

Floating Treatment Wetlands – evaluation for pollutant removal improvement in cold climate stormwater ponds



April 2018

Final Report

Prepared by:

Becky Tharp and Tom Dipietro

Lake Champlain Sea Grant/ University of Vermont and City of South Burlington

For:

The Lake Champlain Basin Program and

New England Interstate Water Pollution Control Commission

This report was funded and prepared under the authority of the Lake Champlain Special Designation Act of 1990, P.L. 101-596 and subsequent reauthorization in 2002 as the Daniel Patrick Moynihan Lake Champlain Basin Program Act, H. R. 1070, through the US EPA and the Great Lakes Fishery Commission. Publication of this report does not signify that the contents necessarily reflect the views of the states of New York and Vermont, the Lake Champlain Basin Program, or the US EPA and the GLFC.

The Lake Champlain Basin Program has funded more than 80 technical reports and research studies since 1991. For complete list of LCBP Reports please visit:
<http://www.lcbp.org/media-center/publications-library/publication-database/>



South Burlington
Stormwater Services



Final Report

NEIWPCC Job Code: 0100-306-010 & 0993-003-001

Project Code: L-2015-021 & L-2017-027

Prepared by: Becky Tharp and Tom Dipietro
Lake Champlain Sea Grant/
University of Vermont and City
of South Burlington

Date Submitted: December 2017

Date Approved: [month and year]

Floating Treatment Wetlands – evaluation for pollutant removal improvement in cold climate stormwater ponds

Contact Information

Becky Tharp

705 Spear St, South Burlington, VT 05405

rtharp@uvm.edu

This is a Lake Champlain Basin Program funded project
54 West Shore Road
Grand Isle, VT 05482
802.372.3213
www.lcbp.org

This project was selected for funding by the Lake Champlain Basin Program (LCBP) Steering Committee and it has been supported directly by an agreement or sub-award issued by the New England Interstate Water Pollution Control Commission (NEIWPCC). NEIWPCC manages LCBP's personnel, contracts, grants, and budget tasks through a partnership with the LCBP Steering Committee.

Although the information in this document may have been funded wholly or in part by the United States Environmental Protection Agency (under agreement CE982720010), the National Park Service, or by the International Great Lakes Fishery Commission, through their respective contracts to NEIWPCC, it has not undergone review by the Agency, Service, or Commission, and no official endorsement of the content of the document should be inferred. The viewpoints expressed here do not necessarily represent those of NEIWPCC, the LCBP, the USEPA, the NPS, or the GLFC, nor does mention of trade names, commercial products, or causes constitute endorsement or recommendation for use.

Executive Summary

Floating Treatment Wetland (FTW) units were evaluated for their suitability in north-eastern United States conditions to improve the pollutant removal effect of a wet extended detention stormwater basin. A stormwater pond treating runoff from a residential townhouse development was monitored for chemical (TN, TKN, nitrate/nitrite, TP, TDP, TSS) and physical (Dissolved oxygen (DO), pH, and temperature) parameters for one year (2015) prior to FTW installation and two years (2016-2017) with FTW rafts covering 25% of the pond surface. Flow-weighted composite samples at the inlet and outlet structures of the pond resulted in representative measurements of water quality coming into and leaving the ponds. FTW rafts were designed using three layers of Polyflow biological filter material and a two-part marine foam for floatation. Four plant species were selected based on their referenced use in the FTW literature in other areas: *Pondetia cordata* (pickerelweed), *Schoenoplectus tabernaemontani* (Softstem Bulrush), *Carex comosa* (Longhaired Sedge), *Juncus effusus* (Common Rush). Plants were evaluated for survivability through a growth season as well as over one winter. Additionally, species' biomass was measured as an indicator of robustness of growth. The raft material itself was evaluated for damage after a winter to indicate potential challenges in cold, freezing conditions. The plant that performed the best based on survival and biomass production is the Longhaired sedge (*Carex comosa*). Water quality performance of the pond was compared between 2015 (pre-FTW) and 2017 (post-FTW and with established root zones). Storm size and antecedent dry days did not differ between the years. Water temperature did not differ between years but DO was lower in the post-FTW than in the time prior to FTW installation ($p=0.027$). Total nitrogen (TN) influent and effluent values were not affected. Total suspended solids (TSS) influent concentrations were consistent between years but the post-FTW period was characterized by greater TSS concentration in the effluent ($p=0.015$). Total phosphorus (TP) and total dissolved phosphorus (TDP) had variable influent concentrations between pre- and post-FTW period. As a result, those data were analyzed as a percent difference in concentration between in and out. No difference was detected in percent difference of TP or TDP between years.

Table of Contents

	Page
Executive Summary	3
1 Project Introduction	6
2 Tasks Completed	8
3 Methodology	13
4 Quality Assurance Tasks Completed.....	16
5 Deliverables Completed.....	18
6 Conclusions	30
7 References.....	31
8 Appendices	32

Table of Figures

Figure 1: Wet pond removal efficiency from CWP 2007	6
Figure 2: Automated sampler set up at the inlet structure	8
Figure 3: Plan view of FTW units in the Quarry Ridge pond	9
Figure 4: Plan view of a FTW raft pair with planting and floatation foam configuration	9
Figure 5: Cross section of a FTW unit pair as installed (showing anchoring mechanism)	10
Figure 6: Plants after delivery from wetland plant supplier	10
Figure 7: Rolls of Polyflow biological filter material being rolled and cut for installation preparation.....	11
Figure 8: FTW mats are cut to size, stacked, and foam is poured for floatation.....	11
Figure 9: Project team inserts plugs and launches FTW rafts in Spring 2016.....	12
Figure 10: Project team counts and records individuals on mats in the fall of 2016.....	12
Figure 11: Example of hydrographs of the inflow and outflow.....	14
Figure 12: Example hydrographs from storms in each study year	20
Figure 13: Plant species survival after first growth season.....	21
Figure 14: Percentage of plant individuals that survived the winter on each mat by species.	22
Figure 15: Biomass production by species' individuals.....	23
Figure 16: Comparison of <i>e. coli</i> and total coliform counts at pond outlet before and after FTW installation.....	24
Figure 17: Water temperature at the center of the Quarry Ridge stormwater pond.....	25
Figure 18: Dissolved oxygen in the center of pond by year of study.....	26
Figure 19: pH at center of pond in each study year (with and without FTW present)	26
Figure 20: Captured storms were more intense in 2015 than 2017	28
Figure 21: Influent pollutant values between pre- and post-FTW (units in y-axis are mg/L).	28
Figure 22: TSS concentration in the effluent of the pond by pre- and post-FTW period.....	29
Figure 23: TP and TDP concentration differences between year.....	30

1 Project Introduction

Wet extended detention stormwater ponds are among the most commonly employed stormwater management practice in Vermont. They are typically shallow (≤ 2.5 m), sited at low points in the landscape, and are surrounded by urban, suburban, or commercial development. Perched orifices of varying sizes control flow out of the pond during storm events, effectively retaining peak flow and providing flood protection by storing and slowly releasing water over 12-24 hours (depending on design and ecological considerations). For improved water quality, these basins are required to include a forebay - a small basin preceding the pond where influent water first settles before flowing over a spillway to the main pond. Forebays provide pretreatment and confine the bulk of sediment to an accessible area for periodic dredging of solids which extends the useful life of the pond (United States Environmental Protection Agency, 2009).

While stormwater ponds are very effective at controlling peak flow, their nutrient removal capacity is limited. The Center for Watershed Protection's 2007 National Pollutant Removal Performance Database report collated data on removal rates from 46 wet pond studies (CWP, 2007). This report (and its predecessor from 2000) have been cited in dozens of state stormwater manuals establishing pollutant removal rates for a range of practices, including retention ponds. Focusing on the median removal efficiencies, it appears that total phosphorus (TP) and the total dissolved phosphorus (TDP) being captured by ponds are similar; 52% and 64% removal, respectively. However, the spread in these data is concerning. Figure 1 shows a minimum value for soluble P removal at -64% and a maximum at 92%. This means that in some of the studies that contributed to this dataset, 1.64 times more soluble P was being exported from the ponds than was coming in to them. Interestingly, the measure for TP never dips below 12% removal. This departure between the two measures of P forms indicates that while TP consistently measures at lower concentration in the effluent than the influent, the form of P (particulate versus dissolved) changes as it moves through the ponds, leading to a loading of the dissolved form even as the total measure is consistently reduced.

