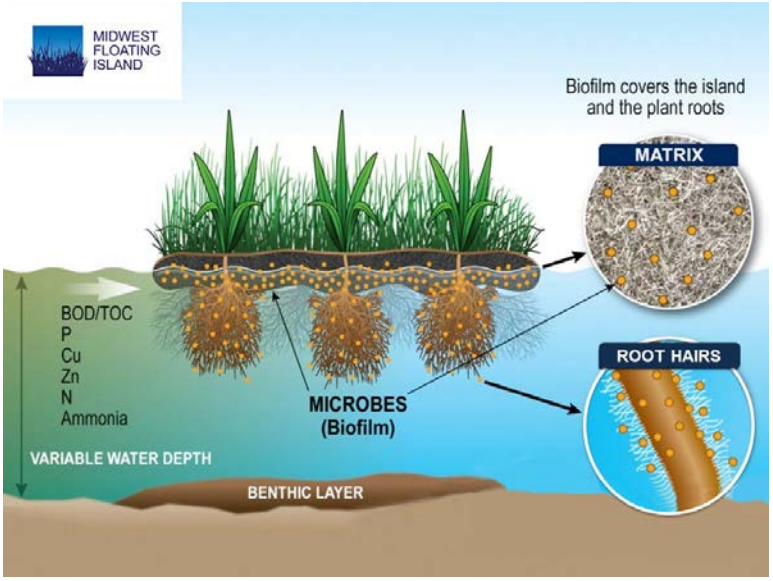



*Figure 1. Cut-away diagram of the components of an FTW (Floating Islands West, 2017).*

A recent project undertaken by the University of Minnesota and Midwest Floating Island, funded by an Enbridge Ecofootprint Grant, installed sixteen FTWs in Fleming Lake in Aitkin, Minnesota to evaluate the effectiveness of FTWs at reducing the severity of the algal blooms the lake experiences every summer. The FTWs were installed on August 23, 2016 and have remained in place since installation. A report on BioHaven Floating Wetland Technology stated that the lifespan of the FTWs is estimated to be ten years (Martin Ecosystems, 2014). Personal conversations with Midwest Floating Island have established that FTWs have a projected lifespan of fifteen years.

A potential issue when leaving FTWs in a water body over the winter is stress caused by freeze-thaw cycles. A freeze-thaw cycle is defined as a day in which the maximum temperature is 0°C or above, and the minimum temperature is -2.2°C or below (Russell, 1943; Schmidlin, Dethier, & Eggleston, 1987). This definition was applied in this study to estimate the number of freeze-thaw days a body of water in Minnesota may experience. The tear strength of the matrix material is 13,671 kilograms per square meter for a five-centimeter-thick section (Martin Ecosystems, 2014), but it is possible that freeze-thaw cycles may weaken the PET fibers, leading to production of microplastics. The term “microplastics” has been used in previous studies to identify small pieces of plastic polluting a body of water, although the diameter range varies (Andrady, 2017): less than 10 mm (Graham and Thompson, 2009), less than 5 mm (Betts, 2008; Barnes et al., 2018), 2-6 mm (Derraik, 2002), less than 2 mm (Ryan et al., 2009), and less than 1 mm (Browne, Galloway, and Thompson, 2007; Browne et al., 2011; Claessens et al., 2011). For the purposes of this study, since this material used for this purpose had yet to

be tested for microplastic production, microplastics are defined as any particle that is greater in diameter than 0.50 µm.

In addition to contributing to plastic pollution, microplastics can act as a disruptor to aquatic trophic systems. Aquatic invertebrates sometimes mistake microplastics for food and ingest them, which can cause lingering health effects. Microplastics may absorb other environmental pollutants, such as nonylphenol (an endocrine disruptor), phenanthrene (a respiratory irritant), and triclosan and PBDE-47 (hormone disruptors) and transfer said pollutants, among others, to the digestive tracts of aquatic invertebrates, fish, and even birds (Mark Anthony Browne, Niven, Galloway, Rowland, & Thompson, 2013; Faure, Demars, Wieser, Kunz, & de Alencastro, 2015; Lu et al., 2016). Microplastics have also been shown to bioaccumulate, occurring at low concentrations in organisms at the lowest trophic levels, such as invertebrates, and increasing in concentration in higher tropic level organisms, such as loons and seagulls (Ryan et al., 2009; Graham and Thompson, 2009). This can lead to increased exposure to environmental pollutants in higher-level organisms, which can, in turn, cause disruptions to food chains.

### Existing Research and Research Needs

FTWs have been examined for their nutrient reduction capabilities and other water treatment functions in at least seventeen countries, but results remain inconsistent and difficult to generalize (Wang & Sample, 2013). FTWs have been primarily used to treat wastewater and polluted freshwater through growth of biofilms and plants that remove nutrients from the water. However, they have not been much studied in their capacity to lower pollutant concentrations in freshwater ponds and lakes. This study aimed to examine the ability of the FTWs as in situ treatment for excess nutrients and chlorophyll-

*a* concentration in freshwater with known algae problems. Further, the accumulation rate of biofilm and periphyton growth had not yet been quantified for bodies of water in Minnesota, so this study created a method for doing so and some preliminary research on rates of accumulation. The FTW matrix material has not been tested for the possibility of production of microplastics outside of this study. As such, the following research provides a basic platform for the studies undertaken here.

Wang and Sample (2014) performed a mesocosm analysis of FTWs' removal efficiency of several nutrients, as well as their ability to reduce chlorophyll-a concentrations. Their experiment consisted of four experimental groups: a control, a floating mat treatment with no plants, a floating mat treatment with pickerelweed, and a floating mat treatment with softstem bulrush. Wang and Sample hypothesized that the shading effect of the FTWs reduced chlorophyll-a concentrations. Over the course of six stages, they found that the difference in chlorophyll-a concentration between the control and experimental mesocosms was not statistically significantly different. These results indicate that neither FTWs nor the plants on them inhibit the growth of algae, which was the main source of chlorophyll-a in the water. Nutrient competition between the FTW microbes and biofilms, and algae, was considered a major factor for chlorophyll-a reduction in previous studies, but the results of this study suggest that this may not be the case (Wang & Sample, 2014). The study undertaken here aimed to replicate the methods of Wang and Sample to examine the chlorophyll-*a* reduction role of FTWs in actual field settings, and to determine whether the results of the Wang and Sample study are applicable to field conditions.

Lynch et. al (2015) examined the ability of Beemat and BioHaven floating islands to reduce total nitrogen (TN) and phosphorus (TP) concentration in batch-fed mesocosms filled with runoff from a stormwater retention pond. The FTWs were planted with soft rush prior to the start of the experiment, and the study included four replicates of three treatments: a control, the Beemat FTWs, and the BioHaven FTWs. For all treatments, the FTWs covered 65% of the water's surface. Over the entire study, the Beemat FTWs removed 40% and 48% of the TN and TP, respectively, while the BioHaven FTWs removed 25% and 4% of the TN and TP, respectively. The control treatment removed 28% and 31% removal of TN and TP, respectively. It was hypothesized that differences in the material used to create the FTW matrix were the cause of the difference in removal rates. The biomass of the plants on the BioHaven FTWs was significantly greater than that of the plants on the Beemat FTWs. Further, the two FTW treatments had a higher average temperature over the course of the study than the control treatments, likely due to the dark-colored material absorbing incoming solar radiation and transferring heat to the water. The FTW treatments had lower average DO and pH readings than the control, although the Beemat FTW treatment had the highest average conductivity readings (Lynch et al., 2015). The work undertaken here used this study as a basis for the physiochemical characteristics portion of the FTW field experiment, in addition to estimations of nutrient removal and plant growth.

Winston et. al (2013) evaluated FTWs as retrofit solutions to moderating temperature and mitigating concentrations of TN and TP in two urban stormwater retention ponds in Durham, NC. The two ponds, called the DOT pond and the Museum pond, were studied from summer 2008 to February 2010 before FTWs were installed, and from March 2010

(when the FTWs were installed) to September 2011. The ponds had different surface area coverage of FTWs: the DOT pond had 9% coverage, and the Museum pond had 18% coverage. Water samples were collected by ISCO machines when rainfall events were recognized, defined as any precipitation 3 mm or greater. Temperature readings were taken by temperature sensors fixed to the undersides of the FTWs and sensors fixed 2 m away from the edge of the FTWs in both ponds. In the DOT pond, TN concentration was reduced from 1.05 mg/L to 0.61 mg/L after FTW installation, and TP was reduced from 0.17 mg/L to 0.12 mg/L. However, these results were not statistically significant. In the Museum pond, TN concentration went from 0.41 mg/L and 0.43 mg/L after FTW installation, and TP was reduced from 0.11 mg/L to 0.05 mg/L. The reduction in TP concentration in the Museum pond was statistically significant. The temperature measurements in the open water of the two ponds were not statistically significantly different than those measured beneath the FTWs, which suggested that the FTWs did not provide temperature moderation from shading. The results overall suggested that a higher percent surface area coverage by FTWs increased removal of pollutants (Winston et al., 2013). This study was used as a further basis for the research performed here, specifically with regards to percent surface area coverage and the FTW shading hypothesis.

A report by the MPCA in 2014 performed an analysis of the effects of plastic microbeads in Minnesota, and the research on their impacts. The most common sources of microplastic pollution in Minnesota previously came from personal care products. However, other sources include fibers from synthetic fabrics, spillages of pre-production plastic pellets, and fragments from degradation of larger plastic products or coatings. Several studies have found these plastics in aquatic organisms at varying concentrations.

The study most relevant to Minnesota waters was done at the University of Wisconsin – Superior. In this study, 110 fish stomachs from Lake Superior were examined, and 18% were found to contain plastic filaments. Other research has shown that aquatic invertebrates that consume microplastics have lowered energy levels and are more susceptible to injury from sorbed pollutants. The report recommended removing microplastics in personal care products as the main action to prevent microplastic pollution. This was addressed by H. F. No. 2414, which made it illegal in July 2015 to sell personal care products containing plastic beads with a diameter of 5 mm or less (Mullery, 2014). In addition, the report recommended that biodegradable plastics be used in place of non-biodegradable plastics whenever possible. It was also recommended that the MPCA and the University of Minnesota continue to monitor the issues of consumption of microplastics by aquatic organisms and the potential risk of toxicity associated with microplastic ingestion. These documents informed the creation of the microplastics laboratory experiment undertaken here.

### Research Overview

The research undertaken here had several goals, involving both field and laboratory observations. The goals of this study were to:

1. Quantify the effects of FTWs on chlorophyll-*a* content in the water column;
2. Quantify the effects of FTWs on water quality parameters pH, dissolved oxygen, temperature, conductivity, and Secchi depth;
3. Quantify the amount of periphyton growth that accumulates on the FTW matrix material over time; and

4. Quantify the effects of freeze-thaw cycles on the FTW matrix material in terms of mass, particle, and area loss over the FTWs' fifteen-year lifespan.

Findings will aid FTW manufacturers, Midwest Floating Island in particular, to determine the reduction in chlorophyll-a in waters surrounding the FTWs, as well as the potential for the PET matrix to produce microplastics. This will determine in what contexts FTWs are an appropriate BMP for mitigating nutrient pollution in situ, and whether the possible benefits of using FTWs outweigh the risk of plastic pollution.

# Chapter 1: Floating Treatment Wetlands Field Study

## 1 Project Background

This study aimed to quantify the chlorophyll-*a* reduction capacity of the FTWs, and the FTWs' effect on physiochemical characteristics of bodies of water. Two study sites were used: Fleming Lake in Aitkin, Minnesota (46.6294° N, 93.4951° W) and an unnamed pond in Vadnais Heights, Minnesota (45.068118° N, 93.093542° W) hereafter called Vadnais Pond. The Minnesota Pollution Control Agency (MPCA) monitored Fleming Lake from May to September during the study period in 2015 and 2016.

Fleming Lake has a surface area of 1.23 $km^2$ and maximum depth of 4.57 m (Minnesota Pollution Control Agency, 2015). The FTWs cover about 93.08 $m^2$ of Fleming Lake's surface area, or about 0.08% of the total surface area. It lies directly south of Wilkins Lake, and is connected to Wilkins Lake through a shallow ephemeral stream that flows from Wilkins Lake into Fleming Lake. As such, the watershed of Wilkins Lake is considered part of the watershed of Fleming Lake. The combined watershed is 18.72 $km^2$ in area and contains mostly wetland (50% of land use) and forest (37% of land use), although there are private residences surrounding each lake as well (4% of land use), and there is some agricultural land to the west (10% of land use). The agricultural land was of concern since runoff from manure and fertilizer could be a source of nutrient pollution to Fleming Lake. The strong algal blooms Fleming Lake experiences in the summer, especially in contrast to Wilkins Lake's clear water, made it a candidate for one of Midwest Floating Island's first FTW installations in a freshwater lake.

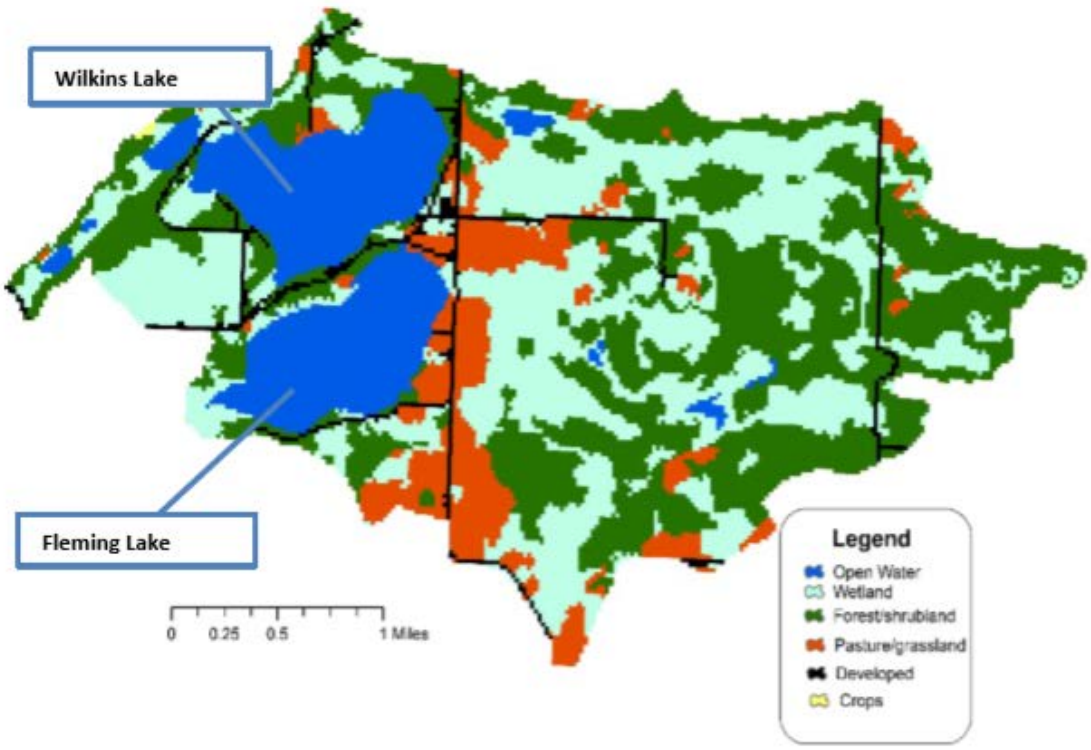



*Figure 2. Diagram of land use in the Fleming Lake and Wilkins Lake combined watershed (Martin, 2017).*

Since Fleming Lake is a shallow lake (less than six meters in depth at its deepest point), the MPCA report identified it as a polymictic lake. This was corroborated by the temperature and dissolved oxygen (DO) data collected in 2015 and 2016, which showed relative consistency from the surface to the bottom.

This study also examined the total phosphorus (TP) concentration in Fleming Lake and its chlorophyll-*a* content for comparison to past studies. The average TP concentration from the two summers was 70 µg/L (40 µg/L in 2015, 90 µg/L in 2016). 2016 was a particularly rainy summer, so it was hypothesized that the increase in TP concentration was due to additional runoff from the agricultural lands in the watershed. These values are much higher than the typical range for lakes in the area, which is 14-27 µg/L. Previous studies show that the TP concentration in Fleming Lake is increasing by about

10 µg/L per decade (Martin, 2017). The average chlorophyll-*a* concentration from the two summers was 45 µg/L. Concentrations of 10-20 µg/L are considered conditions for a mild algal bloom, and 30 µg/L indicating severe nuisance conditions, so this value is extremely high. As with TP concentration, chlorophyll-*a* concentration is also increasing, up from 33 µg/L in 1996. Secchi depth readings were also taken in Fleming Lake over the course of the MPCA study. The average Secchi depth for the two summers was significantly lower than that of other lakes in the region, which was expected based on the high TP and chlorophyll-*a* concentrations. For seven of the ten sampling dates, the Secchi depth did not exceed 1 meter. However, examining the twenty-year trend of Secchi depth based on citizen lake monitoring, this is not unusual; Fleming Lake has an approximate ten-year cycle of Secchi depth, with the maximum being approximately 1.3 m and the minimum around 1.0 m. Analysis of the Secchi depth data in the report showed a decrease of average Secchi depth by 0.0335 m from 1991 to 2016, but since the data was on its minimum as of the writing of the MPCA report, it will likely be several years before this trend can be confirmed (Martin, 2017).


*Figure 3. Location of Fleming Lake and experimental site.*

Vadnais Pond has a surface area of 2,433 $m^2$ and maximum depth of 0.81 m, as measured in this research by analysis of satellite imagery in ImageJ and depth soundings, respectively. Its surrounding area is primarily residential, with a set of train tracks running along the southeastern border of the pond, separated by approximately 10 m of trees and gravel. Water flows into the pond from the surrounding land, then out to a stream that flows into Sucker Lake. Vadnais Pond was selected to be evaluated in this study since FTWs were installed there around the same time as those in Fleming Lake. The differences between the two systems may provide an insight into the relationship between the size of the body of water and the necessary percent coverage by FTWs. The three FTWs in Vadnais Pond cover about 13.91 $m^2$ of the pond, or about 0.57% of the total surface area.


*Figure 4. Location of Vadnais Pond and experimental site.*

# 2 Methods

## 2.1 Experimental design

Three FTWs were installed in Vadnais Pond on September 8, 2016, in the following configuration:


*Figure 5. Vadnais Pond FTW configuration.*

Each island was planted with two varieties of plants as follows:

*Table 1. Configuration of plants on FTWs in Vadnais Pond.*

| Island ID | Plants |
|---|---|
| 1 | 24 Wool Grass, 54 Riddell's Goldenrod |
| 2 | 24 Ironweed, 54 Bulrush |
| 3 | 24 Swamp Milkweed, 54 Common Rush |

All islands are 4.64 $m^2$ in area.

16 FTWs were installed in Fleming Lake on August 23, 2016, in the following configuration:

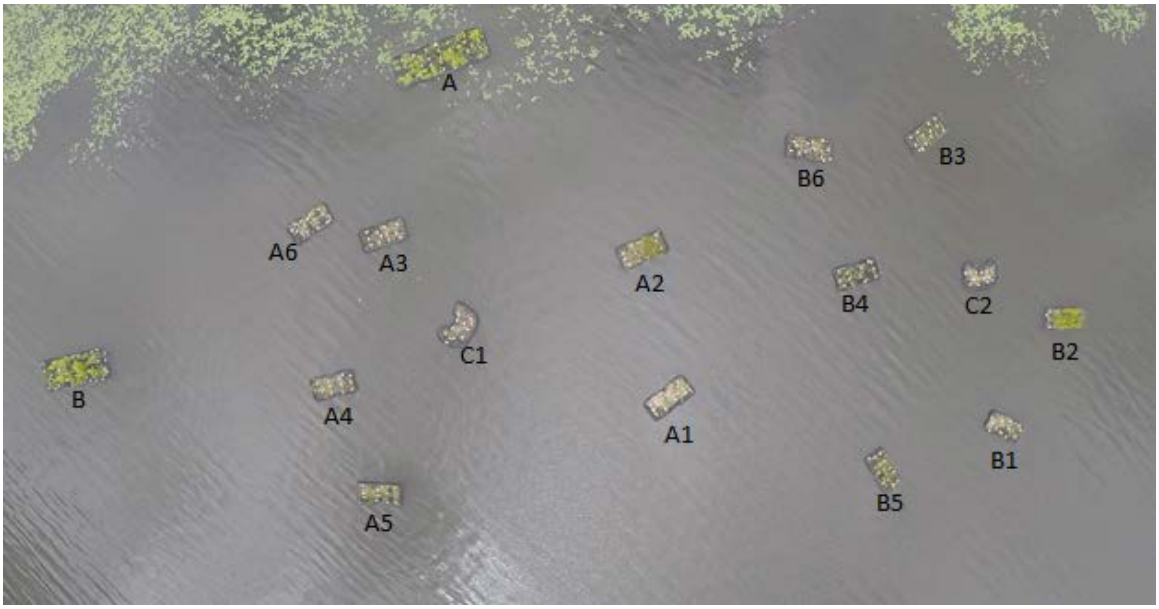



*Figure 6. Fleming Lake FTW configuration.*

Each island was planted with a variety of aquatic and wetland plants as follows:

*Table 2. Configuration of plants on FTWs in Fleming Lake.*

| Island ID | Plant Species |
|---|---|
| A1 | 24 Tussock Sedge, 76 Bottle Brush Sedge |
| A2 | 24 Swamp Milkweed, 76 Common Rush |
| A3 | 24 New England Aster, 76 Fowl Manna Grass |
| A4 | 33 Monkey Plant, 33 Bebbs Oval Sedge, 33 Sweet Flag |
| A5 | 24 Flat Top Aster, 76 Woolly Sedge |
| A6 | 24 Ironweed, 76 Bulrush |
| C1 | 12 Wool Grass, 78 Riddell's Goldenrod |
| B1 | 24 Tussock Sedge, 76 Bottle Brush Sedge |
| B2 | 24 Swamp Milkweed, 76 Common Rush |
| B3 | 24 New England Aster, 76 Fowl Manna Grass |
| B4 | 33 Monkey Plant, 33 Bebbs Oval Sedge, 33 Sweet Flag |

| | |
|---|---|
| B5 | 24 Flat Top Aster, 76 Woolly Sedge |
| B6 | 24 Ironweed, 76 Bulrush |
| C2 | 12 Wool Grass, 78 Riddell's Goldenrod |
| A | Mix |
| B | Mix |

Islands A1-A6 and B1-B6 are 4.64 $m^2$ in area, Islands C1 and C2 are 6.50 $m^2$ in area, and Islands A and B are 13.94 $m^2$ in area. Numbered A and B islands with the same number (A1 and B1, A2 and B2, etc.) were planted with the same plants.

### 2.2 Experiment execution

Every three weeks from June 26, 2017 to August 31, 2017, water samples were taken in the following locations in Vadnais Pond:


*Figure 7. Sampling locations in Vadnais Pond.*

At each site, samples were taken at 0.30 m and 0.60 m, with the exception of the Bridge site, which was too shallow to permit a 0.60 m sample. This sampling process allowed for an estimation of the entire water column, by taking samples approximately one-third and two-thirds down in the water column. Further, drone photos were taken of each FTW from 2 to 3 m in height with a GoPro Karma to estimate plant return.

Every four weeks from June 29, 2017 to September 2, 2017, water samples were taken in the following locations in Fleming Lake:

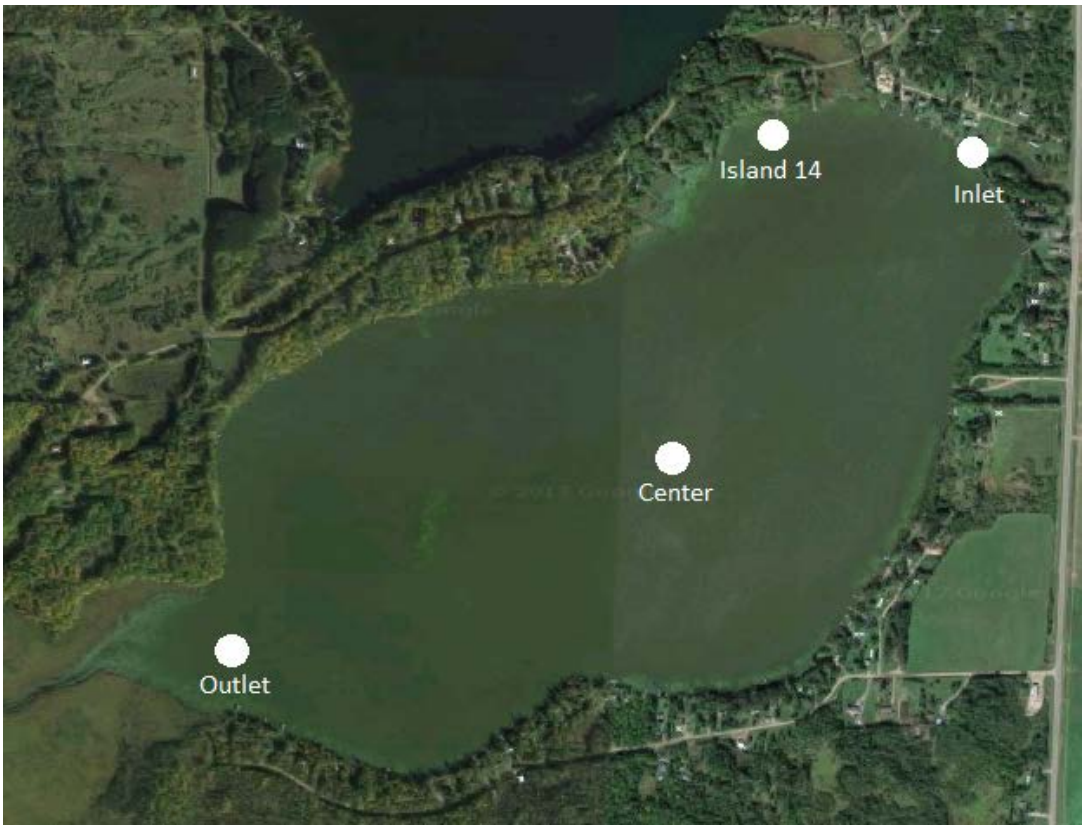



*Figure 8. Sampling locations in Fleming Lake.*

At each site, samples were taken at 0.60 m and 1.20 m, with additional samples taken at 2.40 m and 3.60 m at the Center site, and a sample taken at 2.40 m at the Outlet. Drone photos were taken of each FTW from 2 to 3 m in height with a GoPro Karma to estimate plant return.

### 2.3 Data collection

At each site, a 2-liter Van Dorn sampler was used to collect the water samples. FTW water samples were collected at the edge of the FTW. A small amount of water was released through the sampler's siphon to rinse it, and then the siphon was used to fill a 1 L Nalgene high-density polyethylene (HDPE) bottle. The bottle was then labelled, wrapped in aluminum foil, and placed in a cooler. In addition to the water samples, the

following water quality data was collected using a YSI sonde: pH, temperature, conductivity, and dissolved oxygen. Secchi depth was measured using a Secchi disk.

When sampling was complete, a GoPro Karma drone was used to take overhead photos of each island from an approximate height of 2.1 meters, as well as an overhead photo of the entire set of islands. These photos were taken to assist in determining the health of plants on the islands, as well as the resilience of the fencing to geese and other environmental effects. Islands A1-A6 and B1-B6 with the same number (A1 and B1, A2 and B2, and so on) had identical initial setups.

### 2.4 Data analysis

Chlorophyll-*a* concentration was calculated using the 90% methanol method. 50 mL of each water sample was pipetted into a 50 mL centrifuge tube and centrifuged at 3000g for 15 minutes. The chlorophyll-containing cells were distributed among three 1.5 mL cuvettes. 1 mL of a 90% methanol solution was added to each tube along with 3 glass beads 0.5 cm in diameter. The tubes were then vortexed for 15 minutes at speed 8 before being placed in a refrigerator for 24 hours to allow for the chlorophyll-containing cells to break down.

After 24 hours, the samples were processed on a Hach DR 5000 spectrophotometer at wavelengths of 480, 650, and 665 nm. The results for each sample were then added and analyzed using the following equation to determine the chlorophyll *a* content:

$$[\mathrm{Chl}a] = (16.5 * A_{665}) - (8.3 * A_{650})$$

*Equation 1. Chlorophyll¬-a concentration based on spectrophotometry.*

Phosphorus concentration was estimated two ways using the chlorophyll-*a* concentration. The first estimation used the widely-accepted relationship between chlorophyll-*a* concentration and phosphorus concentration (Dillon & Rigler, 1974):

$$\log[Chla] = 1.449 * \log[\mathrm{P}] - 1.136$$

*Equation 2. Phosphorus concentration estimation based on Dillon & Rigler, 1974.*

The second estimation was performed by creating a relationship between the chlorophyll-*a* measured and total phosphorus measured in 411 lakes with the NCHF ecoregion, then using the chlorophyll-*a* values found in this experiment to estimate total phosphorus concentration (Minnesota Pollution Control Agency, 2017b):

$$[\mathrm{P}] = 0.6426 * [\mathrm{Chl}a]^{0.648}$$

*Equation 3. Phosphorus concentration estimation based on NCHF ecoregion data.*

# 3 Results

## 3.1 Chlorophyll-*a*

Chlorophyll-*a* was highest in Vadnais Pond overall on 07/17/17 (average 0.019 mg/L), although the concentration on 06/26/17 was close to that value (0.016 mg/L). After 07/17/17, there was a drop-off in concentration to 08/31/17 (0.0018 mg/L) and 08/07/17 (0.0011 mg/L). The concentration at the Bridge and Island sampling sites was statistically significantly different on two of three days when a comparison was possible.

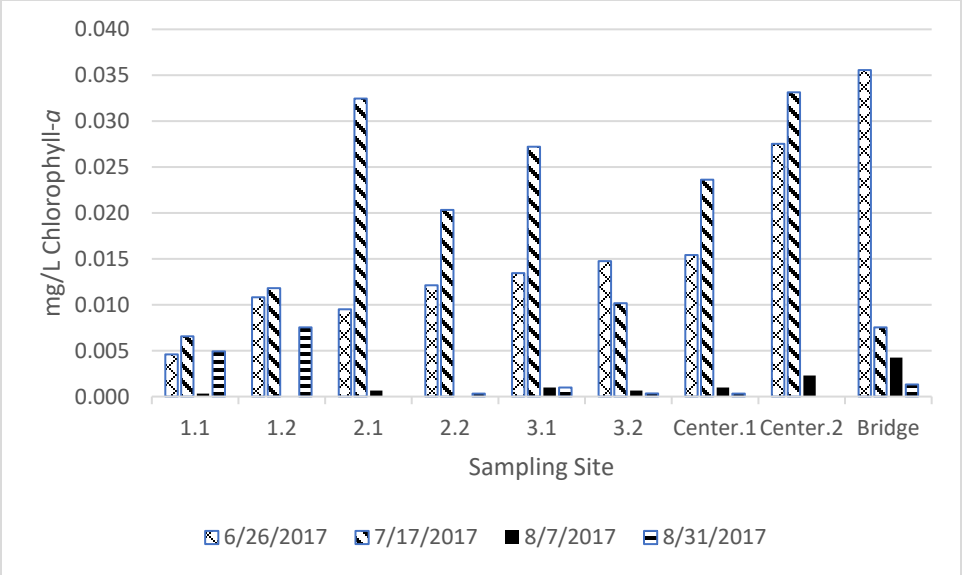



*Figure 9. Chlorophyll-a concentration of experimental sites in Vadnais Pond.*

An ANOVA test was run for each date to compare the Center data to all Island sites to determine the circle of influence of the FTWs. None of the comparisons were statistically significantly similar on any sampling date ($p<0.05$).

An ANOVA test was run for each date to compare the Bridge data to all other sites. On 06/26/17, the difference between the Bridge and Island 1, 2, and 3 chlorophyll-*a* concentration was statistically significantly different ($p<0.05$) but the difference between the Bridge and Center chlorophyll-*a* concentration was not statistically significantly different. On 07/17/17, only the difference between the Bridge and Island 2 chlorophyll-*a* concentration was statistically significantly different ($p<0.05$). On 08/07/17, difference between the Bridge and Island 1, 2, and 3 chlorophyll-*a* concentration was statistically significantly different ($p<0.05$) but the difference between the Bridge and Center chlorophyll-*a* concentration was not statistically significantly different. On 08/31/17, the

Bridge chlorophyll-*a* concentration was below detection, so it was not possible to run an ANOVA test.

In Fleming Lake, chlorophyll-*a* was highest overall on 06/29/17 (average 0.018 mg/L). The concentration was much lower on 07/27/17 (0.0013 mg/L) and was below detection on 09/02/17.

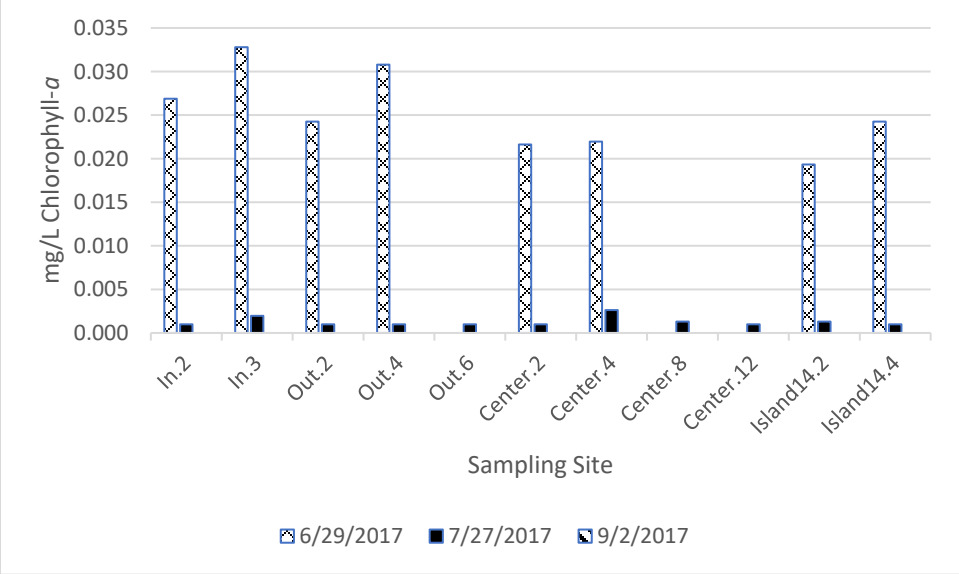



*Figure 10. Chlorophyll-a content of experimental sites in Fleming Lake.*

Samples were not taken on 06/29/2017 in the Out.6, Center.8, or Center.12 locations. An ANOVA test was run for each date to compare the Island 14 data to all other sites. None of the chlorophyll-*a* concentration values were statistically significantly different for any of the days.

### 3.2 Phosphorus concentration

Assuming a quantitative relationship between chlorophyll-*a* concentration and phosphorus concentration as described by Dillon and Rigler, the chlorophyll-*a*

concentrations measured here were used to calculate the approximate phosphorus concentration of each sampling site (Dillon & Rigler, 1974).

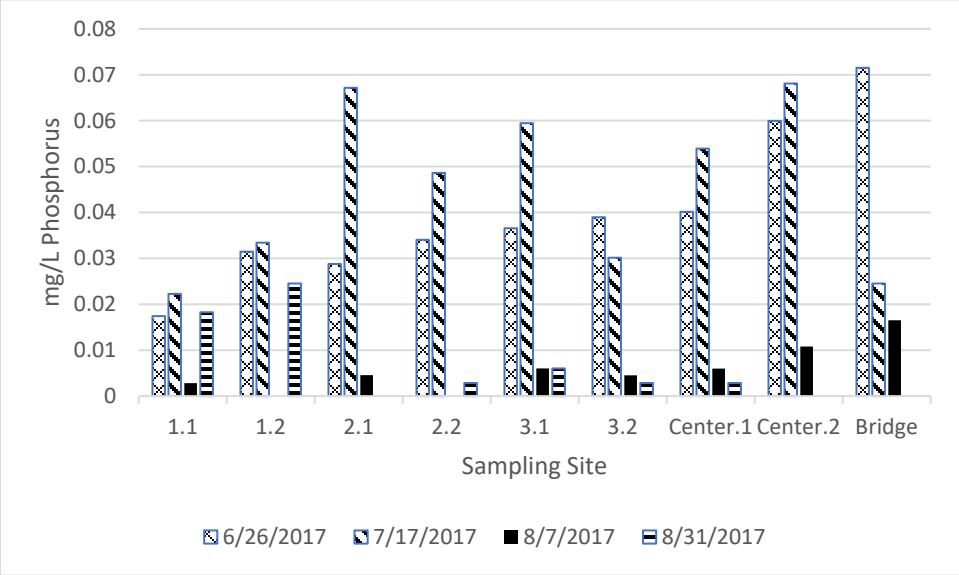
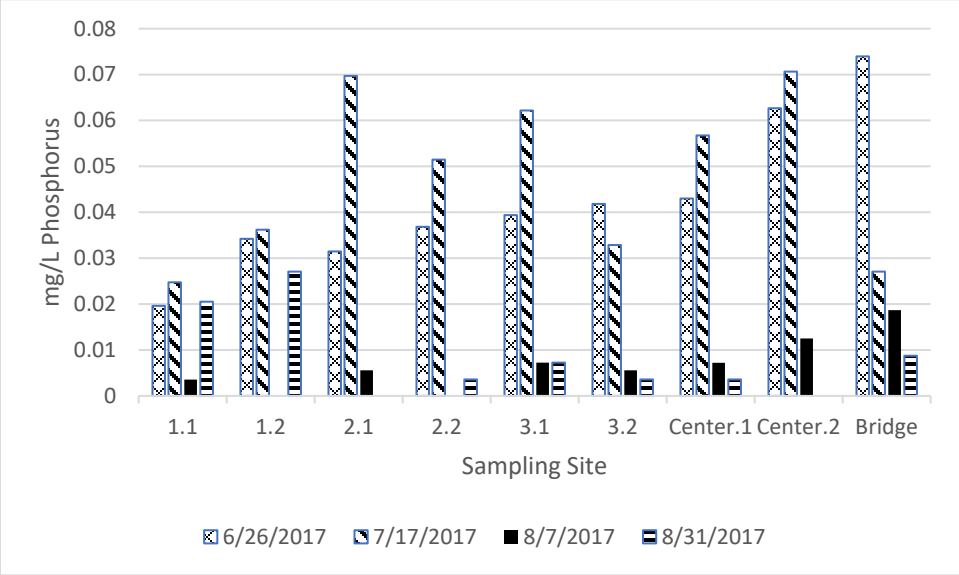



*Figure 11. Vadnais Pond estimated phosphorus concentration and standard deviation based on Dillon & Rigler, 1974.*

A second estimation of phosphorus concentration was performed using the 2017 summary of total phosphorus and chlorophyll-*a* for the North Central Hardwood Forest (NCHF) ecoregion.

*Table 3. Vadnais Pond estimated phosphorus concentration and standard deviation based on data from the NCHF in 2017.*




An ANOVA test was run for each date to compare the Bridge data to all other sites. None of the estimated phosphorus concentration values for either method were statistically significantly different for any of the days. A second ANOVA was run to compare the two methods of estimating phosphorus concentration. The values were not statistically significantly different.