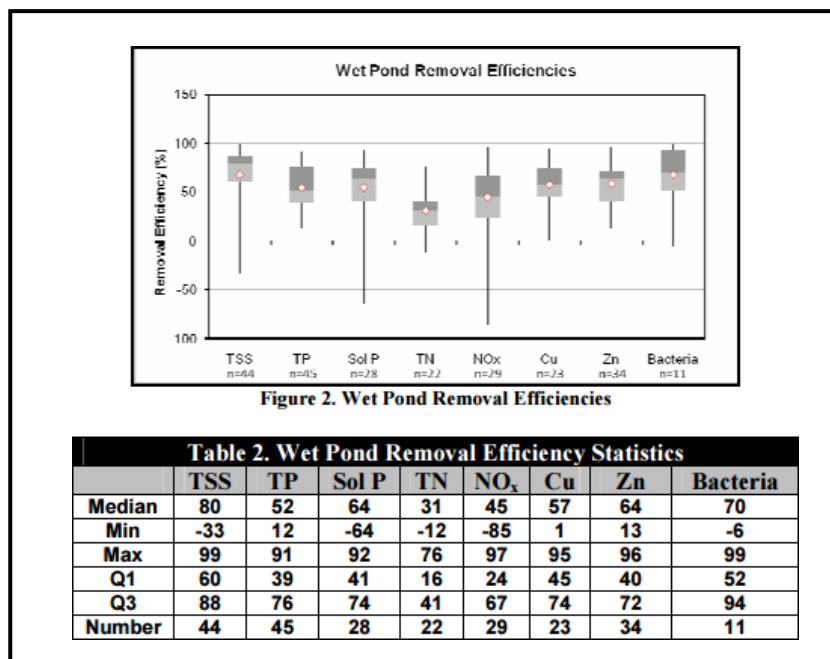


Figure 1: Wet pond removal efficiency from CWP 2007

Common Green Stormwater Infrastructural (GSI) practices including bioretention, gravel wetlands, and infiltration swales are well regarded as superior to stormwater ponds in pollutant removal performance (Ballestro, Houle, & Puls, 2016) but they lack the capacity to manage as much volume in one practice.

The use of floating mats of vegetation, known as Floating Treatment Wetlands (FTWs), as tools for pollutant uptake in natural water bodies was pioneered in the 1970s by Dr. John Todd at the Massachusetts-based New Alchemy Institute. Since his early investigations into their application, FTWs have gained popularity in other parts of the country and, in more recent years, have been proposed in three U.S. regions as a permitted best management practices to improve pollutant reduction in stormwater ponds (Winston et al., 2013). The mats float on top of the water, making them well-suited for the variable water levels in stormwater ponds. Further, their potential for improving stormwater control structures performance without the use of additional land makes them desirable in urban areas where undeveloped parcels are limited. Several mat designs are commercially available. The most common versions consist of a >6-inch thick extruded polymer filter material with marine foam inserts for floatation. Pockets are created in the surface of the material to hold plants and growth media for establishment. Plant roots grow into the water column, providing filtration and nutrient uptake.

A small number of high-quality, peer reviewed, in situ studies of FTW stormwater pond retrofits have been published (Borne, 2014; Borne, Fassman, & Tanner, 2013; Ladislav, Gérente, Chazarenc, Brisson, & Andrès, 2014; Nichols, Lucke, Drapper, & Walker, 2016; C. Wang, Sample, Day, & Grizzard, 2015; Winston et al., 2013). Their experimental foci include plant nutrient uptake (C. Y. Wang & Sample, 2014), optimal surface area coverage (Nichols et al., 2016; Winston et al., 2013), and metals removal (Borne et al., 2013; Ladislav et al., 2014). Despite the small number, these studies illuminate some important characteristics of FTW performance in stormwater ponds.

These studies informed an expert panel recommendation regarding incremental pollutant removal rates attributable to FTWs based on percent coverage of stormwater ponds in the Chesapeake Bay Watershed (Table 1).

Table 1: FTW pollutant removal crediting recommendations in Chesapeake Bay Watershed (Lane et al., 2016)

Incremental Pollutant Removal Rates for FTW Pond Retrofits					
Pollutant	Raft Coverage in Pond				
	10%	20%	30%	40%	50%
TN	0.8%	1.7%	2.5%	3.3%	4.1%
TP	1.6%	3.3%	4.9%	6.5%	8.0%
TSS	2.3%	4.7%	7.0%	9.2%	11.5%

Despite this guidance for the Chesapeake Bay region there are no published studies of FTWs focused on cold climate performance. The authors of the report recommending FTW removal rates for application in the Chesapeake Bay watershed acknowledge this and list cold weather investigations as one of five high priority research endeavors for future studies (Lane et al., 2016). Understanding FTW performance in cold climates is important for calibration purposes, but it is also critical to understand differences in maintenance operations and longevity of systems where stormwater ponds ice over for months of each year. Little is known about how FTW rafts will

perform in these conditions and whether the plants can rebound after harsh winter exposure in a frozen water column.

The focus of this investigation considers incremental pollutant removal capacity of 25% FTW coverage in a suburban stormwater pond in South Burlington, VT as well as an examination of plant species selection for winter survivability and biomass production.

South Burlington Stormwater Division staff managed equipment maintenance, provided hydraulic modelling support, automated sampling equipment use and programming expertise, as well as overall project goal setting and data visualization input. Lake Champlain Sea Grant staff managed daily operations at the study site (installing and programming equipment, changing batteries, collecting samples, operating handheld measurement equipment, and general troubleshooting), FTW design, building, and installation, as well as data management, analysis, and reporting.

2 Tasks Completed

The following tasks are associated with Project L-2015-021 and/or Project L-2017-027. Project tasks exclusively relevant to Project L-2017-027 are denoted with an asterisks*.

Evaluate site for presence of invasive species. Install and program 2 ISCO samplers (inlet and outlet), solar panel chargers, and associated probes to take flow-based samples and ongoing monitoring of pH and Temperature, turbidity, conductivity and DO

Objective: Evaluate presence/absence of invasive species and install monitoring equipment

The stormwater retention pond for the Quarry Ridge townhouse development on Juniper Drive in South Burlington, Vermont, was evaluated for presence or absence of invasive species. A catalogue of macrophytes at the site was completed and submitted to LCBP. Automated sampling units (ISCO Automatic Water Samplers) were installed at the inlet and outlet structures of the pond in the spring of each study year (2015-2017). Level probes measured water level in the structures and converted level to flow rate. Samplers were programmed to sample based on flow throughout storm events, capturing a composite sample to represent each storm.

Collect storm-based samples and monitor for: TP, TDP, TSS, TN, TKN, BOD, total coliform/E. coli

Objective: Test collected water samples over a minimum of 6 events/ year.

Samples were collected during stormwater runoff events throughout the growing season in 2015, 2016, and 2017 to measure baseline pond pollutant removal performance and evaluate differences in pond performance after the installation of FTWs. Water samples were transported to Endyne laboratory for analysis of total Phosphorus, total dissolved Phosphorus, total Nitrogen, Total Kjeldahl Nitrogen, nitrate/nitrite, and Total Suspended Solids. Biological oxygen demand was analyzed in 2015 but omitted in subsequent years due to below detect readings in the first year. Physical measurements (DO, pH, temperature, and conductivity) were measured with a handheld YSI multi-probe when storm



Figure 2: Automated sampler set up at the inlet structure

samples were collected from the pond. Grab samples were also collected at the inlet, center, and outlet of the pond and tested for total coliforms/ *E. coli* content. Screening analysis of priority pollutant 13 metals, petroleum hydrocarbons, and volatile organic compounds were run in mid-summer of 2015; all were below detection limits.

Experiment with an appropriately sized restorer and select plant species (based on outcomes of testing)

Objective: Plan FTW design and planting

The results of chemical testing in the first year indicated that metals and hydrocarbons were not pollutants of significant concern in the pond. TSS was effectively managed but TP and TDP were more variable. As a result, a focused literature review on phosphorus removal as a target for FTWs informed plant species selection. Based on published literature, the project team determined that 25% pond surface area coverage was optimal to influence pollutant removal. Furthermore, species found to be successful in other FTW applications were selected for application in Vermont: *Pondetia cordata* (pickerelweed), *Schoenoplectus tabernaemontani* (Softstem Bulrush), *Carex comosa* (Long haired Sedge), *Juncus effusus* (Common Rush). (see design drawings included in Figures 3, 4 and 5).

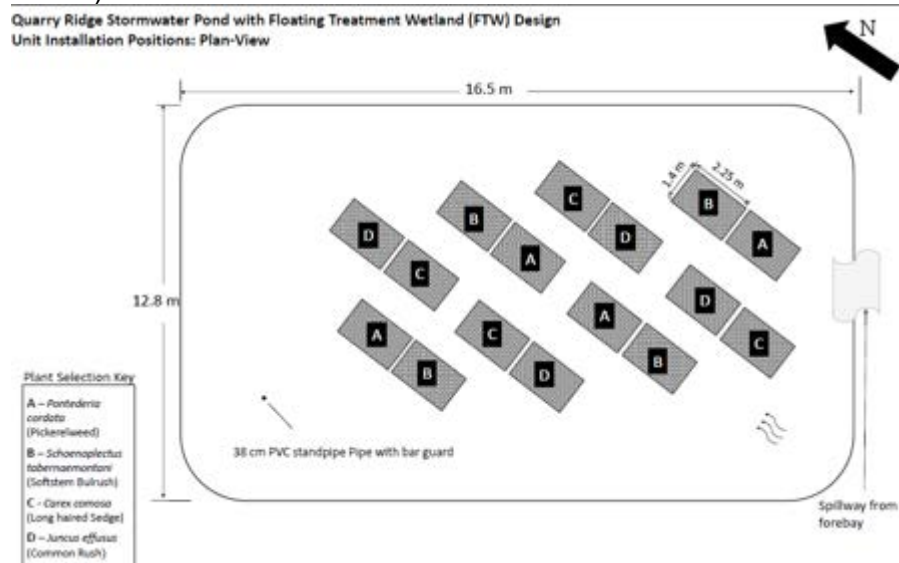


Figure 3: Plan view of FTW units in the Quarry Ridge pond

Floating Treatment Wetland Unit Layout: Plan-View

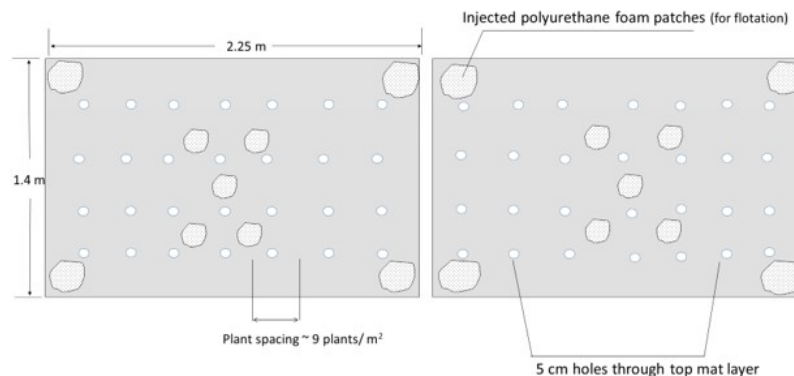


Figure 4: Plan view of a FTW raft pair with planting and floatation foam configuration

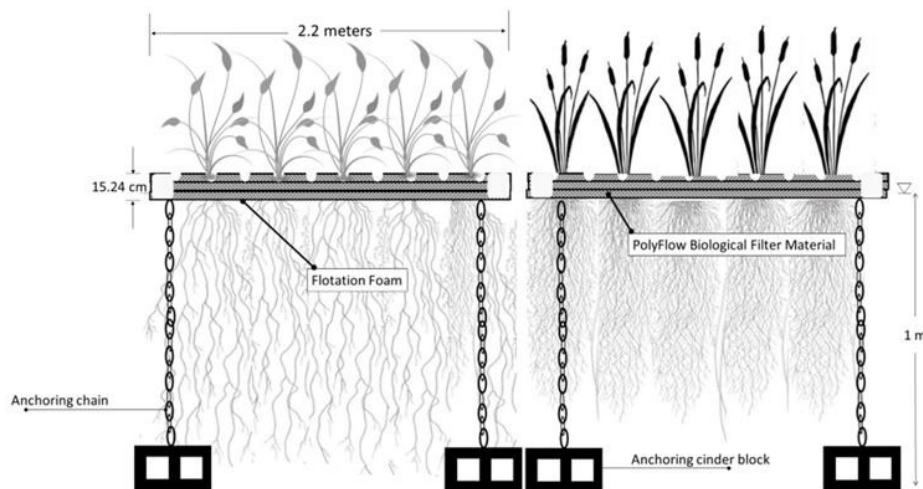


Figure 5: Cross section of a FTW unit pair as installed (showing anchoring mechanism)



Figure 6: Plants after delivery from wetland plant supplier

Obtain seeds from authorized native wetland plant dealer and grow plants in a greenhouse for use in the FTW

Objective: Grow Plants

Plants were purchased as plugs from a wetland plant supplier in Virginia to ensure high quality stock that was further along in spring growth before installation in the pond. Plugs of selected species were acclimated to local conditions for 14 days before planting in the rafts on the pond. Twenty-eight plants were installed on each mat for a total of 112 individuals of each species. A total of 448 individual plugs were planted on the rafts that were floated on the pond (Figure 6).

Assemble FTW on dry land in preparation for launch

Objective: Design/ Build Floating Treatment Wetland units

The FTW units were constructed of three layers of biological filter material and a two-part marine foam for floatation. Holes were formed in the top two layers of the mats for plant plug installation and the bottom layer was left whole to provide a floor for the seedlings to establish (Figures 7 & 8).



Figure 7: Rolls of Polyflow biological filter material being rolled and cut for installation preparation



Figure 8: FTW mats are cut to size, stacked, and foam is poured for floatation

Launch FTWs on the pond with added plants

Objective: Install FTW

In the spring of 2016, the water in the stormwater pond was drawn down to allow easier movement within the basin. Plants were inserted into the built FTW mats and they were launched onto the surface of the pond. The outflow structure was then adjusted to return the water level to its standard ponding depth (Figure 9).



Figure 9: Project team inserts plugs and launches FTW rafts in Spring 2016

***Measure and record plant and mat winter survivability**

Objective: Record conditions of mats and plants to inform replanting and repair needs

Mats and plants were evaluated for damage and survivability after the first winter (2016-2017). Species survivability was measured based on the number of individuals to sprout after winter after no modifications or management throughout the cold season (Figure 10).



Figure 10: Project team counts and records individuals on mats in the fall of 2016

***Plug replacement and mat repair (if necessary)**

Objective: Replace missing plants with new plugs and fix any ice damage to mats

One minor repair of a mat that had delaminated over the winter was addressed by refastening the layers together. Pickerelweed individuals suffered complete loss. New plugs were reordered and replanted to establish similar conditions to the previous year of summer monitoring.

Compare water quality monitoring results from “before” and “after” FTW installation

Objective: Evaluate monitoring results

The levels of pollutants, suspended solids, dissolved oxygen, and other water quality parameters from the baseline monitoring year (May-November 2015) were compared with levels after the installation of the floating restorer (May-November 2016, and May-November 2017) to determine FTW influence at reducing the target pollutants and improving water quality. Eight storms in 2015, five storms in 2016, and nine storms in 2017 were collected and analysed. Results of that analysis are given in the “results” section below.

3 Methodology

Location

The experimental site is a wet extended detention stormwater basin located in South Burlington, VT. The pond accepts runoff from a townhouse development with a total watershed area of approximately 10 acres. The pond itself is 3,000 square feet in surface area (279 square meters). The pond serves a peak flow control function as well as the associated water quality credited to stormwater ponds in the state of Vermont. The pond discharges to Centennial Brook – a waterway impaired due to uncontrolled stormwater runoff from developed lands within its watershed

FTW Design and installation

FTW mat units were constructed with three layers of PolyFlow biological filter material with a two-part marine foam for flotation. Each FTW mat is 2.25 m x 1.4 m. Installed in the spring of 2016, total FTW area coverage in the pond is 50.4 m² on a 211 m² pond (~25% surface coverage). Mat installation required anchoring units to the bottom of the pond (and to each other in pairs) using concrete cinder blocks (see Figure 3). The length of anchoring rope allowed for vertical movement as water levels adjust during storm events but prevented excess lateral movement that could alter raft placement within the pond.

Plant species were selected based on precedent in the scientific literature (Borne et al., 2013; Headley & Tanner, 2006; Ladislav et al., 2014) to include *Pondetia cordata* (pickerelweed), *Schoenoplectus tabernaemontani* (Softstem Bulrush), *Carex comosa* (Long haired Sedge), and *Juncus effusus* (Common Rush). A total of 448 individual plant plugs were installed on the pond (112 per species, 28 individuals per mat, and 4 mats per species).