*Table 4. Fleming Lake estimated phosphorus concentration and standard deviation based on Dillon & Rigler, 1974.*

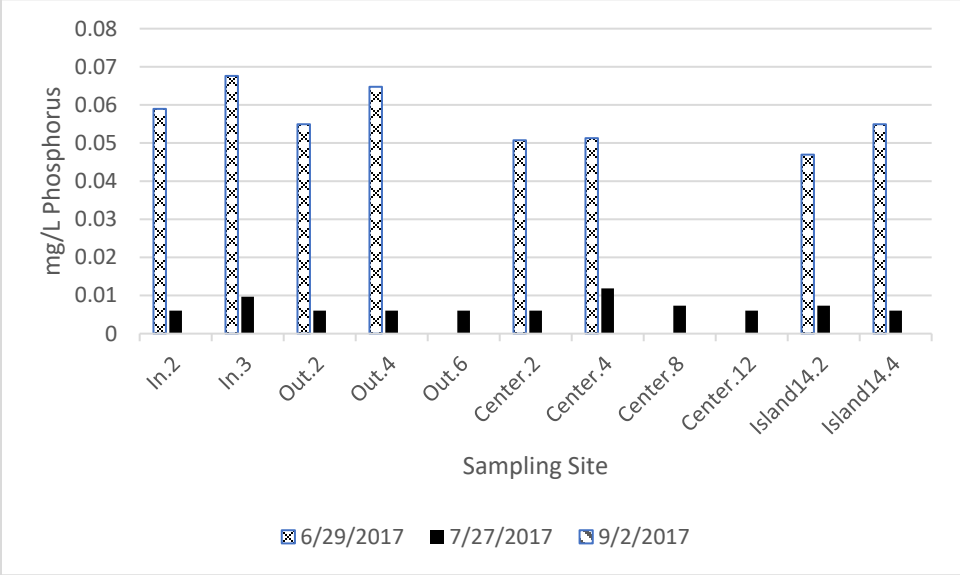
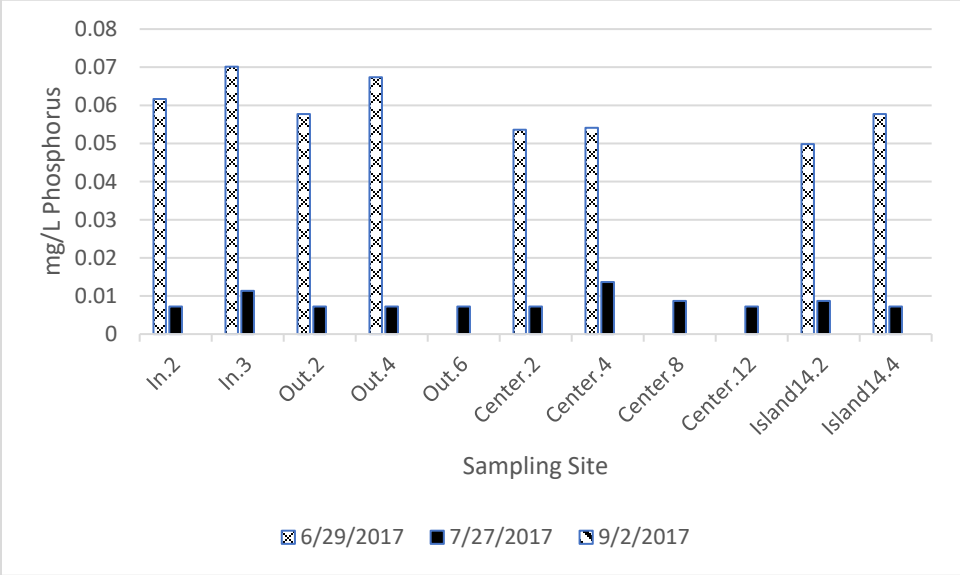



*Table 5. Fleming Lake estimated phosphorus concentration and standard deviation based on data from the NCHF in 2017.*




An ANOVA test was run for each date to compare the Island 14 data to all other sites. None of the estimated phosphorus concentration values for either method were

statistically significantly different for any of the days. A second ANOVA was run to compare the two methods of estimating phosphorus concentration. The values were not statistically significantly different.

### 3.3 Secchi depth

In Vadnais Pond, Secchi depth followed trends expected from the chlorophyll-*a* data.

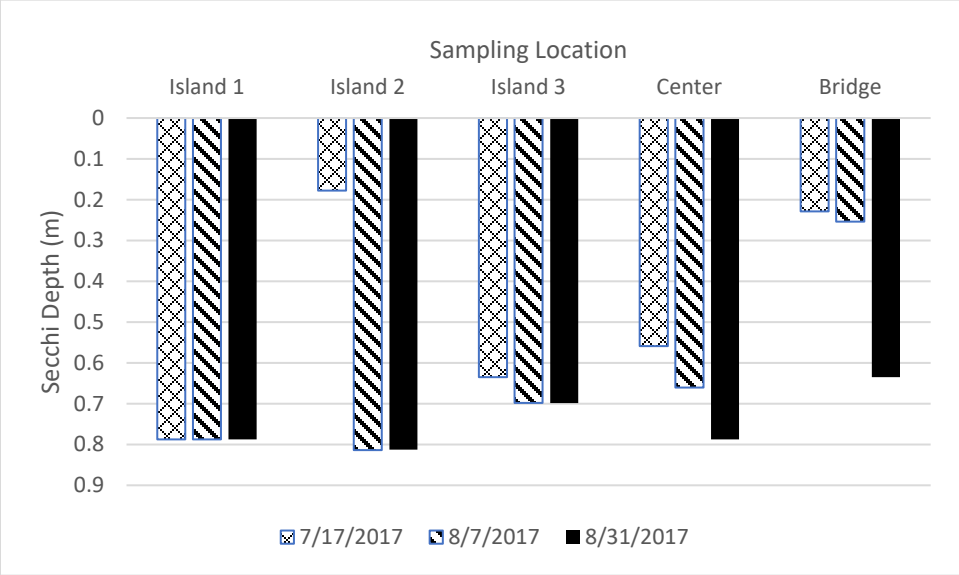



*Figure 12. Secchi depth measured at each sampling site in Vadnais Pond.*

Secchi depth was not measured on 06/26/17.

*Table 6. Analysis of co-variance for Secchi depth measured at each site in Vadnais Pond.*

| | *Island 1* | *Island 2* | *Island 3* | *Center* | *Bridge* |
|---|---|---|---|---|---|
| Island 1 | 1.67E-08 | | | | |
| Island 2 | -1.9E-05 | 0.089672 | | | |
| Island 3 | -2E-06 | 0.008928 | 0.000889 | | |
| Center | -1.1E-05 | 0.023285 | 0.002331 | 0.008746 | |
| Bridge | -2.4E-05 | 0.030413 | 0.003067 | 0.015986 | 0.034552 |

In Fleming Lake, Secchi depth did not follow expected patterns when compared with chlorophyll-*a* concentration, but followed the expected multi-year variation in the MPCA report.

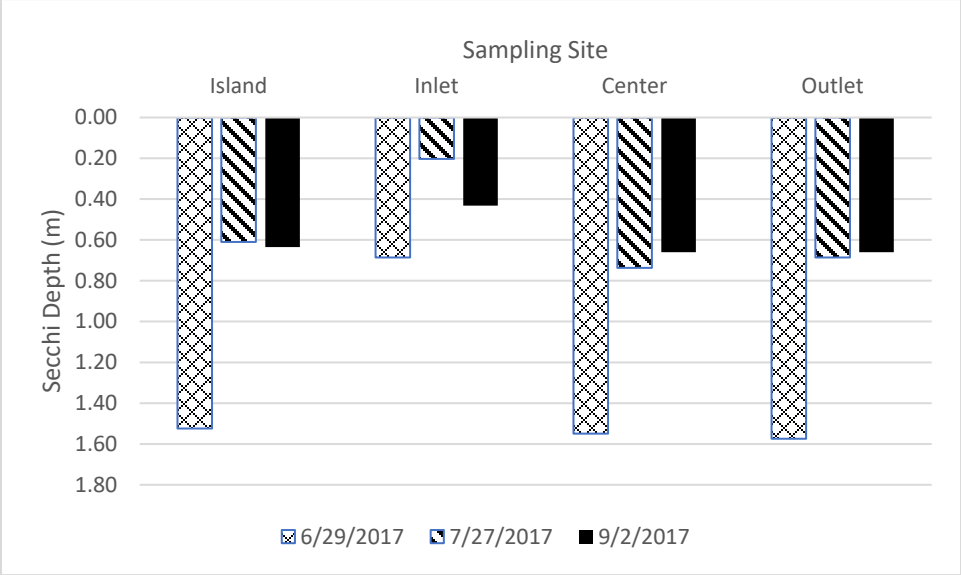



*Figure 13. Secchi depth measured at each sampling site in Fleming Lake.*

*Table 7. Analysis of co-variance for Secchi depth measured at each site in Fleming Lake.*

| | *Island* | *Inlet* | *Center* | *Outlet* |
|---|---|---|---|---|
| Island | 0.180788 | | | |
| Inlet | 0.074767 | 0.038853 | | |
| Center | 0.170179 | 0.066738 | 0.161863 | |
| Outlet | 0.180573 | 0.072831 | 0.170824 | 0.180788 |

### 3.4 Physiochemical properties

In Vadnais pond, measurements for Islands 1, 2, and 3 and Center were compared to the Bridge data. The results were similar to those of the chlorophyll-*a* data, in which there was a statistically significant difference between the Bridge and Island sites for most parameters on three of the four dates.

In addition, the measurements for Islands 1, 2, and 3 were compared to the Center data. Within the physiochemical properties at Vadnais Pond, there is no standard deviation for the Bridge site because it was not deep enough for more than one measurement.

*Table 8. Vadnais Pond physiochemical properties.*

| Physiochemical Property | Island 1 | Island 2 | Island 3 | Center | Bridge |
|---|---|---|---|---|---|
| **6/26/2017** | | | | | |
| Temperature (°C) | 17.21 ± 0.2051 | 17.38 ± 0.5374 | 18.19 ± 0.2262 | 17.77 ± 0.0990 | 15.35 ± 0.00 |
| Conductivity (mS/cm) | 0.384 ± .0035 | .394 ± 0.0071 | 0.377 ± 0.00 | 0.383 ± 0.00 | 0.367 ± 0.00 |
| pH | 8.37 ± 0.0071 | 8.22 ± 0.2899 | 8.44 ± 0.0141 | 8.49 ± 0.0354 | 8.00 ± 0.00 |
| Dissolved Oxygen (‰) | 145.70 ± 21.92 | 133.75 ± 22.27 | 118.85 ± 6.58 | 135.95 ± 0.78 | 8.20 ± 0.00 |
| **7/17/2017** | | | | | |
| Temperature (°C) | 22.27 ± 0.3394 | 22.49 ± 1.3435 | 23.12 ± 0.2051 | 23.01 ± 0.1980 | 21.68 ± 0.00 |
| Conductivity (mS/cm) | 0.450 ± 0.0120 | 0.436 ± 0.0099 | 0.436 ± 0.0057 | 0.437 ± 0.0042 | 0.419 ± 0.00 |
| pH | 7.69 ± 0.2121 | 8.31 ± 0.2616 | 7.77 ± 0.2546 | 7.94 ± 0.1202 | 7.93 ± 0.00 |
| Dissolved Oxygen (‰) | 91.15 ± 28.92 | 137.85 ± 48.15 | 67.60 ± 9.33 | 86.95 ± 14.35 | 13.3 ± 0.00 |
| **8/7/2017** | | | | | |
| Temperature (°C) | 18.70 ± 0.0071 | 18.94 ± 0.2051 | 18.53 ± 0.0071 | 18.75 ± 0.0778 | 17.17 ± 0.00 |
| Conductivity (mS/cm) | 0.50 ± 0.0028 | 0.50 ± 0.0054 | 0.46 ± 0.0003 | 0.47 ± 0.0001 | 0.34 ± 0.00 |
| pH | 7.79 ± 0.2121 | 7.60 ± 0.0212 | 7.62 ± 0.0071 | 7.63 ± 0.0141 | 7.89 ± 0.00 |
| Dissolved Oxygen (‰) | 76.20 ± 2.26 | 86.30 ± 4.67 | 59.50 ± 2.55 | 79.75 ± 0.35 | 18.10 ± 0.00 |
| **8/31/2017** | | | | | |
| Temperature (°C) | 18.20 ± 0.0424 | 18.19 ± 0.0283 | 17.90 ± 0.0141 | 18.23 ± 0.0354 | 17.6 ± 0.00 |
| Conductivity (mS/cm) | 0.387 ± 0.0007 | 0.391 ± 0.0092 | 0.364 ± 0.0007 | 0.371 ± 0.0014 | 0.242 ± 0.00 |
| pH | 7.95 ± 0.1838 | 7.57 ± 0.1202 | 7.49 ± 0.0283 | 7.51 ± 0.0283 | 7.54 ± 0.00 |
| Dissolved Oxygen (‰) | 101.45 ± 0.07 | 94.75 ± 6.58 | 89.45 ± 3.46 | 99.4 ± 4.24 | 22.6 ± 0.00 |

On 06/26/2017, all parameters were statistically significantly different between the Bridge and all other sites ($p<0.05$) except for the pH between Island 2 and Bridge. There was almost no statistically significant difference between the Island and Center data, with the only exception being the pH between the Center and Island 1 sites ($p<0.05$). Dissolved oxygen was the most variable, and conductivity the least.

On 07/17/2017, there was little significant difference between the physiochemical properties measured at the Bridge and the other sampling sites. There was no significant difference between the Island and Center data for any parameter. Conductivity varied the

least, and dissolved oxygen the most. There was a significant difference between the temperature measured at Island 3 and the Bridge, the conductivity between the Center and the Bridge; and the dissolved oxygen between Island 3 and the Bridge and the Center and the Bridge ($p<0.05$ for said comparisons).

On 08/07/2017, all parameters were significantly different between the Bridge and all other sites ($p<0.05$) except for the pH between Island 2 and Bridge. There was a significant difference between the Center and all Island data for conductivity, and for the dissolved oxygen data for Island 3 ($p<0.05$). Dissolved oxygen was the most variable, and temperature the least.

On 08/31/2017, all parameters were significantly different between the Bridge and all other sites ($p<0.05$) except for the pH for all sites. There was a significant difference between the Center and Island 3 data for temperature and for the conductivity data for Islands 1 and 3 ($p<0.05$). Dissolved oxygen was the most variable, and temperature the least.

For Fleming Lake, Island 14 (the representative location for all FTWs within the lake) was compared to all other locations within the lake with one-way ANOVA tests. There was overall little statistically significant difference between Island 14 and the other sites for any parameter measured.

*Table 9. Fleming Lake physiochemical properties.*

| Physiochemical Property | Island 14 | Inlet | Center | Outlet |
|---|---|---|---|---|
| **6/29/2017** | | | | |
| Temperature (°C) | 19.61 ± 0.1556 | 15.90 ± 0.1414 | 19.66 ± 0.0212 | 19.75 ± 0.1626 |
| Conductivity (mS/cm) | 0.107 ± 0.0007 | 0.112 ± 0.0035 | 0.106 ± 0.00 | 0.107 ± 0.0007 |
| pH | 7.31 ± 0.1273 | 6.92 ± 0.1414 | 7.49 ± 0.0071 | 7.28 ± 0.1980 |
| Dissolved Oxygen (‰) | 61.95 ± 1.06 | 3.80 ± 1.70 | 64.30 ± 0.14 | 69.25 ± 0.07 |
| **7/27/2017** | | | | |
| Temperature (°C) | 24.03 ± 0.1556 | 20.76 ± 0.7000 | 24.85 ± 0.8132 | 25.81 ± 1.0960 |
| Conductivity (mS/cm) | 0.130 ± 0.0007 | 0.188 ± 0.0127 | 0.130 ± 0.0007 | 0.131 ± 0.0007 |
| pH | 8.97 ± 0.0919 | 7.14 ± 0.3677 | 9.11 ± 0.424 | 9.25 ± 0.0566 |
| Dissolved Oxygen (‰) | 127.25 ± 13.08 | 3.20 ± 0.57 | 139.30 ± 12.73 | 141.00 ± 3.39 |
| **9/2/2017** | | | | |
| Temperature (°C) | 24.03 ± 0.1556 | 20.76 ± 0.7000 | 24.85 ± 0.8132 | 25.81 ± 1.0960 |
| Conductivity (mS/cm) | 0.130 ± 0.0007 | 0.188 ± 0.0127 | 0.130 ± 0.0007 | 0.131 ± 0.0007 |
| pH | 8.97 ± 0.0919 | 7.14 ± 0.3677 | 9.11 ± 0.424 | 9.25 ± 0.0566 |
| Dissolved Oxygen (‰) | 127.25 ± 13.08 | 3.20 ± 0.57 | 139.30 ± 12.73 | 141.00 ± 3.39 |

On 06/29/2017, there was little statistically significant difference between the physiochemical properties measured at Island 14 and the other sampling sites. Temperature varied the least, and pH the most. There was a significant difference between the temperature measured at Island 14 and the Inlet, as well as the dissolved oxygen between Island 14 and the Inlet and Island 14 and the Outlet ($p<0.05$).

On 07/27/2017, there was a statistically significant difference only between the Island 14 and Inlet sites for all parameters measured ($p<0.05$ for said measurements). Dissolved oxygen varied the most overall, and pH the least.

On 09/02/2017, there was little statistically significant difference between the physiochemical properties measured at Island 14 and the other sampling sites. Conductivity varied the most overall, and temperature the least. The difference was statistically significant between the temperature measured at Island 14 and the Inlet and

Island 14 and the Center, between the pH measured at Island 14 and the Center and Island 14 and the Outlet; and between the dissolved oxygen measured at Island 14 and the Inlet ($p<0.05$ for said measurements).

### 3.5 Plants and fencing

The images of each island can be found in the Appendix.

The results of the plant return study, as performed using the drone photos for Vadnais Pond on 06/23/17 and 08/07/17, are summarized as follows:

*Table 10. Plant return on FTWs in Vadnais Pond.*

| Island ID | Plant | Number Return, 06/23/17 | Percent Return, 06/23/17 | Number Return, 08/07/17 | Percent Return, 08/07/17 |
|---|---|---|---|---|---|
| 1 | Wool grass | 6 | 25.00% | 6 | 25.00% |
| 1 | Riddell's goldenrod | 54 | 100.00% | 54 | 100.00% |
| 2 | Ironweed | 11 | 45.83% | 16 | 66.67% |
| 2 | Bulrush | 12 | 22.22% | 15 | 27.78% |
| 3 | Swamp milkweed | 24 | 100.00% | 24 | 100.00% |
| 3 | Common rush | 51 | 94.44% | 51 | 94.44% |

The results of the plant return study, as performed using the drone photos for Fleming Lake on 06/29/17, are summarized as follows:

*Table 11. Plant return on FTWs A1, A2, A3, A4, A5, A6, B1, B2, B3, B4, B5, and B6 in Fleming Lake.*

| Island Number | Plant | Number Return, A | Percent Return, A | Number Return, B | Percent Return, B | Average Percent Return |
|---|---|---|---|---|---|---|
| 1 | Bottlebrush sedge | 49 | 64.47% | 33 | 43.42% | 53.95% |
| 1 | Tussock sedge | 20 | 83.33% | 22 | 91.67% | 87.50% |
| 2 | Common rush | 45 | 59.21% | 48 | 63.16% | 61.18% |
| 2 | Swamp milkweed | 15 | 62.50% | 15 | 62.50% | 62.50% |
| 3 | Fowl manna grass | 72 | 94.74% | 73 | 96.05% | 95.39% |
| 3 | New England aster | 6 | 25.00% | 8 | 33.33% | 29.17% |
| 4 | Sweet flag | 28 | 84.85% | 9 | 27.27% | 56.06% |
| 4 | Monkey plant | 27 | 81.82% | 33 | 100.00% | 90.91% |
| 4 | Bebb's oval sedge | 0 | 0.00% | 1 | 3.03% | 1.52% |
| 5 | Woolly sedge | 72 | 94.74% | 68 | 89.47% | 92.11% |
| 5 | Flat top aster | 1 | 4.17% | 4 | 16.67% | 10.42% |
| 6 | Ironweed | 1 | 4.17% | 1 | 4.17% | 4.17% |
| 6 | Bulrush | 60 | 78.95% | 66 | 86.84% | 82.89% |

*Table 12. Plant return on FTWs C1 and C2 in Fleming Lake.*

| Plant | Number Return, C1 | Percent Return, C1 | Number Return, C2 | Percent Return, C2 | Average Percent Return |
|---|---|---|---|---|---|
| Riddell's goldenrod | 12 | 15.38% | 18 | 23.08% | 19.23% |
| Wool grass | 12 | 100.00% | 12 | 100.00% | 100.00% |

*Table 13. Plant return on FTWs A and B in Fleming Lake.*

| Island | Number Return | Percent Return |
|---|---|---|
| A | 187 | 66.79% |
| B | 172 | 61.43% |

The string along the border of Island A1 was knocked down, as was one post. There was some goose fecal matter. Island B1, however, suffered no damage due to geese. Island A2 had two posts knocked over, and the side of the island without the tall common rush had some goose fecal matter. The border string was very low and in places was at the bottom of the posts. One post had also been knocked over on Island B2, although it appears as

though the common rush was the disruptor rather than geese, as there was not any goose fecal matter or feathers. Island A3 had three posts knocked down, along with most of the string, both the border string and string across the island. There were some goose fecal matter and feathers. In contrast, Island B3 was in fine condition, with no posts down or any evidence of geese. Two posts were knocked over on Island A4, and there was a large amount of goose fecal matter. The border string was mostly at the bottom of the posts. There were three posts knocked down on Island B4 and there was some goose fecal matter. Islands A5 and B5 suffered no damage from geese. Island A6 had one post knocked down, and there was a small amount of goose fecal matter. The border string was very low. Island B6 had three posts down and both the border string and the string across the island were down completely. There was some goose fecal matter.

Island C1 suffered no damage from geese, while Island C2 had two posts knocked down and a small amount of goose fecal matter.

Islands A and B suffered almost no damage to their fencing, with the exception being one corner of Island B, which is still standing although slightly dented inwards. They also had no goose fecal matter.

## 4 Discussion

This study found that the influence of FTWs in Fleming Lake on chlorophyll-*a* concentration is minimal, while there is some effect in Vadnais Pond. In Fleming Lake, there was little to no measured statistically significant difference between the FTW sampling site and the other sampling sites in the physiochemical properties and chlorophyll-*a* concentration. In Vadnais Pond, three of the four days had a statistically

significant difference between the FTW sampling sites and the control site with regards to both physiochemical properties and chlorophyll-*a* concentration. The plant return of specific plants varied greatly between the two bodies of water, suggesting that their biogeochemical characteristics played a large role in plant growth.

### 4.1 Chlorophyll-*a*

In Vadnais Pond, the statistically significant differences between the Island 1, 2, and 3 sites, with regards to both chlorophyll-*a* and the physiochemical characteristics, indicates that the FTWs have an effect on these parameters in the water beside and below them. However, due to the constraints of this experiment, it is difficult to determine exactly how far that influence extends. Since there was no statistically significant similarity between the chlorophyll-*a* concentration of the Island and Center sites, it is unlikely that the FTWs' influence reaches the Center site, about 11 m from the FTWs. Thus, it is unlikely that the FTWs' circle of influence is greater than 10 m in radius, which gives a maximum estimate of 314.16 $m^2$ of pond surface area influenced per FTW, which in turn would be likely to overlap with the circle of the other FTWs. The area of overlap could also change from day to day, as the FTWs have some slack in their mooring lines that allows them to drift slightly in the water. If the circles do not overlap, the FTWs in Vadnais Pond could influence a maximum area of about 942.48 $m^2$ of the pond's surface area, or about 38.74% of the pond's total surface area. Considering that each FTW has a surface area of 4.64 $m^2$, this indicates that each square meter of FTW could potentially have an impact on about 67.71 $m^2$ of pond surface. However, it is important to reiterate that this is an estimation based on the maximum possible effectiveness of the FTWs. It is also possible that the FTWs' circle of influence is no greater than 1 m in radius, which

would only affect 3.14 $m^2$ of pond surface area per FTW, which is less than the surface area of each FTW. From this data, the circle of influence cannot be accurately determined.

It is further difficult to determine if the FTWs affect chlorophyll-*a* concentration within Vadnais Pond. The results show that two days had lower chlorophyll-*a* concentration at the Bridge site than the Island and Center sites, but these days do not follow a pattern such as the FTWs being more effective at higher chlorophyll-*a* concentrations. The four sampling dates all showed a different pattern concerning chlorophyll-*a* concentration and the rank of the concentration at the Bridge site: on 06/26/17 the Bridge concentration was highest and the average concentration for the entire pond was high, on 07/17/17 the Bridge concentration was lowest and the average concentration for the entire pond was high, on 08/07/17 the Bridge concentration was highest and the average concentration for the entire pond was low, and on 08/31/17 the Bridge concentration was lowest and the average concentration for the entire pond was low. This variation makes it difficult to determine at what chlorophyll-*a* concentration the FTWs are most effective.

In Fleming Lake, the chlorophyll-*a* concentration was not statistically significantly different between the Island 14 site and any other site on any day. This indicates that the chlorophyll-*a* concentration within Fleming Lake is consistent throughout, and the FTWs do not significantly affect the concentration. The average chlorophyll-*a* concentration, excluding 09/02/17 since the value was below detection throughout, was 0.00982 mg/L, or 9.82 µg/L. This was quite low compared to the average value from the MPCA report, which had a two-summer average of 45 µg/L. However, the MPCA used the 2-meter integrated sampling method, which is likely to account for the difference in chlorophyll-*a*

concentration. A study comparing the 2-meter integrated sampling method to the method used in this study, in addition to two other methods, showed that the 2-meter integrated sampling method could find a chlorophyll-*a* concentration nearly twice that of methods that included water from deeper in the water column that contained lower concentrations of algae (Golnick, Chaffin, Bridgeman, Zellner, & Simons, 2016). Thus, since the MPCA sampling included water exactly at the surface of the lake and the sampling method here did not, the MPCA chlorophyll-*a* results would show a much higher concentration of chlorophyll-*a*. Adjusting for only the top 2 meters of water sampled in this study gives an average concentration of 13.30 µg/L, which is still comparatively low, but is likely because surface water was not collected in this study. The lower concentration may be further explained by the fact that the MPCA data was only collected in one location within Fleming Lake, whereas this study collected samples in four locations in the lake, and none of those locations was the same as where the MPCA samples were taken. Further, 2017 (42.06 cm of rain) was also a drier summer than either 2015 (45.62 cm of rain) and 2016 (61.34 cm of rain), which may also have contributed to the lower chlorophyll-*a* concentration in the lake, as there would be less runoff inputs from the agricultural areas in the watershed as well as less overland flow from Wilkins Lake (U.S. Climate Data, 2018). This study also only collected water samples on three days throughout the summer, as opposed to the six sampling dates in 2015 and five in 2016 during the MPCA study. This means that it was possible that this study did not sample during the peak chlorophyll-*a* concentration time frame. It is interesting to note, however, that the highest concentrations of chlorophyll-*a* in the MPCA study were on 08/11/15 and 08/29/16, which are fairly close to the final sampling date of this study, which was

09/02/17 (Martin, 2017). Thus, it is most likely that there was a very mild algae bloom in summer 2017, which is reflected in the chlorophyll-*a* results found in this study.

### 4.2 Phosphorus concentration

For both Vadnais Pond and Fleming Lake, the two methods of estimating phosphorus concentration differed by less than 10% for all measurements except Vadnais Pond's Island 1 on 08/07/17 (NCHF estimation was 40.31% higher), Island 2 on 08/07/17 (NCHF estimation was 35.99% higher), and Center on 08/31/17 (NCHF estimation was 10.58% higher). This indicates that the two estimation methods were fairly accurate compared with one another. However, there was no statistically significant difference between the experimental sites for any of the dates for either Vadnais Pond or Fleming Lake. It is thus difficult to determine whether the FTWs have an effect on phosphorus concentration, especially since these values are estimates and not true measured values. The values estimated for Vadnais Pond are lower than those found in nineteen bodies of water throughout the Twin Cities metropolitan area of Minneapolis-Saint Paul; the average TP concentration for Vadnais Pond for the summer is in the range 0.024-0.026 mg/L, but the nineteen sites in Minneapolis-Saint Paul had a range of 0.15-0.49 mg/L. This suggests that the estimations may be very low, or that Vadnais Pond has a very low TP concentration relative to other bodies of water in the Minneapolis-Saint Paul area (Janke, Finlay, & Hobbie, 2017).

Examining only the Fleming Lake estimates gives an approximation of the TP concentration throughout the summer. The data collected here provides an estimate of 24.02 µg/L, which is lower than either 2015 (40 µg/L) and 2016 (90 µg/L) as measured in the MPCA study. Again, it is difficult to make determinations based on this data as it is

only an estimation, but the lower value is likely due to the same variation in chlorophyll-*a* concentration: inclusion or exclusion of surface water, difference in sampling location, more sampling dates in the MPCA study, difference in the amount of precipitation throughout the summer, and timing of the presence of an algal bloom, if one was present.

### 4.3 Secchi depth

The analysis of co-variance of Secchi depth did not provide a useful metric for determining the effectiveness of the FTWs in either Vadnais Pond or Fleming Lake. The Secchi depth data did not follow trends expected when compared with the NCHF Secchi depth data. As such, it is likely that Secchi depth, even when paired with chlorophyll-*a* measurements, is not a useful method for estimating the effect of FTWs on the bodies of water studied here.

Comparing the Secchi depth data gathered here with the values found in the MPCA report shows little variation. The average Secchi depth in 2015 and 2016 was about 0.9 m, and the average found here for 2017 was about 0.83 m. This is somewhat unusual compared with the chlorophyll-*a* data, as it indicates a higher concentration of suspended material that would reduce visibility. There may have been additional suspended sediments during summer 2017 that would cause shallower Secchi depth readings. Sediments may also have been stirred up by increased boat use or the disturbance caused by the sampling boat itself. However, this value still falls within the normal variation of the Secchi depth trends in Fleming Lake (0.8 to 1.5 m), and is unlikely to be an anomaly (Martin, 2017).

### 4.4 Physiochemical properties

The physiochemical properties had some similar results to those of previous studies of FTWs. Both Winston et. al (2013) and Lynch et. al (2015) found that the water temperature near the FTWs was higher than in the control, likely due to the dark color of the FTWs absorbing warmth from solar radiation and transferring the heat to the water; higher temperatures near the FTWs were also found in Vadnais Pond. However, in contrast to the results from Lynch et. al (2015), the water near the FTWs in Vadnais Pond had higher average DO and pH readings than the control. These results further emphasize the likelihood that the effect of the FTWs depends highly on the biogeochemical characteristics of the body of water they are in.

The fact that most of the properties measured on 07/17/17 were not statistically significantly different between the sites, coupled with the fact that chlorophyll-*a* concentration was also not statistically significantly different, indicates that Vadnais Pond was particularly well-mixed on that date. This may have been due to weather within the preceding days, such as strong winds or rain, or other environmental effects.

The physiochemical properties on 08/31/17 followed the same trend as the other dates, with the numbers collected at the Bridge site being lower than those collected at the other sites, the exception being the pH; however, the pH measurements were not statistically significantly different between the Bridge and all other sites. Similar to the 06/26/17 and 08/07/17 sampling dates, there was little statistically significant difference between the Center and Island sites. Since the chlorophyll-*a* concentration at the Bridge site on this date was below detection, it is not possible to draw comparisons between chlorophyll-*a* concentration and the physiochemical properties on this date. The data collected was

similar to that of 08/07/17, so it is likely that if the chlorophyll-*a* content was measurable, it would have been comparable to what was found on that date.

In Fleming Lake, most of the statistically significant difference concerning the physiochemical properties measured (eight out of twelve statistically significant comparisons) were between the Island 14 and Inlet site. The Inlet site was likely different from the Island 14 site because it was much shallower than the rest of the sites (approximately 1.1 meters deep), had many aquatic macrophytes growing in it, and was much more frequently disturbed by boats and inflow. The results of the data analysis for this study show that it is not a good site for comparison with the Island 14 site, as its physiochemical parameters are too different. This is particularly evident on 07/27/17, when all parameters measured at the Inlet were statistically significantly different from those measured at Island 14, but there was no statistically significant difference between Island 14 and the other two sites. The remainder of the statistically significant differences between Island 14 and the other sites are difficult to attribute to the FTWs, as the differences are not consistent between the three sampling dates. These results indicate that the effect of the FTWs is not significant enough to provide much service to Fleming Lake beyond the area they occupy.

The physiochemical data collected in Fleming Lake further reinforces the conclusions drawn in the sections above. The average DO value for summer 2017 (8.55 mg/L) was higher than those from both 2015 (7.50 mg/L) and 2016 (7.02 mg/L), which would be expected with a lower chlorophyll-*a* concentration; less algae would be consuming oxygen in the water, so there would be a higher concentration remaining. The average temperature recorded in 2017 (21.4 °C) was similar to that of 2015 (20.3 °C), and lower

than that of 2016 (23.0 °C). Warmer temperatures usually indicate higher concentrations of chlorophyll-*a*, as they provide better growing conditions for algae, whereas cooler waters slow algal growth. These results are expected based on the chlorophyll-*a* and Secchi depth data.

### 4.5 Plants and fencing

In Vadnais Pond, two of the three islands showed no change in the number of each plant that was growing on the islands between 06/23/17 and 08/07/17. These two islands, Island 1 and Island 3, were the healthiest of the islands, so it is likely reasonable to assume that the number of individuals of a particular plant that grow at the beginning of the summer is going to be approximately the same as the final number. Even considering Island 2, which had very low growth rates, there was not a difference of more than five plants among its two plant species. Overall, Island 3 had the highest percentage of its plants grow. Island 3 was shaded by the overhanging trees growing along the southeastern edge of Vadnais Pond, so it is possible that these plants flourished due to preferring partial shade, or due to the particular physical and chemical characteristics of Vadnais Pond being particularly hospitable to these plant varieties (Kirk & Belt, 2011; USDA NRCS Plant Materials Program, 2008). Island 1 had widely varying return percentages of its two plants, ranging from 100.00% to 25.00%. Riddell's goldenrod prefers full sun, which may contribute to its high success rate (Landis, Fiedler, & Isaacs, 2013), although wool grass also prefers full sun and partial shade so it is possible that the characteristics of Vadnais Pond in particular were not hospitable to this variety of plant (Favorite, 2010). Island 1 was also the only FTW in Vadnais Pond to not have a full fence; rather, it simply had twelve posts around its perimeter. Lack of fencing does not

appear to have had any detrimental effects on plant growth, or any negative effects from geese, so it seems that these posts acted as a functional fence. Island 2 had obvious low growth rates from the beginning of the experiment. It was covered by a coconut fiber mat to test the usefulness of such a material, but it may have hindered the plants' growth instead. Vadnais Pond is not large enough, nor the FTWs far enough apart, to explain major differences in plant growth based on lake biogeochemistry alone, so it is most likely that the one thing that majorly differentiated Island 2 from the others is to blame for the low return rates of its plants.

Comparing the return percentages of the plants on islands in Vadnais Pond and Fleming Lake that had the same plant species, there is very little similarity to be found; in fact, the percentages seem to be nearly opposite. For Riddell's goldenrod, for example, there was 100.00% growth in Vadnais Pond, but the maximum growth in Fleming Lake did not reach more than 23.08%. Conversely, growth of wool grass in Fleming Lake was 100.00%, but in Vadnais Pond it did not exceed 25.00%. This indicates that there are very different physiochemical characteristics between the two bodies of water, which is not unexpected due to the vast difference in their size, depth, and surrounding land use. Thus, using Vadnais Pond as a proxy for Fleming Lake is not reasonable.

In both Vadnais Pond and Fleming Lake, the return of the plants in their various percentages may be due to damage suffered the previous year, inability to hold up to the winter, or differences in when the plants begin to grow during the year. Damage the previous year is difficult to ascertain, as are the particular effects of winter on any one plant, but it is likely that the peak growth time is the major contributing factor to return of the plants. For example, common rush peaks in July, which would explain why it was so

much taller and healthier than the other plants even though it only returned at an average of 61.18% (USDA NRCS Plant Materials Program, 2008). Ironweed, on the other hand, is typically a late-summer plant, peaking in August, so it is possible that there was only one of this plant on both Island A6 and Island B6 simply because it had not yet reached its time to grow (Minnesota Wildflower Field Guide, 2018). Many of the plants that had begun to grow on the islands in Fleming Lake were still young and quite short, so they likely have later growing and peak seasons than common rush.

There are some possible patterns among the islands the geese attacked. Islands A4 and B4 were both attacked by geese, with at least two posts knocked over on each. This indicates that the geese may prefer to consume one or more of the plants on these islands (sweet flag, monkey plant, and Bebb's oval sedge). This may explain the very low return of Bebb's oval sedge. Opposing what happened on Islands A4 and B4, Islands A5 and B5 were both unaffected by geese. It is possible that geese do not want to consume the plants on these islands (woolly sedge and flat top aster), as the two islands had nearly the same amount of these plants. However, there are also indications that the type of plant does not matter. Island A3 had three posts knocked down and some goose fecal matter while Island B3 was completely unaffected. The amount of plants on each island did not differ by more than 2 plants, so it does not appear as though the geese affected the number of plants growing. This same phenomenon is observed on Islands A6 and B6: A6 had one post knocked down and B6 had three, but there was little difference in the number of plants on each.

Combining this information gives some indication as to which plants should be used on the FTWs. It would be beneficial to have at least two plants on each island, with each

plant peaking at a different time so that the island has the shortest possible “uncovered” period. A possible solution for the FTWs to take the place of fencing is to use a ring of common rush around the edge of the islands. Since these plants grow early in the year, they will grow tall enough to protect shorter, later-blooming plants while they are young. Using a plant as a natural fence would also allow organisms other than geese to use the FTWs as a habitat, such as turtles and loons, as they are smaller than geese and could slip between the plants. The interior of the FTW could then be planted with two or three other varieties of plants. Swamp milkweed was able to grow within the common rush on Islands A2 and B2, so that may be a good selection. If common rush is not desired to be used as fencing, a full fence as used on Islands A and B is recommended. Neither island had any evidence of being attacked by geese, with the minor exception of a dent on the fencing of Island B. The posts with string are not nearly as effective, even with the string crossing the island to prevent geese from landing on the islands. Of the fourteen islands that only had posts and string to protect them, nine had at least one post knocked down: three had one post knocked down, three had two posts knocked down, and three had three posts knocked down. Thus, full plastic fencing would be most effective in preventing geese from getting onto the FTWs. This will, however, also prevent other wildlife from using the FTWs, so it will be necessary to weigh the risk of destruction geese against providing a habitat for other wildlife.

With only one summer’s worth of data, it is difficult to determine exactly what effect the FTWs have on either body of water. It is possible that the FTWs in Vadnais Pond may have an area of effect that reaches the Center sampling point, and it is also possible that they have no effect at all. The chlorophyll-*a* concentrations measured in Vadnais Pond

are particularly difficult to explain, since each date can be categorized independently based on the overall concentration of chlorophyll-*a* and the rank of the Bridge site among the five sampling sites. In Fleming Lake, there is little indication that they have a broad-reaching impact on the entire body of water. They may have an isolated effect within the group of FTWs, but it is unlikely that that effect reaches any of the other sampling sites.