Pond Hydrographs

Hydraulic performance of the pond was measured at the inflow and outflow structures using automated sampling equipment (ISCO 6712 auto sampling units). ISCO 720 submerged probe flow modules (Lincoln, NE, USA) were installed in the inflow and outflow structures of the pond. These sensors measure differential pressure of the overlying water column to determine level and the attached automated sampling units (ISCO 6712) convert the level measurement to flow using Manning's equation with programmed values of pipe diameter, material, and slope (Manning, 1891). Levels at the inflow and outflow structures of the pond were converted to flow and the data were downloaded from the samplers after each captured rain event. The downloaded tabular data was converted to flow graphs using Microsoft Excel 16 to display influent and effluent flow rates over time as well as the timing of sample collection along each hydrograph (as seen in Figure 11 below).

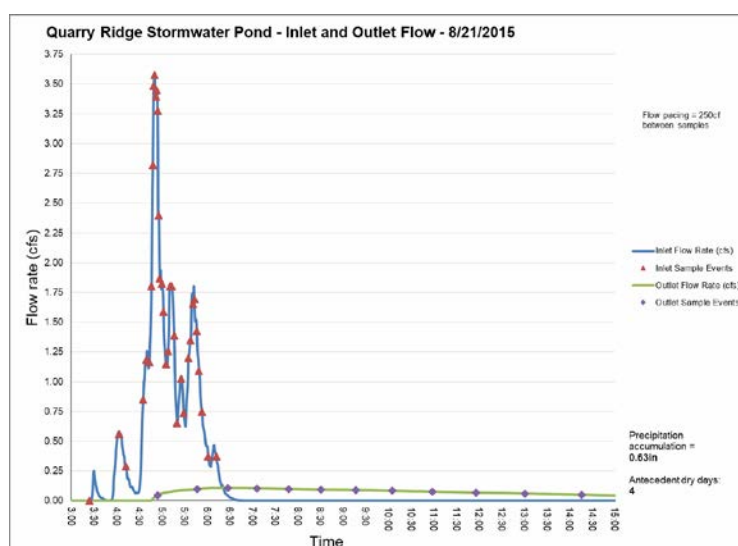


Figure 11: Example of hydrographs of the inflow (blue line) and outflow (green line) from the test pond.

Storm Event Sampling

Automated sampling units were programmed to collect composite, flow-weighted samples throughout storms. After a specified volume entered or exited the pond, the sampling unit collected a 200 mL sample, which was then composited into a storage container within the unit. The volume of flow between samples was adjusted based on predicted storm volume and intensity with a goal of sampling throughout an entire storm event. Samples were collected within six hours of stopped flow and sub-sampled according to EPA protocols, preserved, put on ice and immediately transported to Endyne Laboratories in Williston, VT for processing. Table 1 includes sampling, hold, and transport details for each analyte. (Detailed specific laboratory protocols and procedures can be found here: <http://www.endynelabs.com/statqual.htm0>).

Storm Event Data Analysis

It is common for stormwater control structure performance to be analyzed based on Mass Removal Efficiency (MRE).

$$\text{MRE} = 1 - (\text{M}_e / \text{M}_i) * 100\%$$

Where:

M_e = Mass of pollutant in effluent [concentration of pollutant in effluent (mg/L) * total volume IN (L)]

M_i = Mass of pollutant in influent [concentration of pollutant in influent (mg/L) * total volume OUT (L)]

Determining MRE requires an accurate measurement of volume into and out of a system. This study had intended to analyze these data using the same convention. However, after collecting and exploring the data, the study team noticed a problem with this approach for a study of FTW over multiple years and on the same pond. Ponds themselves remove pollutants through settling and biological transformations. They also remove volume – particularly during long dry periods between rain events or when ambient temperatures are high, and evaporation leads to a reduction of volume in the pond. When this happens, the volume of water entering the pond is greater than the volume leaving it. In this case, if the concentration of a pollutant did not change from inlet to outlet but the volume of water was reduced by half, the MRE would indicate a 50% removal of the pollutant. While that is accurate, it does not reflect or isolate the particular influence of the FTW units. Because the year when pre-FTW (base condition) data was collected was characterized by cool wet conditions and the subsequent years (post FTW installation) were much drier and warmer, the influence of evaporative volume reduction from the pond after the FTW was installed may have been greater. Hence, in that year, the MRE of the pond could have been improved simply

due to evaporation and not because of the FTW. Comparing water quality measures as concentration (versus mass) eliminates this potential error from the analysis and reduces the chance of a type I error – falsely rejecting the null hypothesis due to overestimation of FTW performance as a result of factors unrelated to the addition of the FTW. So, for analysis of pollutant removal data given flow composited samples, this report uses concentration rather than load to account for this variable. The project team acknowledges that this is a departure from the original project plan but believe that loading data analysis results in erroneous conclusions. To accommodate the original proposal, focus on comparison of loads, those data are also displayed in the results section in a table alongside the concentration measures (Table 3).

E. coli and total coliforms

Grab samples were taken at the inlet and outlet structures following storm events using the automated samplers to pull 100 mL into sterile plastic bottles. Center of pond samples were taken following EPA standard methods with a sterile plastic bottle affixed to an extended sampler handle for reaching the centre of the pond. All samples were taken in duplicate. Samples were put on ice for immediate transfer to the UVM lab for processing. IDEXX Colilert bacterial analysis methods can be found here: <http://www.tceq.state.tx.us/assets/public/policy/ta/crp/QA/bactQA3.pdf>.

DO/temperature/pH/conductivity

A handheld YSI Pro DSS multiprobe unit was used to measure water column DO, temperature, pH, and conductivity. Regular calibration to factory standards ensured consistency. An upgraded probe (with optical DO measurement technology) was purchased in year three of the study for improved measurement accuracy.

Table 2: Storage and transport methods by analyte

Analyte	Storage in field/transport	Storage or preservation in lab	Container type, volume, storage conditions
Total dissolved phosphorus (TDP)	10 L rinsed sterile sampler bottle from Isco decanted into sterile Endyne Lab bottle. Transported on ice in cooler (within 10 hours of collection)	Standard sample refrigeration @ Endyne Labs	-8 oz glass (sample size total for TDP & TP) -48 hours -Stored under refrigeration
Total Kjeldahl nitrogen (TKN)	10 L rinsed sterile sampler bottle from Isco decanted into sterile Endyne Lab bottle. Transported on ice in cooler (within 10 hours of collection)	Standard sample refrigeration @ Endyne Labs	-16 oz plastic with H ₂ SO ₄ -28 days -Stored under refrigeration
Nitrate (NO ₃ ⁻) - Total nitrogen (TN)	10 L rinsed sterile sampler bottle from Isco decanted into sterile Endyne Lab bottle. Transported on ice in cooler (within 10 hours of collection)	Standard sample refrigeration @ Endyne Labs	-2 oz plastic (TKN, nitrate and nitrite) -48 hours -Stored under refrigeration
Total phosphorus (TP)	10 L rinsed sterile sampler bottle from Isco decanted into sterile Endyne Lab bottle. Transported on ice	Standard sample refrigeration @ Endyne Labs	-8 oz glass (sample size total for TDP & TP) -48 hours -Stored under refrigeration

	in cooler (within 10 hours of collection)		
Total suspended solids (TSS)	10 L rinsed sterile sampler bottle from Isco decanted into sterile Endyne Lab bottle. Transported on ice in cooler (within 10 hours of collection)	Standard sample refrigeration @ Endyne Labs	-½ gallon plastic (sample size total for BOD and TSS) -7 days -Stored under refrigeration
pH/ Temperature/ Conductivity/ Dissolved oxygen (DO)	NA (measurements taken in field with YSI handheld multiparameter probe)	NA	NA
Total Coliform/ <i>Escherichia coli</i>	Samples collected in sterile 100 mL plastic bottles, capped, placed in cooler with ice, and transported to lab for analysis within 5 hours	Refrigeration. No long-term storage. Processed in UVM lab.	-100 mL sterile plastic -6 hours -stored in dark under refrigeration

Macrophyte biomass

Four plant individuals from each mat were selected via stratified random sampling methods for destructive late season collection in 2016. Portions of the plant located above the roots (leaves, stems, and flowers) were harvested by cutting at the surface of the mat. Plant samples were kept separate by species and mat location and transported to the lab in sealed plastic bags on ice. Plant tissue was oven-dried at 80 degrees for 24 hours (Kalra, 1998) in a UVM lab facility. Dry weight of individuals by species was averaged to represent the biomass by plant type.

Overwintering survivability

Plants were counted at the end of the first summer season and then left in the stormwater pond over winter. After the spring melt, mats and plant material were evaluated and mat condition was recorded in field logs. Plant survivability and regrowth were determined by a count of the number of sprouted individuals on each mat and comparison to pre-winter numbers.

Statistics

All data were tested for normality using the Shapiro Wilk test. Normally distributed plant data were analyzed using ANOVA followed by t-test with Bonferoni correction. Non-normally distributed data were compared by Kruskal Wallis followed by Mann Whitney U test. Because water quality data analysis involves a comparison between just two time periods (pre- and post-FTW), those data were analyzed using either two-tailed students t-test (where they are normally distributed) or Mann Whitney U test where they follow a non-normal distribution. All statistical tests were done using XLStat 2018 (an MS Excel 2016 plugin).

4 Quality Assurance Tasks Completed

****For projects with approved QAPPs only ****

This project aimed to provide accurate water quality data. To ensure data accuracy the collection, storage, sample analysis, and documentation standards were followed at every point in the project. For water quality measures that took place in the field, devices were calibrated regularly following manufacturer's recommendations.

Record keeping: A detailed field notebook was kept throughout the project period, cataloguing every change in sampler programming, battery replacement, and maintenance and sampling events. Digital versions of all field notes were also kept (see Appendix I).

Decontamination/ Invasive species spread prevention: Between sampling events, the Isco samplers were rinsed 3-4 times with deionized (DI) water and samplers were kept on site through the season. After each season, samplers were decontaminated using QUAT-128 in a vehicle washing facility in South Burlington. Waders and other materials entering the pond were cleaned with QUAT-128 before and after use as a cautionary measure to prevent the potential spread of invasive species. The YSI probe was rinsed with DI water and thoroughly dried between uses and stored in a lab according to manufacturer's directions. Grab sample containers for collection of samples for bacterial analysis were single-use sterile plastic 100 mL containers (which were discarded according to laboratory protocols after use).

Flow: Continuous level measurements were taken and converted to flow at the inlet and outlet structures of the pond using Isco brand sampler units. Flow data was downloaded from the units after each storm event, graphed, and composited with antecedent dry period information and the programmed flow rate between samples (see Appendix II for all hydrographs).

Water quality sampling and analysis: Flow composite samples were taken using automated samplers at the inlet and outlet of the Quarry Ridge Stormwater pond in South Burlington, VT (Lat: 44.47394, Long: -73.17678). Those samples were analyzed by Endyne Laboratory in Williston for TP, TDP, TN, TKN, nitrate and nitrite, and total suspended solids (TSS). In 2015, biological oxygen demand (BOD) was also measured, but due to multiple results below detection limits it was removed from the monitoring plan in future years. A single metals and hydrocarbon screen was also performed. This analysis also resulted in below detection limit results, so no additional metals and hydrocarbon sampling were conducted. All samples sent to the laboratory for analysis were submitted with completed chain of custody forms. Lab results were received in digital format via email to Becky Tharp (LCSG) and Tom Dipietro (S. Burlington). Lab results were entered into Microsoft Excel spreadsheets (see Appendix III) by Lake Champlain Sea Grant staff and stored on a UVM server. Concentration results were converted to mass loading calculations by multiplying total volume in (or out) by the concentration in the sample. This information was also stored in a spreadsheet of water quality results. Physical water measurements (DO, pH, conductivity, and temperature) were taken with a YSI Pro Plus handheld unit. (YSI Probe User Manual:

<http://www.ysi.com/media/pdfs/605596-YSI-ProPlus-User-Manual-RevD.pdf>)

Number and Frequency of QA Samples

Endyne Lab in Williston, VT follows the following guidelines for QA.

- Analysis of independent QC standards every 10 samples and continued charting of this data to define method precision and accuracy.
- Monthly performance of intra-laboratory performance tests.
- Duplicate laboratory analyses every 20 samples.
- Analysis of matrix spike samples every 20 samples.
- Analysis of laboratory blanks every 20 samples.

A complete list of Endyne QA/QC procedures including corrective actions and data acceptability criteria can be found here: <http://www.endynelabs.com/statqual.htm>

Total Coliforms and E. coli were measured from grab samples at the inlet, center of the pond, and outlet after rain events. All samples were taken in duplicate, labeled with date, time, and location

information, and transported on ice for immediate measurement in a lab on UVM campus using IDEXX Colilert methods. Measurement methods followed the

Colilert QA procedures found here:

<http://www.tceq.state.tx.us/assets/public/policy/ta/crp/QA/bactQA3.pdf>

Corrective Actions: Early in 2015, there were a number of storm event samples that did not result in usable data (either due to laboratory errors in setting detection limit or lack of quality of the captured storm). These problems were identified early and addressed through discussions with Endyne scientists. Appropriate standards and dilution expectations were adjusted at the lab to reflect the given the source water and improved sampler programming improved sample quality.

This project complies with our signed QAPP.

5 Deliverables Completed

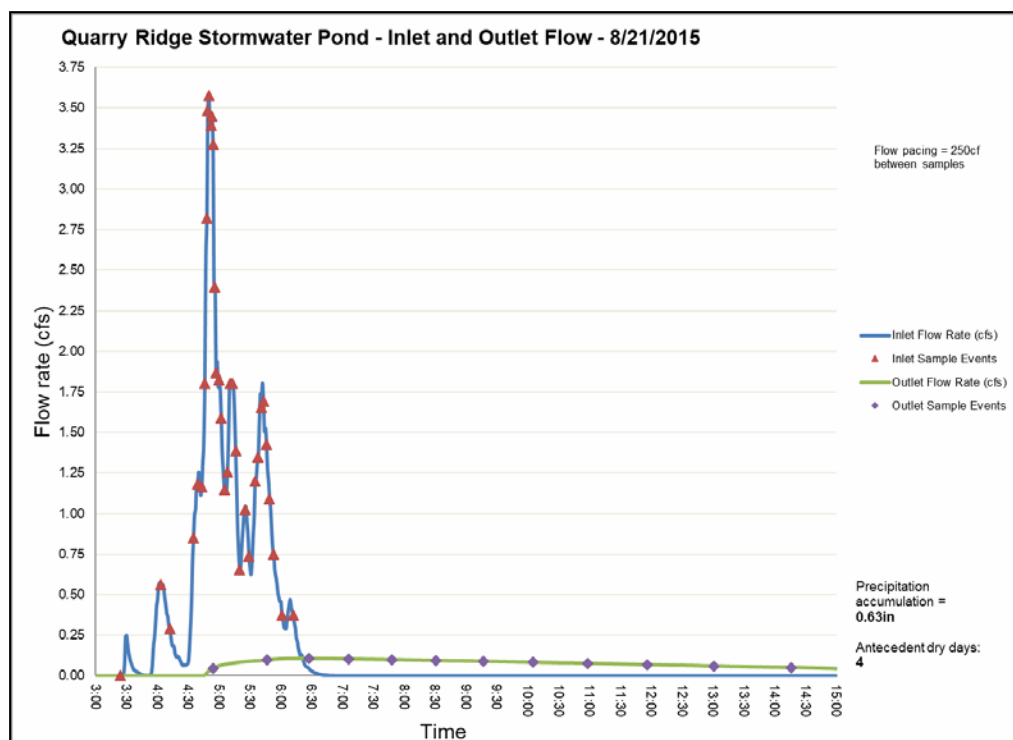
Table 3: List of project deliverables and dates of completion (* indicates tasks that only apply to project L-2017-027. Highlighted rows indicate related data analysis results below.)

Objective	Task Title	Deliverable	Date Completed
QAPP Approval	Describe quality assurance procedures that will maintain project performance.	Approved QAPP	April 2015
Install monitoring equipment	Evaluate site for presence of invasive species. Install and program 2 Isco samplers (inlet and outlet), solar panel chargers, and associated probes to take flow-based samples and ongoing monitoring of pH and Temperature, turbidity, conductivity and DO	Flow and sampling information (field datasheets)	May 2015 May 2016 May 2017
Test collected water samples over a minimum of 6 events/ year.	Collect samples regularly. Have samples tested for: TP, TDP, TSS, TN, TKN, BOD, total coliform/ <i>E. coli</i>	Testing results from the lab	May - Oct 2015 May - Oct 2016 May - Oct 2017
Design FTW	Experiment with an appropriately sized FTW and plan plant species (based on outcomes of testing)	Finalizes FTW Design drawings	January 2016
Build and install FTW	Assemble FTW on dry land, plant with plugs, and launch on pond	Installed FTW	May 2016
*Record mat and plant conditions	Measure and record plant and mat winter survivability	Mat conditions data sheet	May 2017
*Replace missing plants with new plugs and fix any ice damage to mats	Plug replacement and mat repair (if necessary)	Photos of repaired mats	June 2017