However, because the results from Vadnais Pond provided some indication of success from the FTWs, as opposed to those in Fleming Lake, it seems likely that there are broader factors to consider when installing FTWs in a body of water. The FTWs in Vadnais Pond cover about 0.57% of the pond's surface area, whereas the FTWs in Fleming Lake cover about 0.08% of the lake's surface area. In personal communications, an interview done by the Worthington Globe, and a study by Winston et. al (2013), it has been established that at least 10% coverage provides the best results. It is very likely that the results found here were a result of there being less than 1% surface area coverage by the FTWs due to their cost. Even adding enough FTWs to Fleming Lake to reach 0.5% of the surface area would entail adding 55.85 $m^2$ of FTWs, or about twelve additional FTWs – double the number of small rectangular FTWs currently in Fleming Lake. Considering the possible environmental impacts of microplastics produced by the FTWs, this could add about 1.35 kg of plastic among $8.89 \times 10^8$ particles with an area of $1.16 \times 10^8$ $mm^2$ (11.61 $m^2$), an amount equivalent to approximately 130 additional PET water bottles. However, it is difficult to argue that there should be an equivalent amount of surface area covered in Fleming Lake as in Vadnais Pond because the effect of the FTWs in Vadnais Pond is still uncertain. It is likely that there would need to be still more FTWs in Fleming Lake to have a measurable impact on the entire lake: Fleming Lake is about 3.5 m deeper

than Vadnais Pond at their respective deepest points; Fleming Lake has inputs coming from agricultural lands in addition to those from residential sources; and Fleming Lake is also used for recreational activities year-round such as boating, swimming, and ice fishing, whereas Vadnais Pond is too small for such activities. Any or all these factors could influence the number and size of FTWs needed in Fleming Lake to achieve the desired outcomes.

## 5 Future Studies

It is recommended that further studies be carried out to determine the relationship between the volume of the body of water, the surface area, and the effectiveness of FTWs at various percentages of coverage. This study should be continued in Vadnais Pond and Fleming Lake to determine whether more frequent sampling might provide more insights into the function of the FTWs. Nutrient analysis should be done in addition to collection of physiochemical characteristics and chlorophyll-*a* content in order to ensure that comparisons between future studies and the data collected in the MPCA report are possible.

If possible, after three or four years of study, it is recommended that an additional FTW be added to Vadnais Pond to quantify the changes to the properties measured here; alternatively, one or more FTWs could be removed to measure the changes to the pond without the FTWs or with a reduced number of FTWs. Winston et. al (2013) extended the percent of surface area covered to 9% and 18%, whereas in this study the percentages were only 0.08% (Fleming Lake) and 0.57% (Vadnais Pond). It is unlikely to be possible to cover that much surface area in Fleming Lake, as 9% of the surface area would be 0.11 $km^2$, or 111,086 $m^2$; this would require the addition of 7,969 FTWs of the same size as

Islands A and B, or 23,941 FTWs of the same size as Island A1 and the others of the same size. Not only would this be prohibitively expensive, but it would also not be well-received by the citizens who live around Fleming Lake, as they use the lake for recreation such as swimming and boating and the FTWs would limit use of the lake. It may be possible to add more FTWs to Vadnais Pond, although to reach 9% of the surface area an additional 48 FTWs of the same size as the islands already present would be needed, which would similarly be cost-prohibitive. Instead, doubling the number of FTWs already present is suggested, which may provide better results without exceeding budgetary constraints. Since the three FTWs on Vadnais Pond all differ in the amount of plant material that grew on them over the 2017 summer, if this trend continues, it would be beneficial to study whether the effectiveness of the FTWs varies based on growing plant mass.

It is difficult from the data contained in this study to definitively state whether the FTWs had a positive, negative, or neutral effect on the two bodies of water. The continuations of the project suggested here will assist in quantifying their impact.

# Chapter 2: Periphyton Growth Field Study

## 1 Project Background

This study was conducted in two bodies of water in Worthington, Minnesota to determine whether periphyton growth accumulates on the FTWs over time. Accumulation of periphyton would increase the possible area for further growth, thereby increasing the nutrient reduction potential of the FTW. There were four FTWs installed in 2013 and four more installed in 2014 in the E.O. Olson Regional Stormwater Pond on the campus of Minnesota West Community and Technical College (43°37'08.0"N, 95°37'55.7"W).


*Figure 14. Location of E.O. Olson Regional Stormwater Pond and experimental site.*

Additionally, there were six FTWs installed in Sunset Bay (43°36'22.6"N, 95°37'57.4"W), a section of Okabena Lake in 2015, six more installed in 2016, and an additional three installed in 2017. Okabena Lake itself has a maximum depth of 4.88 m and an average depth of 2.11 m, so it likely that Sunset Bay is shallower.


*Figure 15. Location of Sunset Bay and experimental site.*

These FTWs were installed to allow Midwest Floating Island to test their effectiveness and resilience without placing them in a larger body of water; this study was not planed at installation. Lake Okabena had previously experienced nutrient loading pollution, so the FTWs were anticipated to assist with that issue as well (Buntjer, 2015; WENCK Associates, 2015).

## 2 Methods

### 2.1 Experimental design

To test the accumulation of periphyton growth over time, five sets of FTWs installed annually in Sunset Bay and the E.O. Olson Regional Stormwater Pond were studied. Four FTWs were installed in E.O. Olson Regional Stormwater Pond in 2013 and 2014, six were installed in Sunset Bay in 2015 and 2016, and an additional three were installed in Sunset Bay in 2017. All islands are 4.64 $m^2$ in area, although their shape varies slightly.

The 2013 and 2014 FTWs are rectangular, the 2015 and 2016 FTWs are clover-shaped, and the 2017 FTWs are kidney-shaped.

### 2.2 Experiment execution

On 05/09/18, kayaks were used to approach each FTW in both bodies of water. One 2014 island in the E.O. Olson Regional Stormwater Pond was not approached due to the presence of an aggressive goose. The FTWs were categorized into years based on the type of fencing (hexagonal, rectangular, or none).

### 2.3 Data collection

The periphyton mat on each FTW 1 cm below the water surface was measured using calipers. Three separate locations on each FTW were measured. In addition, the diameter of the FTW fibers without periphyton growth was measured to determine the thickness of the periphytn. One 2017 island was unable to be measured due to an algal film that covered the fibers, preventing accumulation of periphyton growth. This film was not possible to measure with calipers because it was not firm enough.

### 2.4 Data analysis

One-way ANOVA was used to compare the periphyton mat thickness of each set of FTWs (as divided by type of fencing) to the others in the same pond. The thickness was not compared across the two ponds to avoid erroneous conclusions due to confounding factors from each body of water's individual physical and chemical characteristics.

## 3 Results

The two bodies of water studied showed that periphyton accumulates on the FTWs over time at a relatively constant rate.

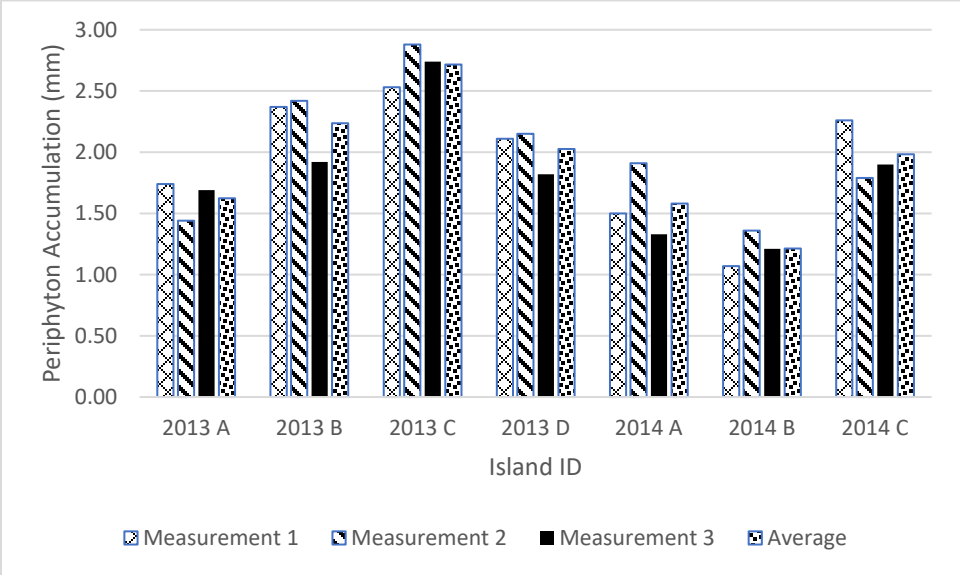



*Figure 16. Thickness of periphyton accumulation on FTWs in E.O. Olson Regional Stormwater Pond.*

The FTW strands in both the E.O. Olson Regional Stormwater Pond and Sunset Bay had an average thickness of 0.15 mm, with a range from 0.10 mm to 0.20 mm.

The two sets of FTWs in the E.O. Olson Regional Stormwater Pond had a statistically significant difference in periphyton accumulation ($p<0.05$). The 2013 FTWs had an average radius of 1.00 mm of periphyton growth accumulated, or about 0.20 mm per year since installation. The 2014 FTWs had an average radius of 0.72 mm of periphyton growth accumulated, or about 0.18 mm per year since installation. The rates of accumulation are consistent within the pond.

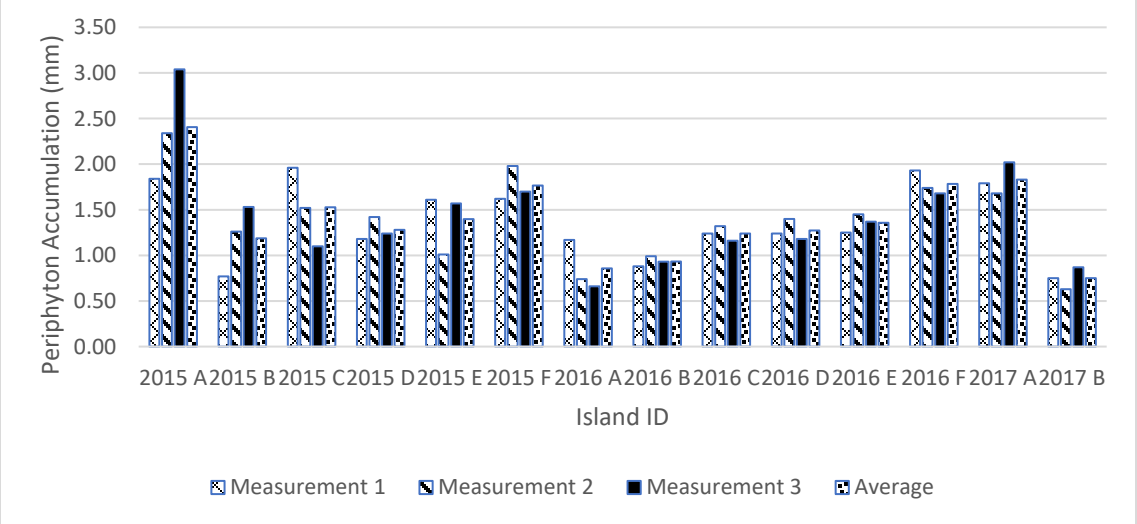



*Figure 17. Thickness of periphyton accumulation on FTWs in Sunset Bay.*

In Sunset Bay, there was a statistically significant difference in periphyton accumulation between 2015 and 2016 ($p<0.05$). However, the difference between 2015 and 2017, and between 2016 and 2017, was not statistically significant ($p>0.05$). The 2015 FTWs had an average radius of 0.72 mm of periphyton growth accumulated, or about 0.24 mm per year since installation. The 2016 FTWs had an average radius of 0.54 mm of periphyton growth accumulated, or about 0.27 mm per year since installation. The 2017 FTWs had an average radius of 0.53 mm of periphyton growth accumulated over the past year.

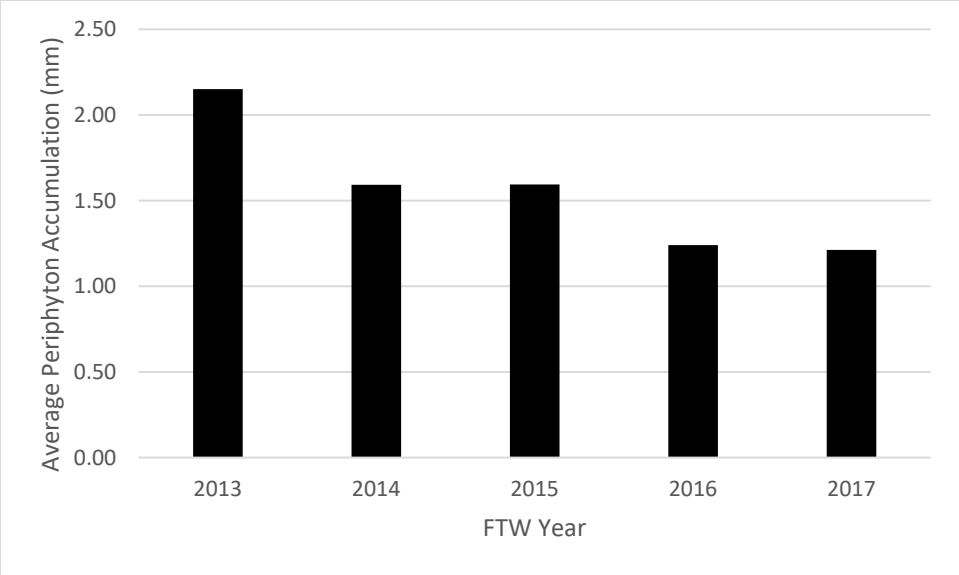



*Figure 18. Average thickness of periphyton accumulation on FTWs in the E.O. Olson Regional Stormwater Pond and Sunset Bay.*

## 4 Discussion

Analysis of the periphyton thickness indicates that the two bodies of water examined has its own relatively steady rate of accumulation. There is definite accumulation of periphyton mass over time, not only on the FTWs themselves, but also on any fencing material that dips into the water. Since the average accumulation in the 2014 FTWs in the E.O. Olson Regional Stormwater Pond was the same as that in the 2015 FTWs in Sunset Bay, and Sunset Bay has a higher rate of accumulation than the E.O. Olson Regional Stormwater Pond, it is not reasonable to directly compare the two bodies of water. Further, with only two sets of FTW in the E.O. Olson Regional Stormwater Pond and only three sets in Sunset Bay, it is not possible at this time to make an estimation of how much accumulation may occur over time.

## 5 Future Studies

It is recommended that this study be continued, with sampling in Worthington necessary only about once per year. This sampling should occur in May, as was done in this study, to maintain consistency with results. It is also suggested that this study be paired with the methods used in the water quality and nutrient analysis field experiment, to determine if the amount of periphyton accumulation on the FTWs correlates with the rate of chlorophyll-*a* and nutrient reduction. It would also be beneficial to add this study to the research being undertaken in Vadnais Pond and Fleming Lake. Further, a study to determine whether the FTWs get clogged by periphyton growth within the matrix would provide valuable information about the effectiveness of the FTWs over time.

# Chapter 3: Microplastics Laboratory Study

## 1 Project Background

The laboratory experiment to examine the possibility of production of microplastics was carried out in the Biological and Agricultural Engineering building on the University of Minnesota Saint Paul campus in Saint Paul, Minnesota (44°58'58.6"N, 93°11'06.7"W**)**. In this experiment, the FTW matrix was exposed to repeated freeze-thaw cycles to simulate the freezing and thawing of the water surrounding an FTW. The FTW used was constructed by Midwest Floating Island, and all water used was deionized to eliminate possible erosion of the FTW matrix by ions present in the water. When not in experimental cycles, all FTW pieces used were stored in an airtight cabinet to prevent deposition of dust or other airborne particulates.

## 2 Methods

### 2.1 Experimental design

To test the resilience of the matrix material to repeated freeze-thaw cycles, twenty-four cylindrical cores with diameters of 7.60 cm were cut from a small FTW using a handheld hole saw. Each core was washed three times with room temperature deionized water to remove dust from the cutting process. Once all cores had been washed, they were air-dried in the cabinet. They were then weighed to determine their initial mass.

### 2.2 Experiment execution

The cores were split into four groups: fifteen frozen wet, three frozen dry, three room temperature wet, and three room temperature dry. The cores were randomly assigned to

their groups and placed on numbered glass Petri dishes. The cores in the frozen wet group had 40 mL of deionized water added to the dishes, and then the cores in the frozen wet and frozen dry groups were placed in a freezer at -20°C. After 24 hours, the cores were removed from the freezer and covered with foil while they thawed at room temperature for 24 hours. The room temperature wet cores then had 40 mL of deionized water added to them, and both sets of room temperature cores were placed in a cabinet. The frozen cores were thawed at room temperature for 24 hours, while the room temperature cores sat undisturbed for 24 hours.

### 2.3 Data collection

At the end of the 24 hours, the cores were removed from their Petri dishes. The dishes from the dry cores had 40 mL of deionized water added to collect any particles in the dishes. Twenty-four 0.45 µm glass microfiber filters were weighed to determine their initial mass, and each filter was assigned to a Petri dish. The water from each dish was then filtered through the corresponding filter using vacuum filtration. The filters were placed in a drying oven at 105°C for 24 hours to dry. Once the filters were dry, they were placed in a desiccator at room temperature for 24 hours to cool and prevent them from absorbing water from the air as they cooled. After 24 hours, the filters were weighed and the initial mass subtracted from the final mass to determine the mass of the core left behind. The cores were air-dried at room temperature in a cabinet for 48 hours, and the Petri dishes were wiped out with Kimwipes. This process was repeated fifteen times to simulate the fifteen-year lifespan of the FTWs. Once the fifteen cycles were completed, the cores were weighed again to determine their final mass.

The particle processing software ImageJ was used to determine the number of plastic particles left behind on the filters by each core. After the fifteen experimental cycles had been completed, a photo was taken of each filter using a Samsung Galaxy S6 camera with a resolution of 5312 by 2988 pixels. Each photo was then individually opened in ImageJ. The photo was cropped and the background eliminated to include only the filter. The scale was set by using the Straight tool to draw a line across the diameter of the filter, and the diameter was set to 43 mm with the Set Scale function. This allowed the program to accurately estimate the area of the particles on the filters in $mm^2$. The photo was then converted to binary using the Make Binary function, and then the number of particles was computed using the Analyze Particles function. To ensure that the program was accurately counting the number and area of the particles, each photo was separately analyzed at least three times. The results were only accepted if the number of particles and the area of the particles were within 5% for all three analyses.

### 2.4 Data analysis

The data was divided by three parameters for analysis: mass of the particles as measured on the scale, number of particles as measured by ImageJ, and cross-sectional area of the particles as measured by ImageJ. A one-way ANOVA test was run on the four experimental groups to determine if there was a significant difference between the frozen wet samples and the frozen dry, room temperature wet, and room temperature dry. An additional ANOVA test was run to determine if there was a significant difference between the values for all samples between cycles.

## 3 Results

For all analyses here, the average amount of the parameter (particles, mass, and area) lost by each experimental group per cycle was analyzed with a one-way ANOVA test. The results were used to create a model to predict the average amount of the parameter lost after a given number of cycles, based on the initial mass of an FTW.

### 3.1 Particle data

The difference between the frozen wet and frozen dry samples was statistically significantly different in one out of fifteen cycles (cycle 1, $p<0.05$). The difference between the frozen wet and room temperature wet samples was statistically significantly different in zero out of fifteen cycles. The difference between the frozen wet and room temperature dry samples was statistically significantly different in two out of fifteen cycles (cycles 1 and 4, $p<0.05$).