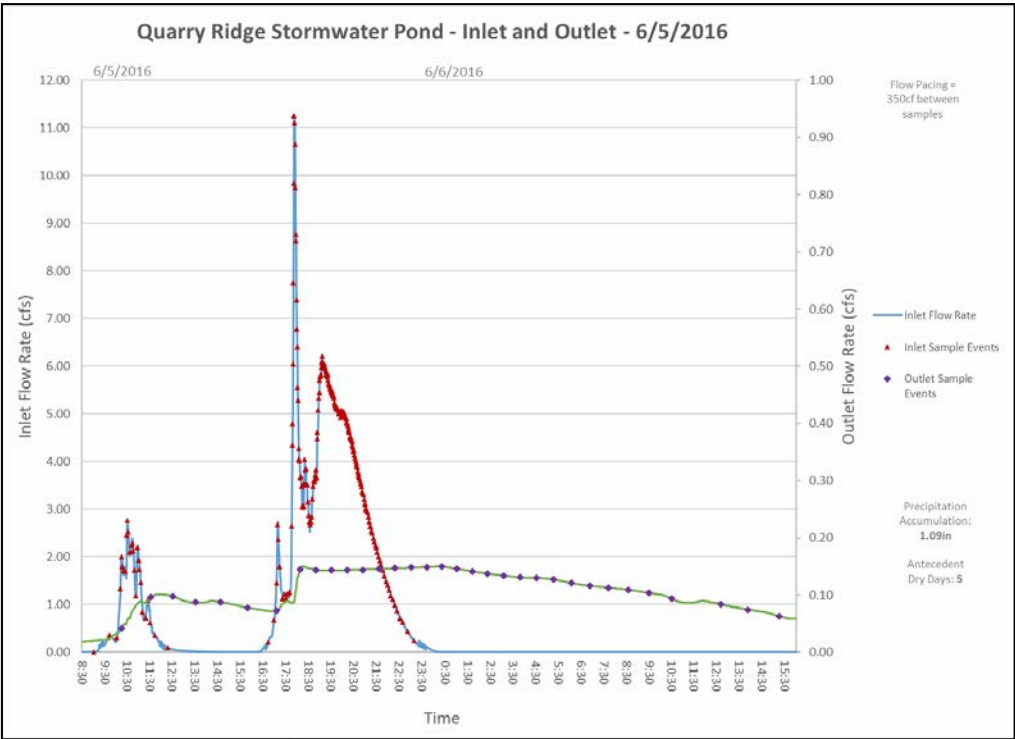
Evaluate monitoring results	Compare WQ monitoring results from “before” and “after” restorer installation	Data evaluation results	December 2017
Final Report	Create final report combining all of the gathered information, outcomes, implications, supporting research, etc.	Report document	December 2017

Flow results

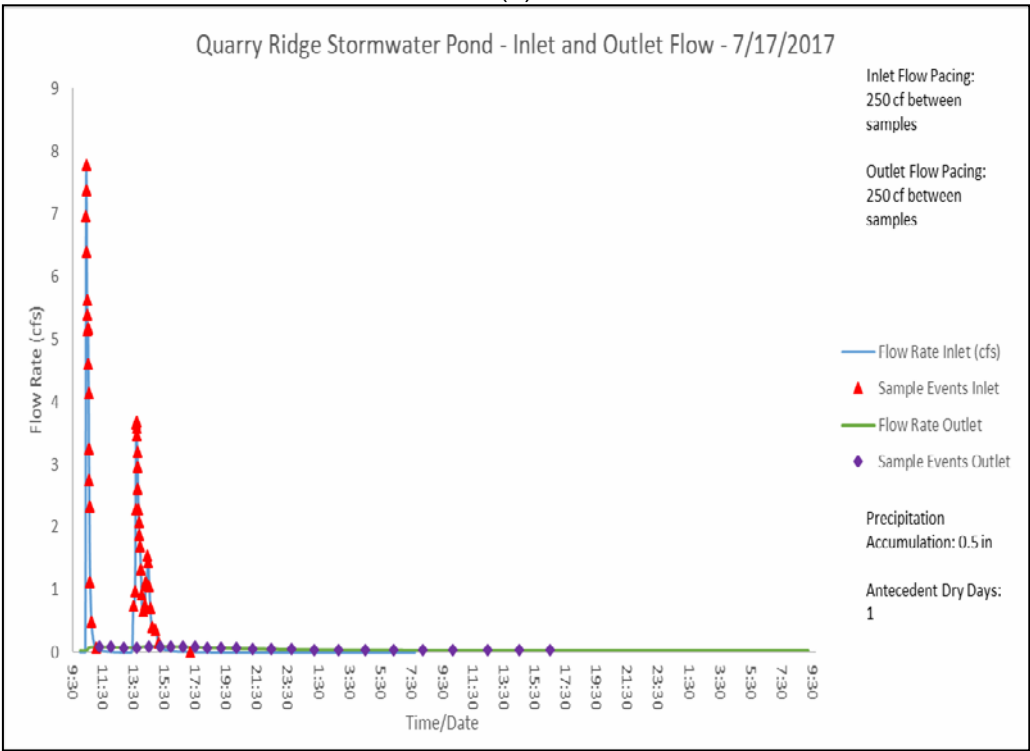
The Quarry Ridge pond is a wet extended detention pond. As such, its primary design objective is peak flow attenuation. The pond is highly successful at achieving this goal – irrespective of FTW installation. Hydrographs from storms in each year are illustrated in Figure 12 a-c.



(a)



(b)



(c)

Figure 12: Example hydrographs from storms in each study year: a.) 2015, b.) 2016, c.) 2017

Hydrographs from every storm included in the study are in Appendix II.

Plant survivability and biomass

The four species selected for trial in the FTW setting were evaluated based on survival and individual shoot biomass production over the first growing season. Their ability to survive winter in the FTWs was also evaluated. *Pondetaria cordata* (pickerelweed), *Schoenoplectus tabernaemontani* (Softstem Bulrush), *Carex comosa* (Long haired Sedge), *Juncus effusus* (Common Rush) were selected based on their presence in the FTW literature from other regions and their native status in wetlands in Vermont.

Evaluation of plant survival over a growing season indicates a plant's suitability for life in the conditions of a FTW on a stormwater pond in Vermont. After the first growing season, surviving plants were counted by species and mat location and compared to the total number planted at the beginning of the season. No effect of mat location (in relation to inlet or outlet) was noted to impact survivability. While pickerelweed suffered significant losses (78%) other plants lost modest numbers that are in keeping with expected fatalities from establishment (Figure 13).

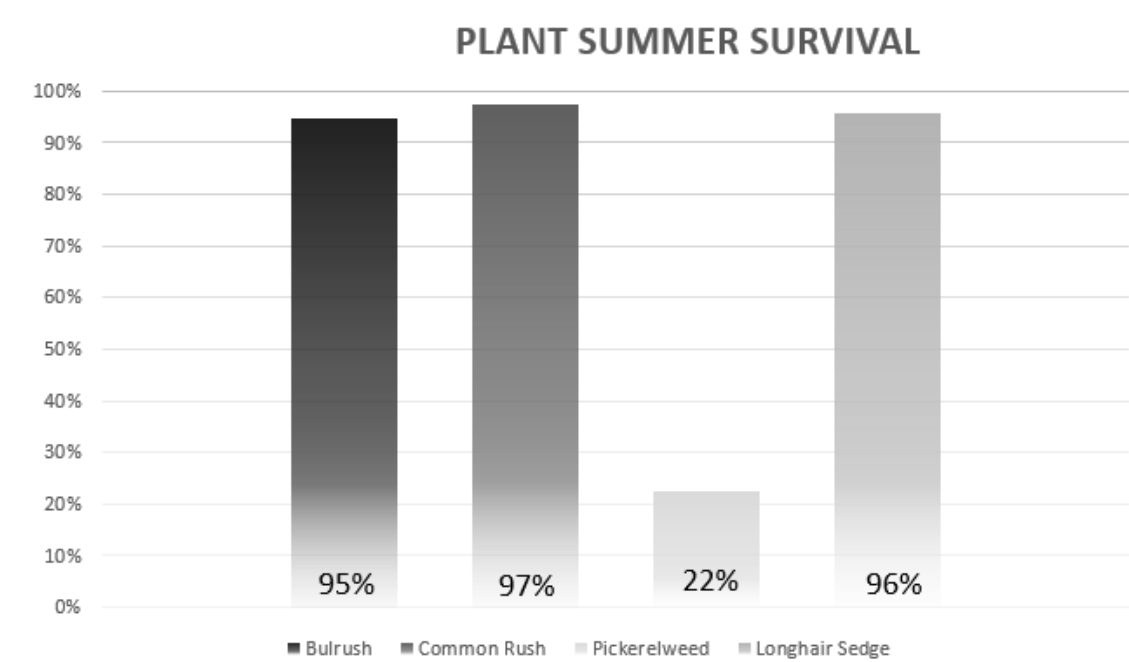


Figure 13: Plant species survival after first growth season. Data were collected by counting surviving individuals on each mat and averaging percent survival by species (mats/ species = 4). Data indicate that all species survived summer conditions well except Pickerelweed which suffered significant die off.

Pickerelweed's losses could be attributed to establishment of the plugs early in the season (May) for a species that typically emerge from a tuber later in the year in Vermont. The cold conditions coupled with plug installation in submerged conditions lacking the insulating properties of wetland soils (which this species prefers) may have contributed to its failure. Other species survived summer conditions on the pond well, with losses ranging from 3-5%.

After the winter of 2016-2017, plants were counted again based on spring emergence and compared to the number of living individuals prior to winter dormancy. The results from that analysis are below (Figure 14).

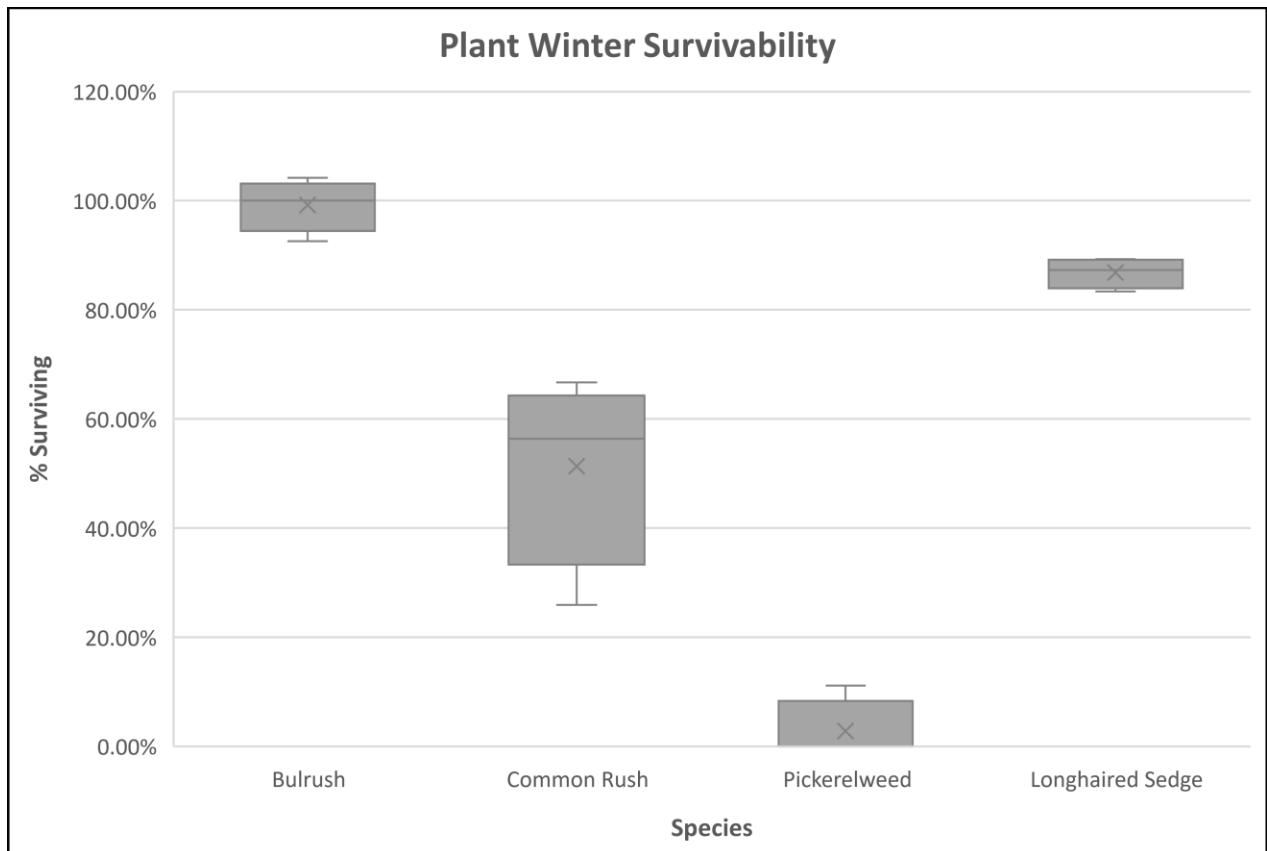


Figure 14: Percentage of plant individuals that survived the winter on each mat by species (4 mats/species). Data were analyzed for differences using Kruskal Wallis followed by Mann Whitney U test. Results indicate Pickerelweed's performance differed from the other species over wintering ($p < 0.05$).

Winter survival analysis indicates a near complete loss of the few pickerelweed individuals that remained at the beginning of the winter season. There was a complete resurgence of the bulrush species and no individual plants were lost. Note that the bulrush data found a greater than 100% winter survival. The research team is unsure if this is a result of a counting error in the fall of 2016 that may have failed to include a plant in the analysis or the regrowth of an individual that had not been visible after the previous growth season. In either case, bulrush and longhair sedge were the most robust plant species in terms of winter survival.

An assessment of biomass production by species gives information regarding which plant type grows the most above-mat biomass and is therefore likely to be more robust to environmental stressors, take up more nutrients, and potentially grow larger root zones. Larger root zones are typically associated with improved particle entrapment and filtration. During the sampling event, a volunteer species was found present in significant numbers on most mats. *Bidens vulgata* is a native species in the daisy family, grows tall woody stems, and multiple small flowers. Seeds germinated and took root on the mats and grew to significant size. As a result of their robust growth, they were included in the biomass analysis in order to characterize the potential significance of their presence and suitability for use in FTW installations. The results of the biomass assessment are below (Figure 15).

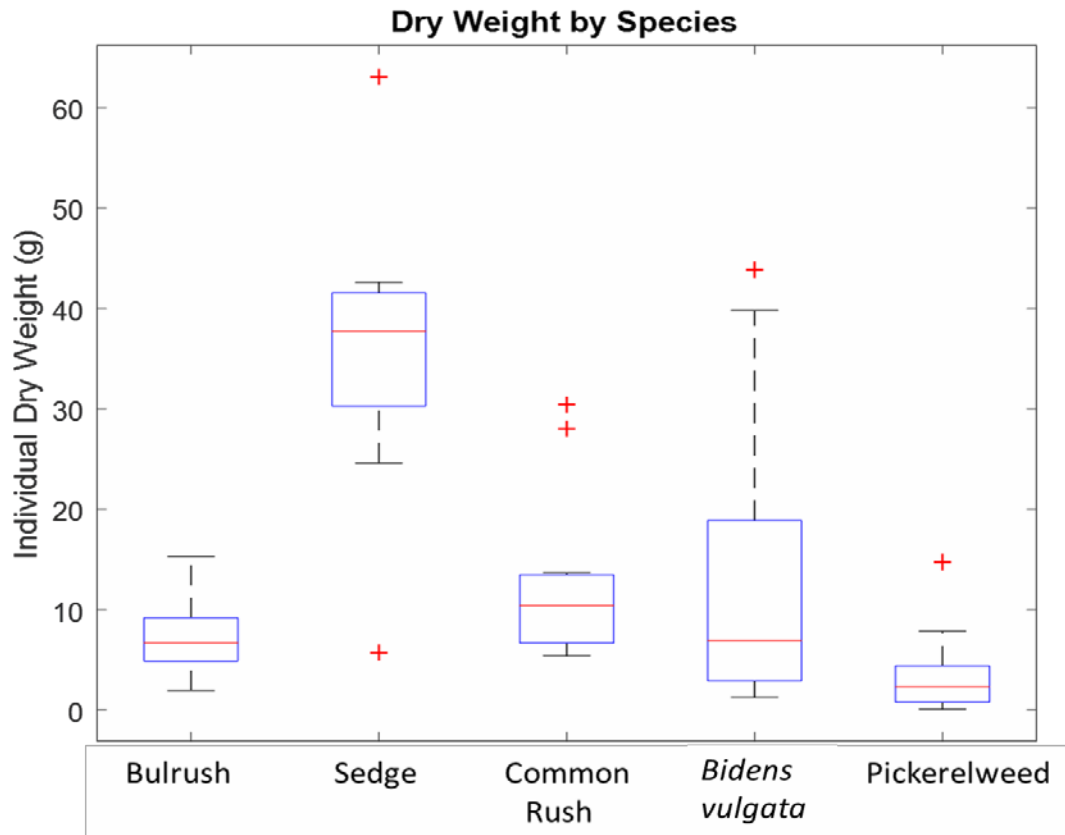


Figure 15: Biomass production by species' individuals ($n=12$ for planted species and $n=28$). Kruskal Wallis followed by Mann Whitney u-test with indicates significant difference between sedge and all other species ($p<0.001$). Pickerelweed was found to result in the lowest biomass production compared to all others ($p<0.01$). *Bidens vulgata* is a weed species that grew on most mats without being planted. It was harvested and analyzed to indicate its potential role as a vegetation choice on FTW in the Northeast. Collected samples indicate a large range of weight between individuals, likely due to the variable age and size because of germination from seed on the mats.