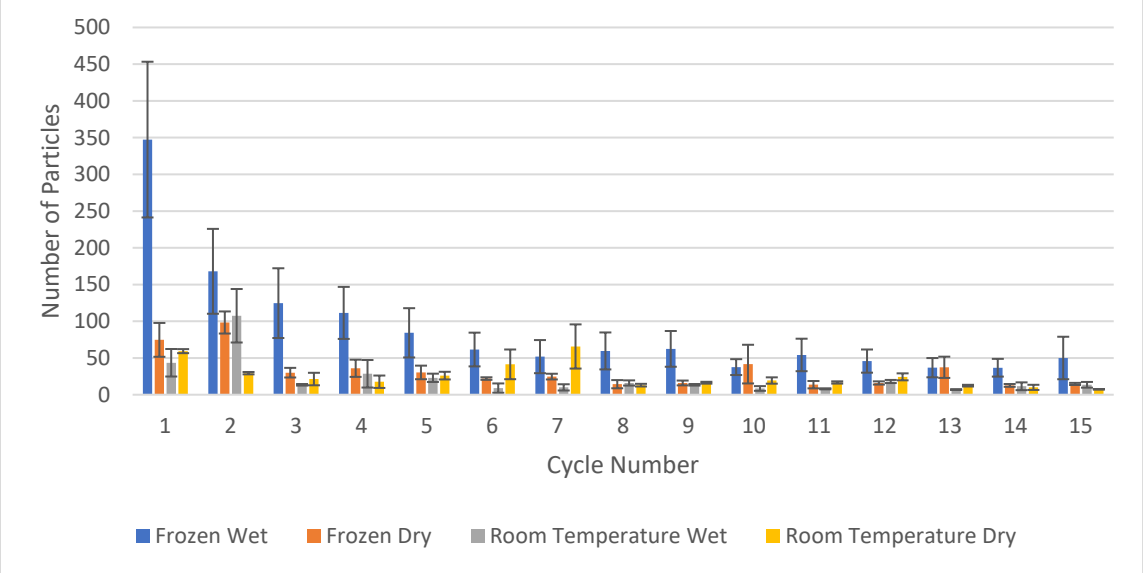



*Figure 19. Average number of particles lost by each experimental group per cycle.*

The number of particles that broke off from the FTW cores per cycle was determined by taking the average number of particles lost in each cycle among all four experimental groups and graphing the results. A trendline was fitted to the data based on the equation that produced the best fit.

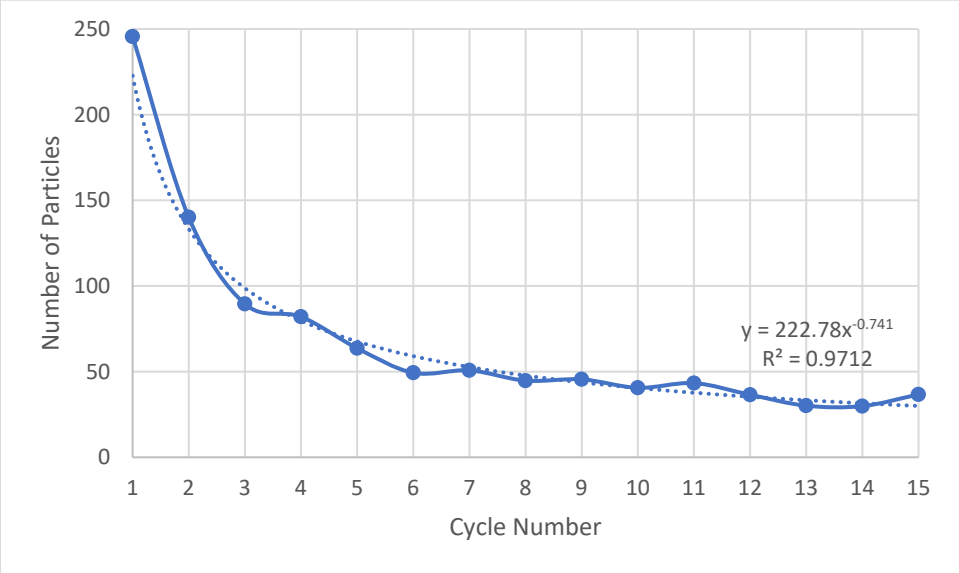



*Figure 20. Number of particles lost, on average, per cycle.*

$$y = 222.78x^{-0.741}$$

*Equation 4. Trendline of average particles lost among all experimental groups.*

Over the course of fifteen freeze-thaw cycles, this model predicted that 1014 particles would be lost on average for the cores studied here. The experimental data found that 1028 particles were lost on average. Thus, the model was able to estimate 98.56% of the particles lost.

To create an equation that could be used to determine the potential number of particles lost for any FTW in a given freeze-thaw cycle if the starting mass is known, the number of particles lost for each core per cycle was divided by the initial mass of the core. The

average was then taken of all values per cycle to estimate the freeze-thaw cycle days, and the average of only the room temperature cores was taken to estimate the wet days without ice. Both evaluations were graphed and a trendline fitted.

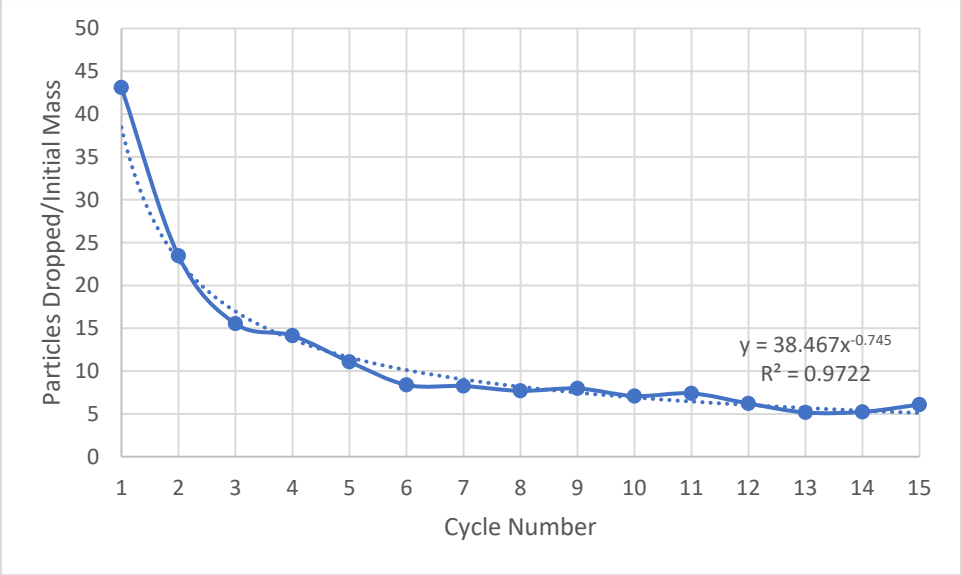



*Figure 21. Particles lost divided by the initial core mass, on average, per cycle for freeze-thaw cycle days.*

$$y = 38.467x^{-0.745}$$

*Equation 5. Trendline of average particles lost per cycle divided by the core initial mass among all experimental groups.*

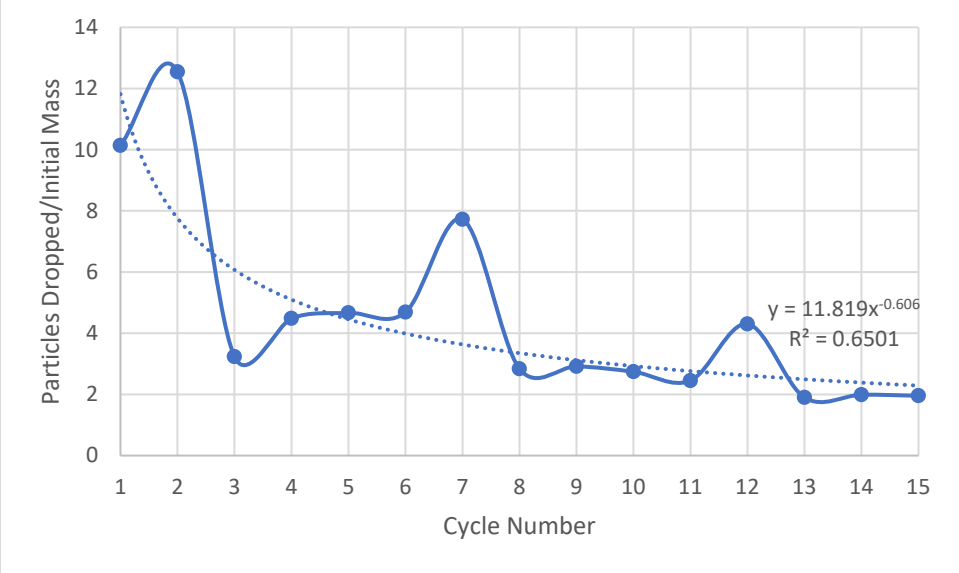



*Figure 22. Particles lost divided by the initial core mass, on average, per cycle for wet days.*

$$y = 11.819x^{-0.606}$$

*Equation 6. Trendline of average particles lost per cycle divided by the core initial mass among room temperature groups.*

The cumulative proportion of particles lost was also graphed and a trendline fitted for both the freeze-thaw cycle days and the wet days to provide a way to estimate how many particles would be lost by the time a given number of cycles had passed.

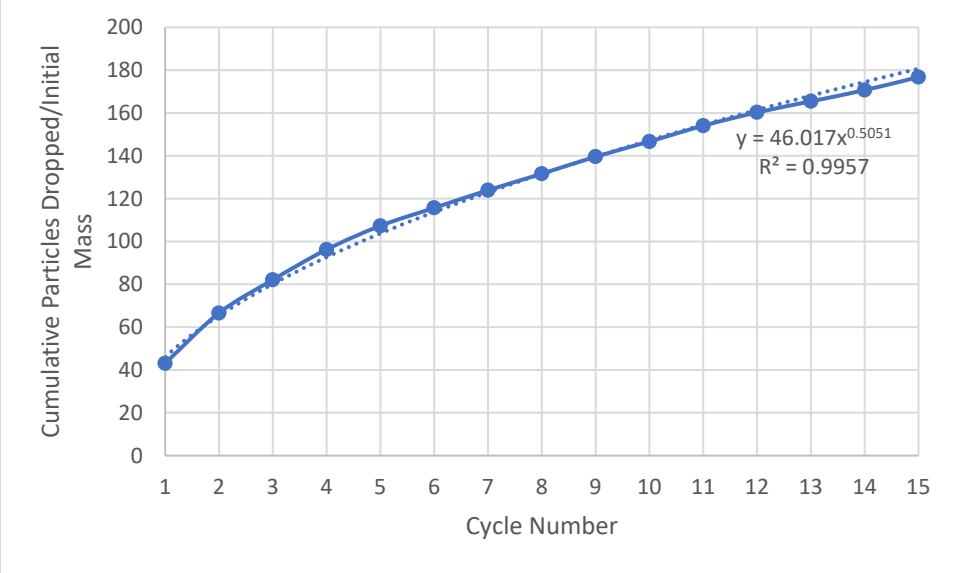



*Figure 23. Cumulative particles lost divided by the initial core mass, on average, per cycle for freeze-thaw cycle days.*

$$y = 46.017x^{0.5051}$$

*Equation 7. Trendline of cumulative average particles lost per cycle divided by the core initial mass among all experimental groups.*

After fifteen freeze-thaw cycles, the model predicted a total of 181 particles would be lost per gram of initial mass. The experimental data found a total of 177 particles. The model overestimated the number of particles by 2.24%.

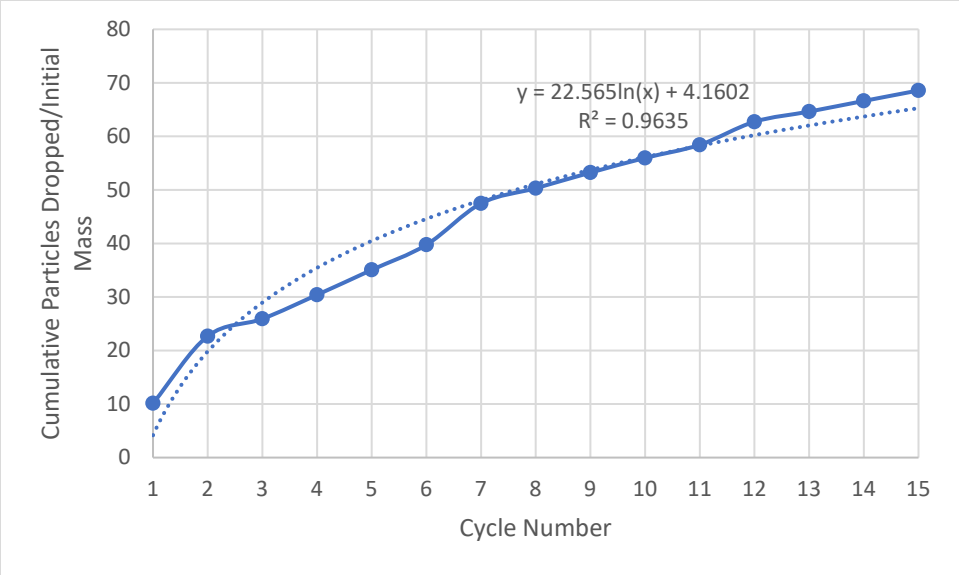



*Figure 24. Cumulative particles lost divided by the initial core mass, on average, per cycle for wet days.*

$$y = 22.565\ln(x) + 4.1602$$

*Equation 8. Trendline of cumulative average particles lost per cycle divided by the core initial mass among room temperature groups.*

After fifteen freeze-thaw cycles, the model predicted a total of 65 particles would be lost per gram of initial mass. The experimental data found a total of 69 particles. The model underestimated the number of particles by 5.00%.

### 3.2 Mass data

The difference between the frozen wet and the other experimental groups was not statistically significantly different in any of the cycles.

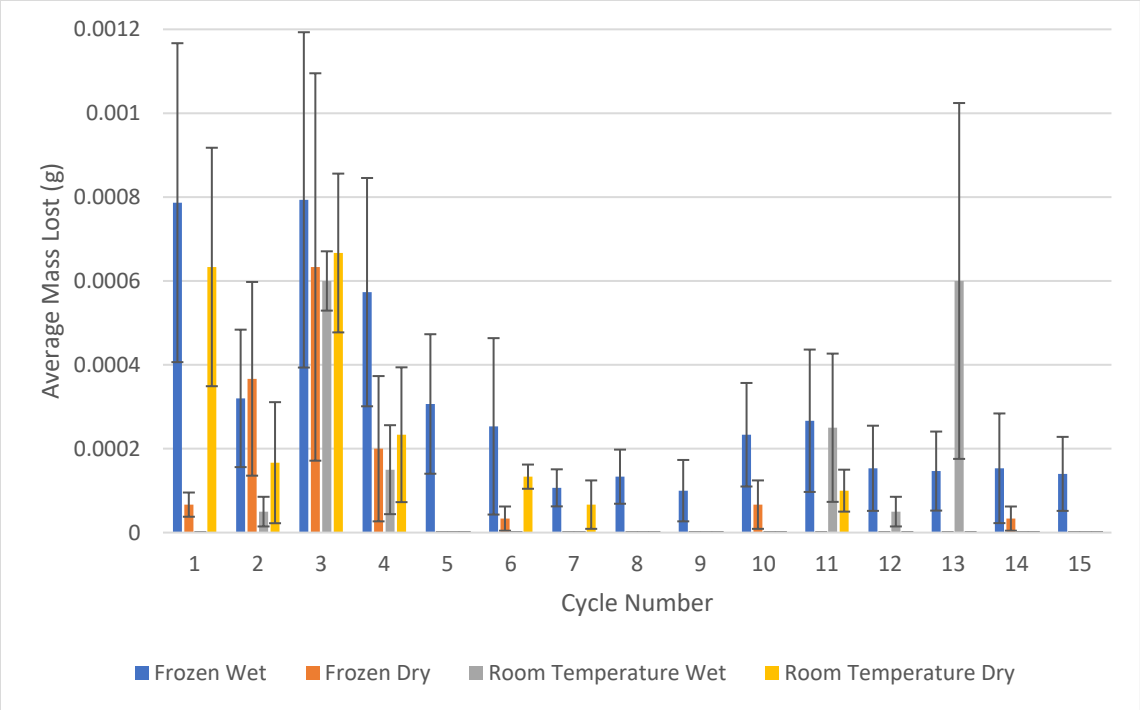



*Figure 25. Average mass lost by each experimental group per cycle.*

The average mass of particles lost per cycle for the cores was estimated by taking the average mass of particles lost in each cycle from all four experimental groups and graphing the results. A trendline was fitted to the data.

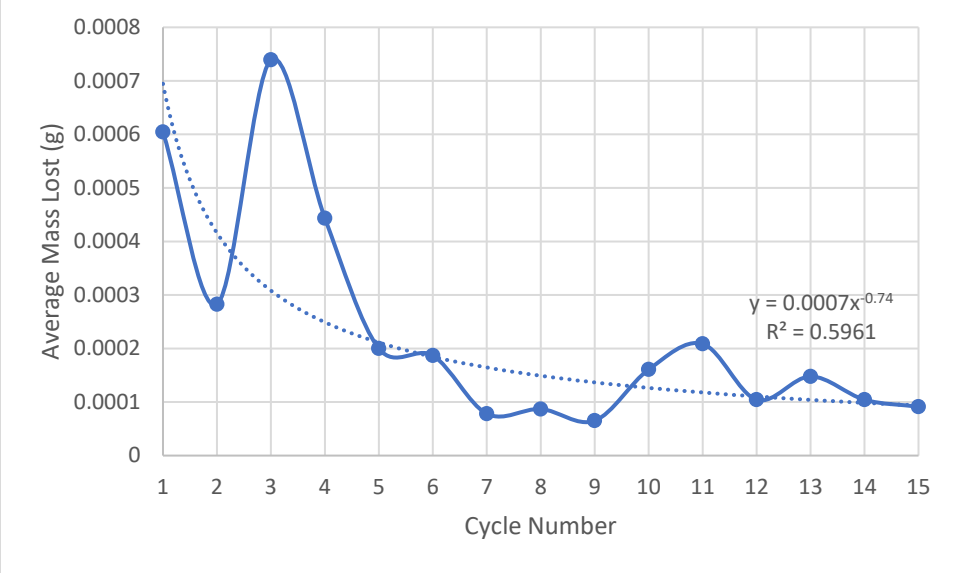



*Figure 26. Mass of particles lost, on average, per cycle.*

$$y = 0.0007x^{-0.74}$$

*Equation 9. Trendline of average mass lost among all experimental groups.*

Over the course of fifteen freeze-thaw cycles, the model predicted that 0.032 g would be lost on average. The experimental data found that 0.035 g were lost on average. The model underestimated of the mass of particles lost by 9.00%.

To create an equation that could be used for any FTW if the starting mass is known, the mass lost for each core per cycle was divided by the initial mass of the core. The average was then taken of all values per cycle to estimate the freeze-thaw cycle days, and the average of only the room temperature cores was taken to estimate the wet days. Both evaluations were graphed and a trendline fitted.

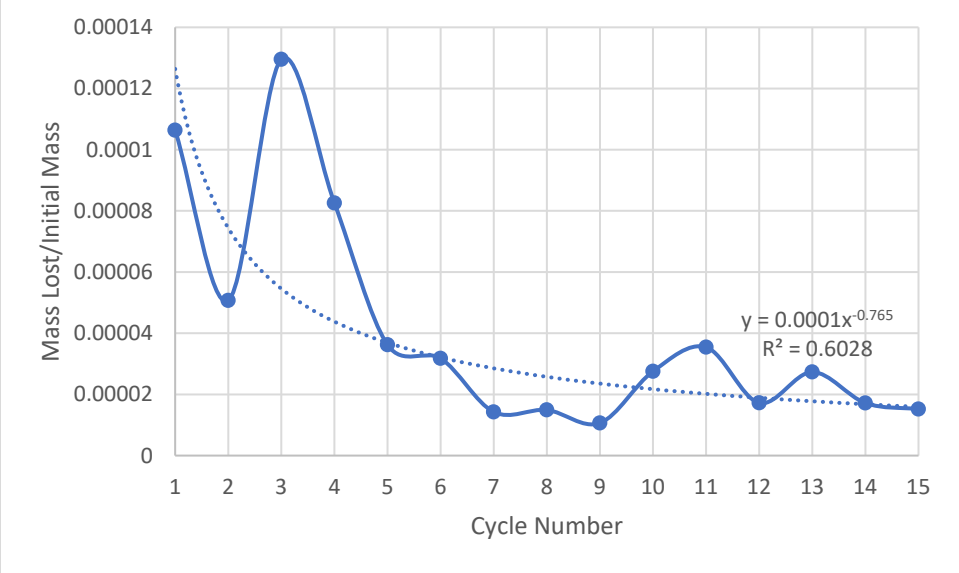



*Figure 27. Mass lost divided by the initial core mass, on average, per cycle for freeze-thaw cycle days.*

$$y = 0.0001x^{-0.765}$$

*Equation 10. Trendline of average mass lost per cycle divided by the core initial mass among all experimental groups.*

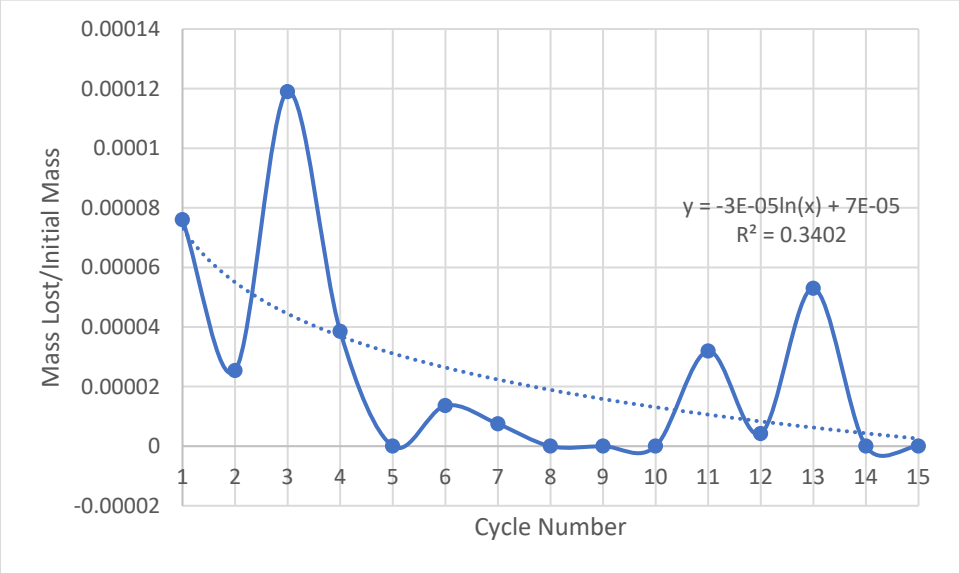



*Figure 28. Mass lost divided by the initial core mass, on average, per cycle for wet days.*

$$y = -0.00003\ln(x) + 0.00007$$

*Equation 11. Trendline of average mass lost per cycle divided by the core initial mass among room temperature groups.*

The cumulative proportion of mass lost was then graphed and a trendline fitted to provide a way to estimate how much mass would be lost by the time a given number of cycles had passed.

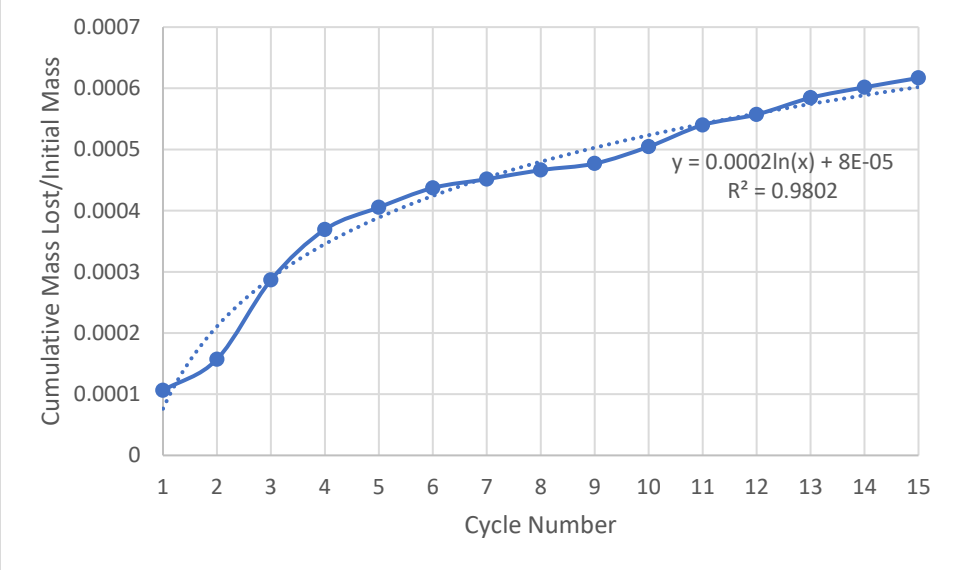



*Figure 29. Cumulative mass lost divided by the initial core mass, on average, per cycle for freeze-thaw cycle days.*

$$y = 0.0002\ln(x) + 0.00008$$

*Equation 12. Trendline of cumulative average mass lost per cycle divided by the core initial mass among all experimental groups.*

After fifteen freeze-thaw cycles, the model predicted a proportion of 0.00062 grams lost per gram of initial mass. The experimental data found a proportion of 0.00061 grams lost per gram of initial mass. The model overestimated the mass by 0.77%.

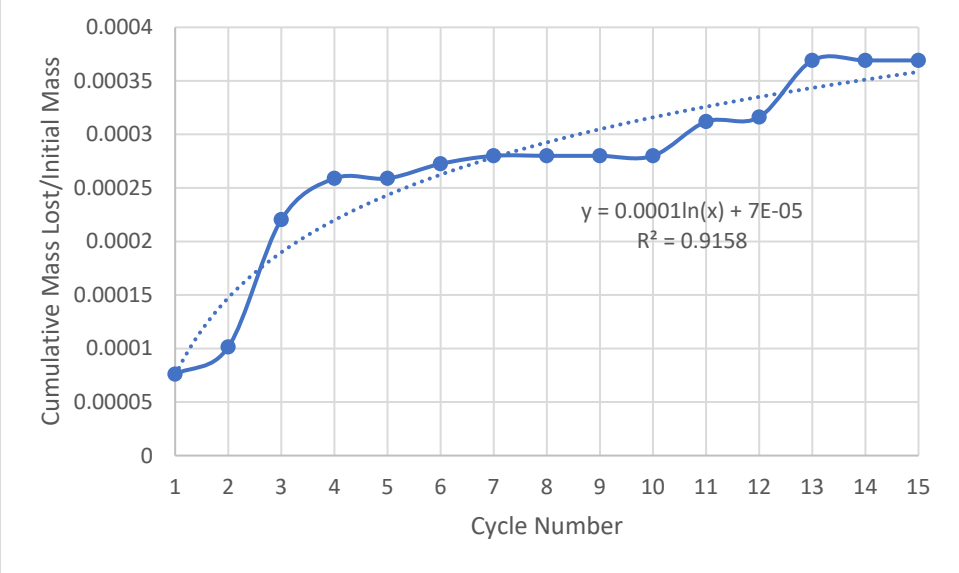



*Figure 30. Cumulative mass lost divided by the initial core mass, on average, per cycle for wet days.*

$$y = 0.0001\ln(x) + 0.00007$$

*Equation 13. Trendline of cumulative average mass lost per cycle divided by the core initial mass among room temperature groups.*

After fifteen freeze-thaw cycles, the model predicted a proportion of 0.00037 grams lost per gram of initial mass. The experimental data found a proportion of 0.00034 grams lost per gram of initial mass. The model underestimated the mass by 7.66%.

At the end of the experiment, the cores were weighed again to determine their final mass. This mass was compared to the final mass the cores should have based on the amount of mass they lost during each experimental cycle. All cores except core 8 (which gained mass) were found to have lost mass outside of the experiment.

On average, the cores lost 0.069% of their initial mass over the course of the experimental cycles. The experimental data shows that the cores lost about 0.00034 grams of material per gram of initial mass on average after fifteen cycles.

### 3.3 Area data

The difference between the frozen wet and frozen dry samples was statistically significantly different in three out of fifteen cycles (cycles 1,3, and 4; $p<0.05$). The difference between the frozen wet and room temperature wet samples was statistically significantly different in two out of fifteen cycles (cycles 2 and 13; $p<0.05$). The difference between the frozen wet and room temperature dry samples was statistically significantly different in zero out of fifteen cycles.

Graphing the average area lost by each experimental group shows that there was no experimental group that had a higher amount of area lost.

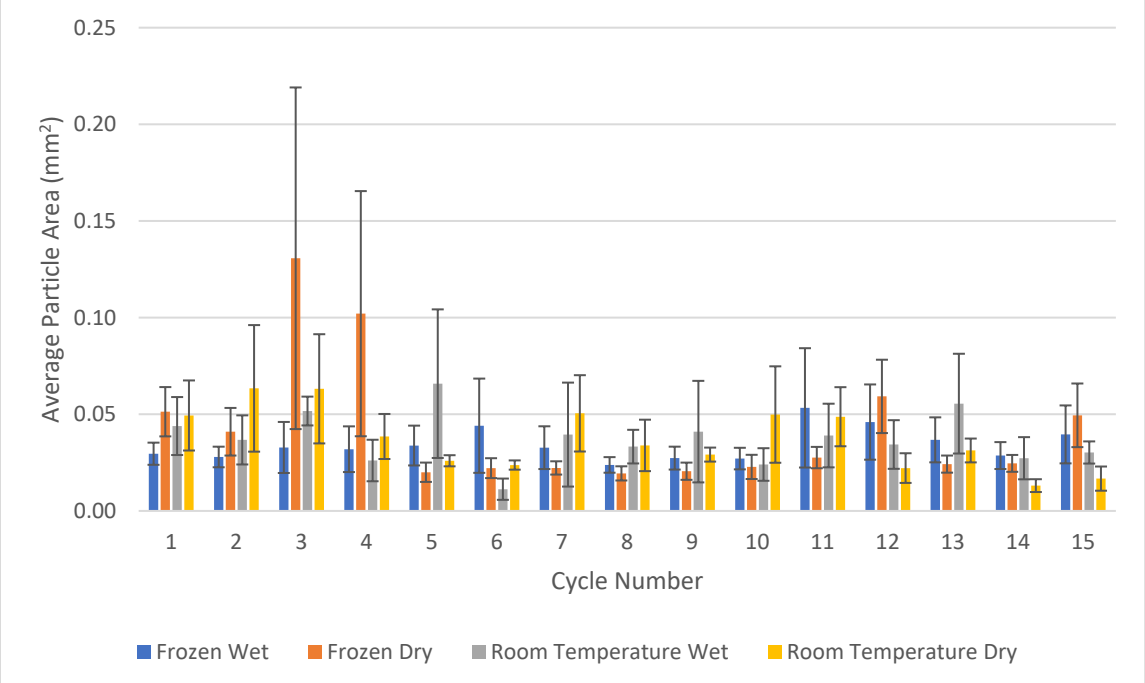



*Figure 31. Average area of particles lost by each experimental group per cycle.*

The average area of particles lost per cycle for the cores was estimated by taking the average area of particles lost in each cycle from all four experimental groups and graphing the results. A trendline was fitted to the data.

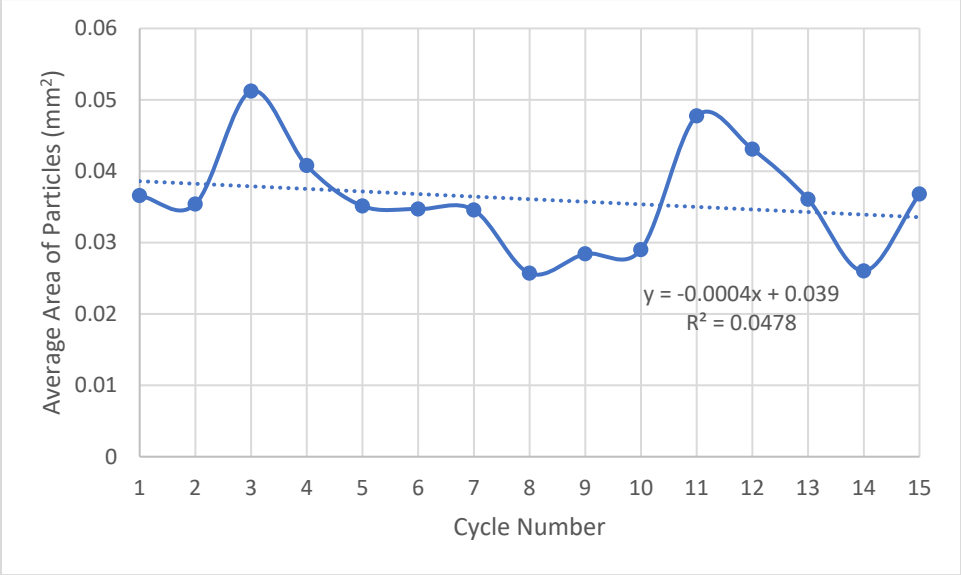



*Figure 32. Area of particles lost, on average, per cycle.*

$$y = 0.0004x + 0.039$$

*Equation 14. Trendline of average particles lost among all experimental groups.*

Over the course of fifteen freeze-thaw cycles, the model predicted that the particles lost would amass to 0.537 $mm^2$. The experimental data found that an area of 0.541 $mm^2$ of particles were lost. The model underestimated of the area of particles lost by 0.77%.

To create an equation that could be used for any FTW if the starting mass is known, the area of particles lost for each core per cycle was divided by the initial mass of the core. The average was then taken of all values per cycle to estimate the freeze-thaw cycle days,

and the average of only the room temperature cores was taken to estimate the wet days without ice. Both evaluations were graphed and a trendline fitted.

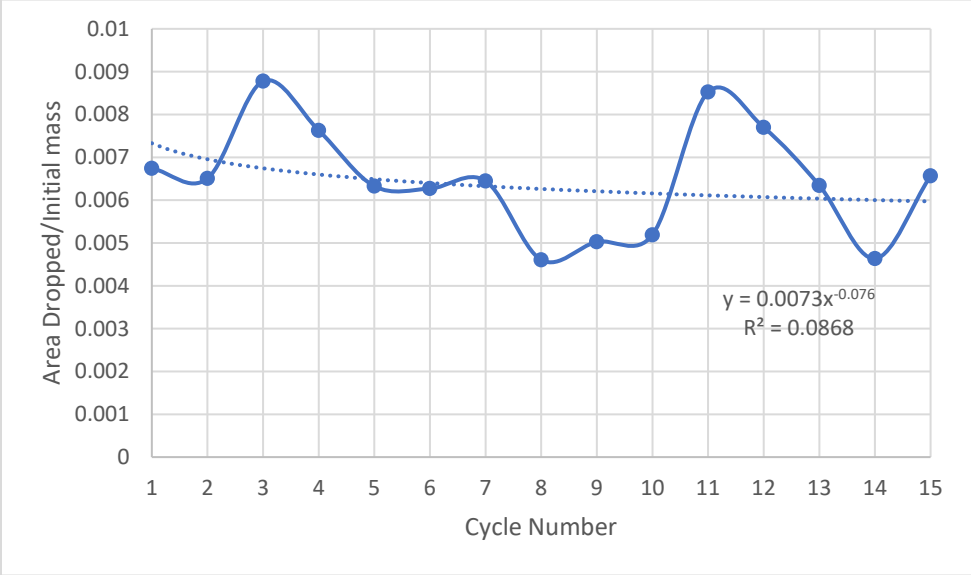



*Figure 33. Area of particles lost divided by the initial core mass, on average, per cycle for freeze-thaw cycle days.*

$$y = 0.0073x^{-0.076}$$

*Equation 15. Trendline of average area of particles lost per cycle divided by the core initial mass among all experimental groups.*

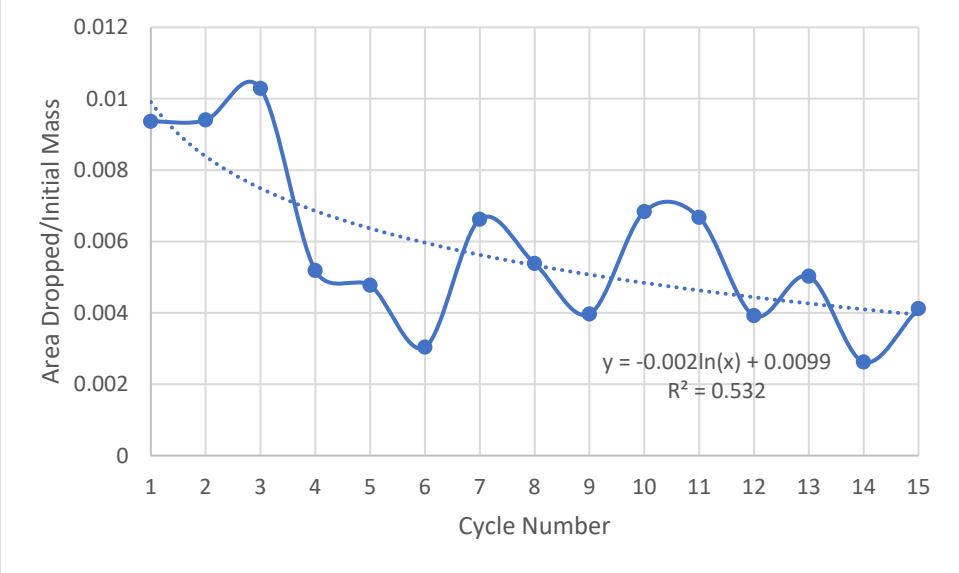



*Figure 34. Area of particles lost divided by the initial core mass, on average, per cycle for wet days.*

$$y = -0.002\ln(x) + 0.0099$$

*Equation 16. Trendline of average area of particles lost per cycle divided by the core initial mass among room temperature groups.*

The cumulative proportion of area of particles lost was also graphed and a trendline fitted, to provide a way to estimate what area of particles would be lost by the time a given number of cycles had passed.

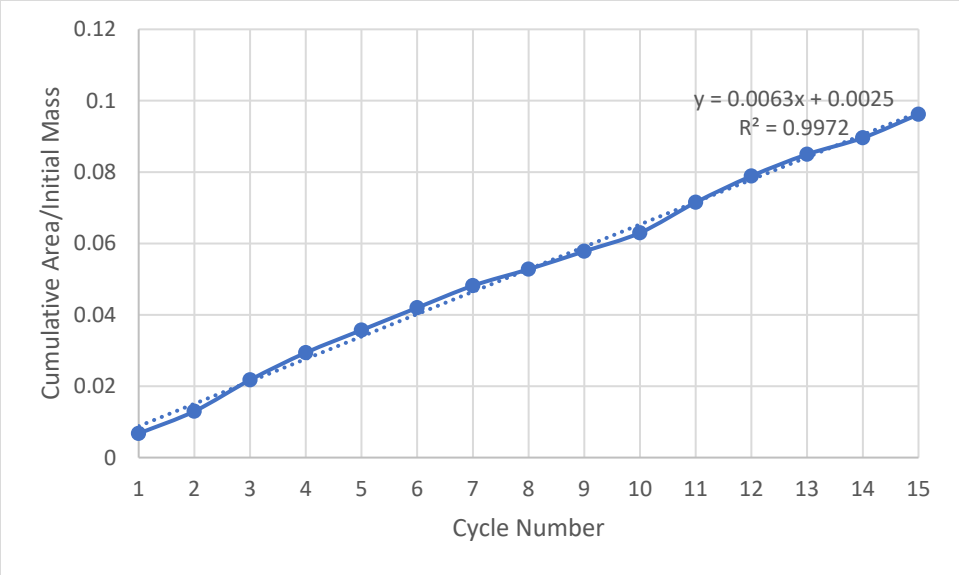



*Figure 35. Cumulative area of particles lost divided by the initial core mass, on average, per cycle for freeze-thaw cycle days.*

$$y = 0.0063x + 0.0025$$

*Equation 17. Trendline of cumulative average area of particles lost per cycle divided by the core initial mass among all experimental groups.*

After fifteen freeze-thaw cycles, the model predicted a proportion of 0.097 $mm^2$ lost per gram of initial mass. The experimental data found a proportion of 0.096 $mm^2$ lost per gram of initial mass. The model overestimated the area of particles by 0.868%.

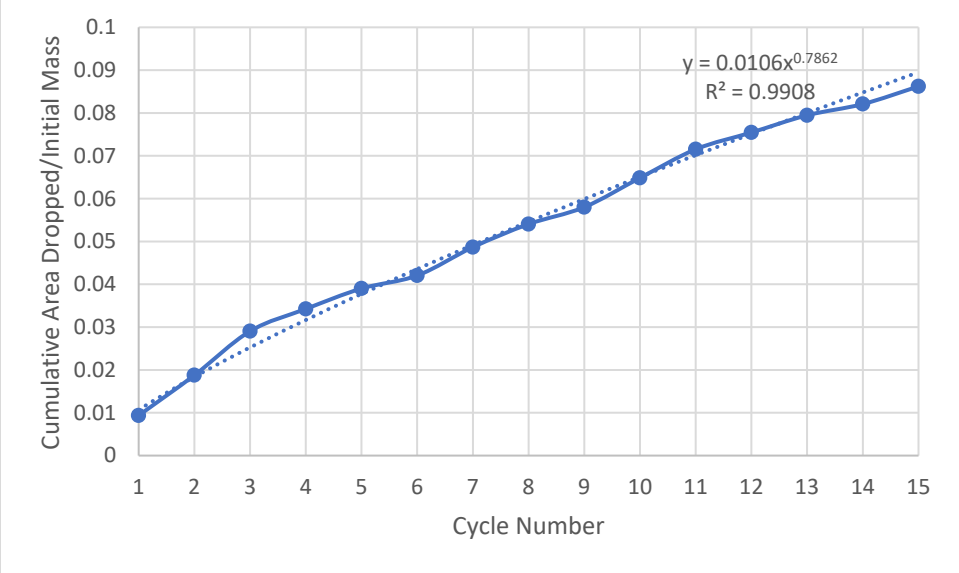



*Figure 36. Cumulative area of particles lost divided by the initial core mass, on average, per cycle for wet days.*

$$y = 0.0106x^{0.7862}$$

*Equation 18. Trendline of cumulative average area of particles lost per cycle divided by the core initial mass among room temperature groups.*

After fifteen freeze-thaw cycles, the model predicted a proportion of 0.089 $mm^2$ lost per gram of initial mass. The experimental data found a proportion of 0.086 $mm^2$ lost per gram of initial mass. The model overestimated the area of particles by 3.38%.

### 3.4 Projected losses

Combining the equations from the above three sections allows for approximations to be made of the number of particles, mass of particles, and area of particles that may be lost by an FTW during its lifespan. This experiment assumed only one freeze-thaw cycle per year, as assumed by Midwest Floating Island (Buntjer, 2015; Martin Ecosystems, 2014); however, northern Minnesota, where Fleming Lake is located, experiences many freeze-thaw cycles every winter. Estimates include 58 cycles (Haley, 2011), 47 to 50 cycles (Ho & Gough, 2006), and 72 cycles (Schmidlin et al., 1987). Additionally, estimates of the number of days of ice cover include 160 to 166 (Fang & Stefan, 2009), 161 to 175 (Stefan, Hondzo, Fang, Eaton, & McCormick, 1996), and 141 to 147 (Johnson, Stefan, Johnson, & Stefan, 2006).

Assuming a conservative 50 freeze-thaw cycle days per year with 160 days of ice, leaving 155 days of open water, gives an estimate of 750 freeze-thaw cycle days and 2,325 days without ice over the course of fifteen years. The FTWs installed in Fleming Lake can be categorized as follows:

*Table 14. Dimensions and mass of FTWs in Fleming Lake.*

| **Number** | **Dimensions (m)** | **Mass (g)** |
|---|---|---|
| 12 | 1.52 by 3.05 (rectangle) | 50,000 |
| 2 | 1.52 by 3.05 (irregular “kidney” shape) | 45,360 |
| 2 | 2.29 by 6.10 (rectangle) | 152,800 |

The trendlines used to estimate the particles, mass, and area lost each cycle were all accurate within 10% of the actual value, so these equations were used to estimate the potential losses for an island installed in a lake that freezes over every winter. For freeze-

thaw days (x=750), Equation 7 was used to estimate the number of particles lost, Equation 12 was used to estimate the mass lost, and Equation 17 was used to estimate the area of particles lost. For wet days (x=2325), Equation 8 was used to estimate the number of particles lost, Equation 13 was used to estimate the mass lost, and Equation 18 was used to estimate the area of particles lost. Each y-value was then multiplied by the mass of the island, and the results multiplied by the number of islands of that size.

The results of these analyses are as follows:

*Table 15. Results of mass, particle, and area approximation for the sixteen FTWs in Fleming Lake over fifteen years.*

| All | 1.52x3.05 rectangle | 1.52 by 3.05 kidney | 2.29 by 6.10 rectangle | Total |
|---|---|---|---|---|
| Mass (g) | 1349.50 | 204.04 | 687.34 | 2240.89 |
| Particles | 8.895E+08 | 1.345E+08 | 4.531E+08 | 1.477E+09 |
| Area ($mm^2$) | 1.161E+07 | 1.755E+06 | 5.913E+06 | 1.928E+07 |

*Table 16. Results of mass, particle, and area approximation for the sixteen FTWs in Fleming Lake over fifteen years, considering only freeze-thaw days.*

| Freeze-Thaw | 1.52x3.05 rectangle | 1.52 by 3.05 kidney | 2.29 by 6.10 rectangle | Total |
|---|---|---|---|---|
| Mass (g) | 842.41 | 127.37 | 429.07 | 1398.85 |
| Particles | 7.82E+08 | 1.18E+08 | 3.98E+08 | 1.299E+09 |
| Area ($mm^2$) | 8.79E+06 | 1.33E+06 | 4.48E+06 | 1.460E+07 |

*Table 17. Results of mass, particle, and area approximation for the sixteen FTWs in Fleming Lake over fifteen years, considering only wet days.*

| Wet | 1.52x3.05 rectangle | 1.52 by 3.05 kidney | 2.29 by 6.10 rectangle | Total |
|---|---|---|---|---|
| Mass (g) | 507.09 | 76.67 | 258.28 | 842.04 |
| Particles | 1.074E+08 | 1.625E+07 | 5.472E+07 | 1.784E+08 |
| Area ($mm^2$) | 2.819E+06 | 4.263E+05 | 1.436E+06 | 4.682E+06 |

The amount of material lost during freeze-thaw cycles indicates that, if left in bodies of water that freeze in the winter, the environment will continue to degrade the plastic FTW matrix. However, there was also a significant amount of material lost during the wet days, indicating that the FTWs are likely susceptible to further degradation by environmental effects.

Since the FTWs are made of waste plastic water bottles, an estimate can be made of the number of water bottles an FTW may lose as microplastics. A report by the American Samoa Power Authority found that the average weight of an empty #1 PET water bottle without the cap was 10.31 g (American Samoa Power Authority, 2013). This indicates that the amount of plastic contributed to the water by the FTWs in Fleming Lake over the course of fifteen years could be equivalent to approximately 217 plastic water bottles. This number, however, is likely to be lower than the actual value. There was little to no outside forcing or environmental impact inflicted upon the cores during this experiment. When the FTWs are deployed, there is a variety of environmental factors that may degrade the matrix material more quickly or more forcefully. This can be seen in some photos taken at Fleming Lake on 09/02/17:

*Figure 37. Image of the edge of an FTW in Fleming Lake.*

*Figure 38. Image of the edge of an FTW in Fleming Lake.*

These images show the distressed edges of two FTWs in Fleming Lake. It is uncertain how this damage occurred, but it is most likely that the damage was caused by geese either biting at the matrix or scratching at it with their feet to get onto the FTW (Martin Ecosystems, 2014). The matrix material is also susceptible to degradation by ultraviolet (UV) light (Martin Ecosystems, 2014). This can be mitigated by the shading effect of the plants growing on the FTW, but in cases where the plants are absent due to unfavorable weather phenomena, their dormancy in winter, or consumption by Canada geese, UV light may weaken the FTW matrix. Thus, there are a variety of possible methods of degradation for the FTW matrix that were not explored here that may increase the amount of loss experienced by the matrix material.

# 4 Discussion

The majority of the FTW matrix material broke off during the freeze-thaw cycles, indicating that this material is weakened by the stress induced by these cycles.

## 4.1 Particle data

The ANOVA tests showed that there was little statistical significance between the frozen wet cores and the cores in the other experimental groups. This finding indicates that the forcing exerted on the FTW cores by ice may not be strong enough to cause increased degradation of the matrix material at the 95% confidence level. However, when taking all fifteen cycles into account, the frozen wet cores lost more particles on average than all the other experimental groups. This may indicate that freeze-thaw cycles do increase the number of particles lost, even if that increase is not statistically significantly different at the cycle level.

Because all experimental groups lost some number of particles during every cycle (there was only one instance of zero particles lost, in cycle 6 by core 19), it is likely that the FTW matrix material drops particles at a consistent rate. The number of particles also follows a very predictable decay pattern and appears to have leveled off or is close to doing so after fifteen cycles. This indicates that there are no significant "break points" where some limit is reached and the matrix material suddenly drops significantly more particles. On average, each core lost about 1019 particles over the course of the experimental cycles, or about 180.70 particles per gram of initial mass.

### 4.2 Mass data

The ANOVA tests showed that there was no statistical significance between the frozen wet cores and the cores in the other experimental groups at the 95% confidence interval. However, in the majority of the cycles, the frozen dry, room temperature wet, and room temperature dry cores lost a measurable number of particles but they were of less mass than was measurable on the scale used, rendering their mass lost below detection. These results further reinforce the findings from the particle analysis, which indicated that freeze-thaw cycles may not significantly increase the degradation of the matrix material. As with the particle analysis, however, examination of the average mass lost by each experimental group per cycle shows that the frozen wet cores lost more mass in thirteen out of fifteen cycles, and the frozen wet cores lost more mass on average considering the fifteen cycles together. This may additionally indicate that freeze-thaw cycles increase the mass lost by the FTW matrix, although it may not be statistically significantly different at the 95% confidence level.

The average mass lost follows an overall downward trend, although there were spikes at cycle 3 and around cycles 10 and 11. Because the particle analysis showed no spike at this time and continued its highly predictable pattern, but the average mass and area of particles both had much higher values, this indicates that these were instances where the same number of particles were lost but they were of much larger size and mass. This may signify that there are indeed “break points” where larger particles, typically long strands, are shed at higher rates after about 3 and 10 or 11 cycles.

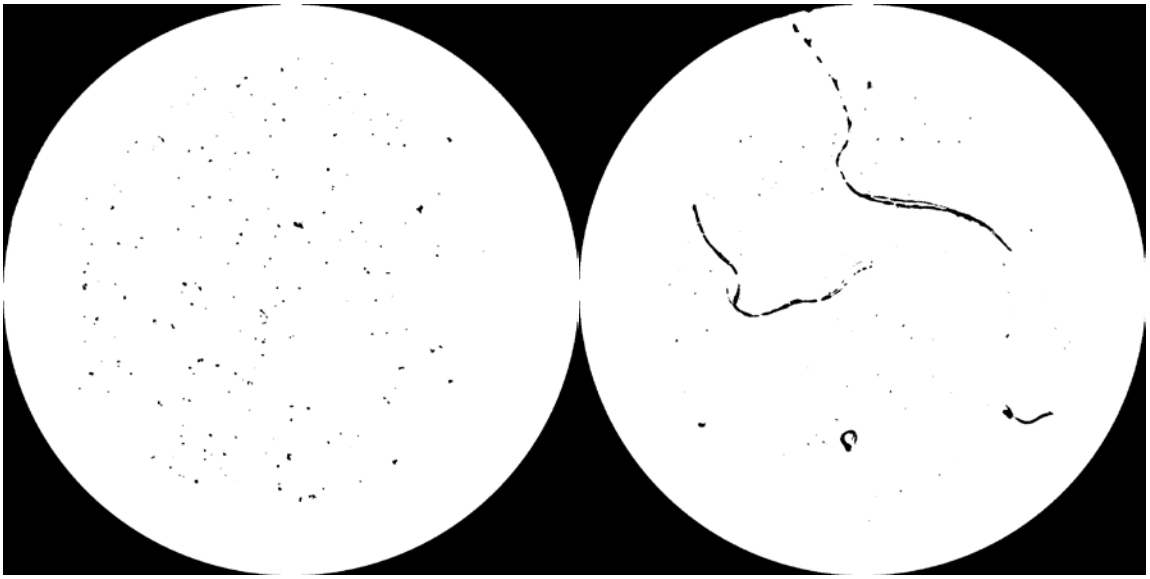


*Figure 39. Filters from core 2 (frozen wet). Left: 199 particles, 0.0001 g, after cycle 2. Right: 75 particles, 0.0036 g, after cycle 3.*

The issue of unaccounted-for mass loss during the course of the experiment is likely explained by the handling of the FTW cores during drying and cleaning of the Petri dishes. There were often particles in the Petri dishes when the dishes were wiped out prior to each cycle, which further lends credibility to the possibility that the FTW matrix constantly sheds particles at a constant rate.

### 4.3 Area data

The ANOVA tests showed that there was little statistical significance between the frozen wet cores and the cores in the other experimental groups, which further reinforces the conclusions drawn from the particle and mass data.

Differing from the particle and mass data, the frozen wet cores did not have a higher average particle area than the other experimental groups in a majority of the cycles; rather, the frozen wet cores had a higher average area of particles in only three cycles: 6, 11, and 14. The frozen dry cores had the highest average particle area in five cycles (1, 3, 4, 12, and 15); room temperature wet in three cycles (5, 8, and 13); and room temperature dry in four cycles (2, 7, 8, and 10). This indicates that the environment of each experimental group likely had little influence on the average size of particle lost. At the end of the fifteen cycles, about 0.096 $mm^2$ of particles were lost per gram of initial mass.

## 5 Future Studies

Because this was a preliminary study, its findings should be confirmed by another study with a larger sample size. Larger-scale freeze-thaw experiments should be carried out with full-size FTWs to better estimate how much mass, area, and particles will be lost as a result of ice stress, as these values may vary with FTW size. The small size of the FTW cores used here may have increased the amount of microplastics, since there was a greater outer edge to internal volume ratio than there would be in an FTW used in the field. A longer study would be beneficial as well, to confirm the accuracy of the equations used to determine how much material would be lost over the course of a certain

number cycles. Such a study should aim to put the FTWs through fifty or more freeze-thaw cycles to simulate one northern Minnesota winter.

PET as a matrix material for FTWs should continue to be examined, particularly if it will continue to be used in lakes that freeze over for any part of the year. Since it was clear from the photos taken at Fleming Lake that the matrix is being degraded by some environmental stress not measured in this experiment, further work may focus on methods for preventing this. Methods for preventing this stress may consist of stronger fencing to prevent geese from climbing onto the FTWs, methods for helping the FTWs evade ice stress such as bumpers, or a protective mat to lay overtop the FTW. Some studies have had preliminary success with coconut fiber as a protective layer for the FTWs, so that material may be useful to continue to study. The effect of UV light should also be examined in more detail, as to date there have been studies on degradation of PET in plastic water bottles but not for PET used in FTW matrix material. It is uncertain whether the PET in the FTWs will react the same way to UV light as the PET in water bottles; the PET in the FTWs may be more susceptible to UV light due to its high surface area to volume ratio.

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## Appendix

*Table 1. Mass of the cores before and after the experiment, demonstrating the mass loss that was not measured in the experiment.*

| Sample ID | Initial Mass (g) | Experimental Mass Lost (g) | Final Mass (Experimental) (g) | Final Mass (Actual) (g) | Unaccounted-For Mass Lost (g) |
|---|---|---|---|---|---|
| 1 | 4.8724 | 0.0016 | 4.8708 | 4.848 | 0.0212 |
| 2 | 5.9903 | 0.0078 | 5.9825 | 5.9629 | 0.0118 |
| 3 | 5.9458 | 0.0061 | 5.9397 | 5.9093 | 0.0243 |
| 4 | 4.8816 | 0.0024 | 4.8792 | 4.8595 | 0.0173 |
| 5 | 4.7502 | 0.0018 | 4.7484 | 4.7245 | 0.0221 |
| 6 | 4.9478 | 0.0023 | 4.9455 | 4.9216 | 0.0216 |
| 7 | 7.7481 | 0.0037 | 7.7444 | 7.7212 | 0.0195 |
| 8 | 4.8881 | 0.0056 | 4.8825 | 5.0471 | -0.1702 |
| 9 | 5.9643 | 0.0042 | 5.9601 | 5.9399 | 0.016 |
| 10 | 7.6174 | 0.0115 | 7.6059 | 7.5817 | 0.0127 |
| 11 | 5.176 | 0.003 | 5.173 | 5.1554 | 0.0146 |
| 12 | 5.0409 | 0.0049 | 5.036 | 5.018 | 0.0131 |
| 13 | 5.0778 | 0.0017 | 5.0761 | 4.8648 | 0.2096 |
| 14 | 4.6055 | 0.003 | 4.6025 | 4.5835 | 0.016 |
| 15 | 5.7671 | 0.0074 | 5.7597 | 5.7401 | 0.0122 |
| 16 | 6.5697 | 0.0021 | 6.5676 | 6.5459 | 0.0196 |
| 17 | 6.6595 | 0.0011 | 6.6584 | 6.6364 | 0.0209 |
| 18 | 4.8129 | 0.001 | 4.8119 | 4.799 | 0.0119 |
| 19 | 4.7667 | 0.0006 | 4.7661 | 4.7497 | 0.0158 |
| 20 | 4.529 | 0.0028 | 4.5262 | 4.4871 | 0.0363 |
| 21 | 6.0815 | 0.0145 | 6.067 | 5.9229 | 0.1296 |
| 22 | 7.0573 | 0.0016 | 7.0557 | 7.0505 | 0.0036 |
| 23 | 4.7721 | 0.0023 | 4.7698 | 4.7621 | 0.0054 |
| 24 | 5.3485 | 0.0021 | 5.3464 | 5.3369 | 0.0074 |

*Figure 1. Island A1 in Fleming Lake, 06/29/17.*

*Figure 2. Island A2 in Fleming Lake, 06/29/17.*

*Figure 3. Island A3 in Fleming Lake, 06/29/17.*

*Figure 4. Island A4 in Fleming Lake, 06/29/17.*


*Figure 5. Island A5 in Fleming Lake, 06/29/17.*

*Figure 6. Island A6 in Fleming Lake, 06/29/17.*

*Figure 7. Island B1 in Fleming Lake, 06/29/17.*

*Figure 8. Island B2 in Fleming Lake, 06/29/17.*

*Figure 9. Island B3 in Fleming Lake, 06/29/17.*

*Figure 10. Island B4 in Fleming Lake, 06/29/17.*

*Figure 11. Island B5 in Fleming Lake, 06/29/17.*

*Figure 12. Island B6 in Fleming Lake, 06/29/17.*

*Figure 13. Island C1 in Fleming Lake, 06/29/17.*

*Figure 14. Island C2 in Fleming Lake, 06/29/17.*

*Figure 15. Island A in Fleming Lake, 06/29/17.*

*Figure 16. Island B in Fleming Lake, 06/29/17.*

*Figure 17. Island 1 in Vadnais Pond, 06/23/17.*

*Figure 18. Island 2 in Vadnais Pond, 06/23/17.*

*Figure 19. Island 3 in Vadnais Pond, 06/23/17.*

*Figure 20. Island 1 in Vadnais Pond, 08/07/17.*

*Figure 21. Island 2 in Vadnais Pond, 08/07/17.*

*Figure 22. Island 3 in Vadnais Pond, 08/07/17.*