Water quality results

Bacterial colony counts

The bacterial data resulted in no difference between pre- and post-FTW years for *e. coli* or total coliform counts (though the range of total coliform counts at the outlet trended towards fewer colonies after FTW installation.) The influence of temperature, solar intensity, and number and size of storm events could be major factors influencing bacteria entering the pond. Concurrent sampling of side-by-side basins with and without FTW could clarify if the FTW had no influence on this metric or if this effect was impossible to see due to weather condition differences between years (Figure 16).

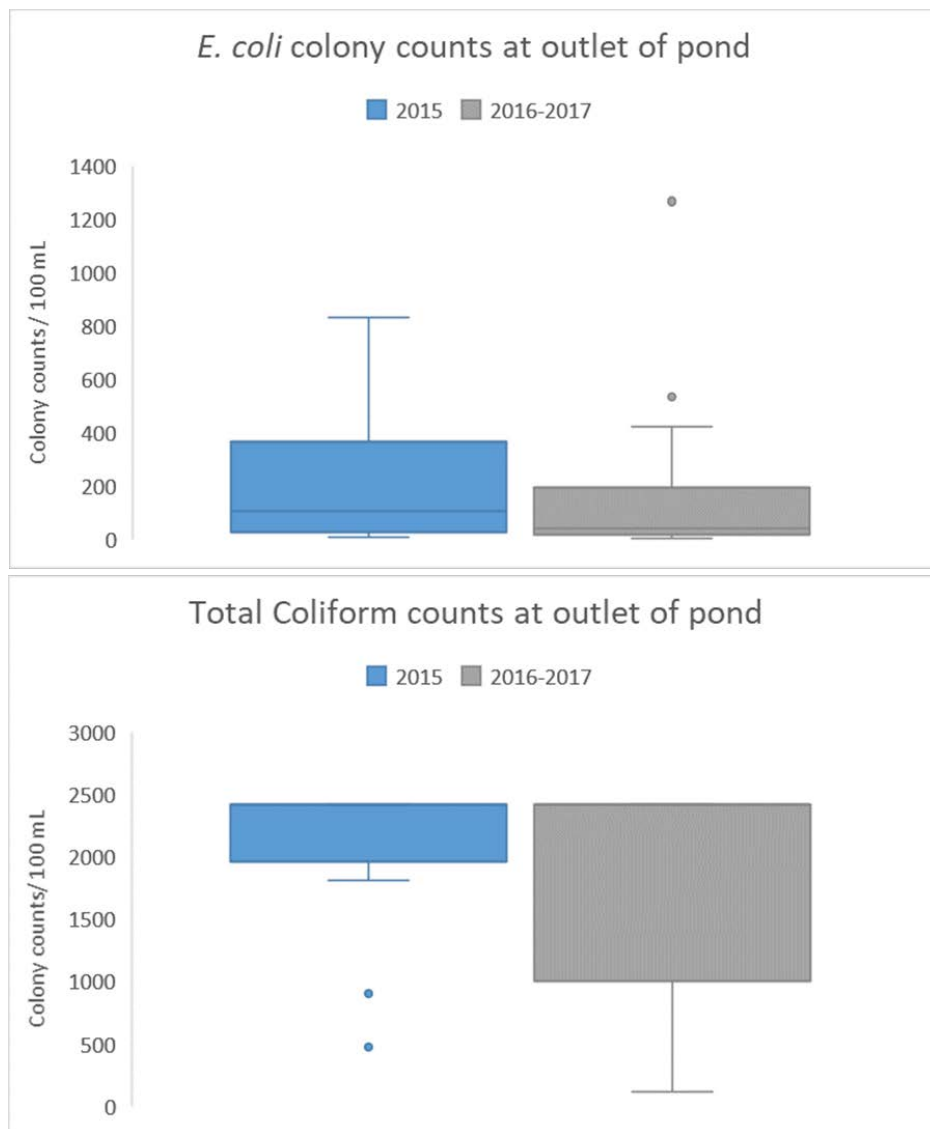


Figure 16: Comparison of *e. coli* and total coliform counts at pond outlet before and after FTW installation. n=12 for 2015, n=17 for 2016-2017. The box indicates the interquartile range. The line within the box indicates the median of the dataset. Coliform graphs are skewed so that the median is at the top of the box (2419.6 colonies/ 100 mL).

Temperature/ DO/ pH

No differences in water temperature at the center of the pond were detected between years. To definitively determine an influence by FTW on pond water temperature, concurrent side-by-side analysis of basins with and without FTWs is necessary as there are confounding factors at play over the course of a multi-year study that are impossible to control for (Figure 17).

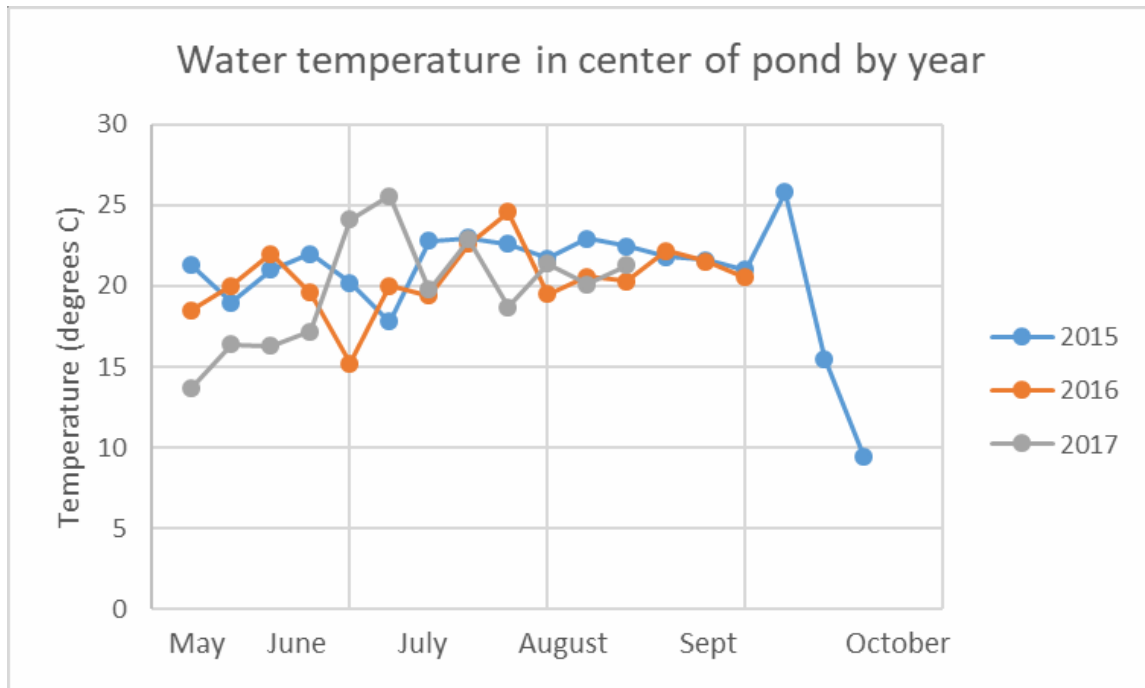


Figure 17: Water temperature at the center of the Quarry Ridge stormwater pond in each year of the study.

Dissolved oxygen was measured in the pond to track the potential for depressed levels as a result of FTW mats reducing fetch and reducing turnover of water in the water column (Lane et al., 2016). Our data show many instances of lower dissolved oxygen levels in the post FTW years as compared to pre-FTW installation. Overall, DO levels in the pond were lower in the post-FTW period than prior to FTW installation (2015) ($p=0.027$). This is a concerning trend as the presence of oxygen influence microbial respiration and the behavior of species bound to redox-sensitive compounds (ie. Fe) (Figure 18).

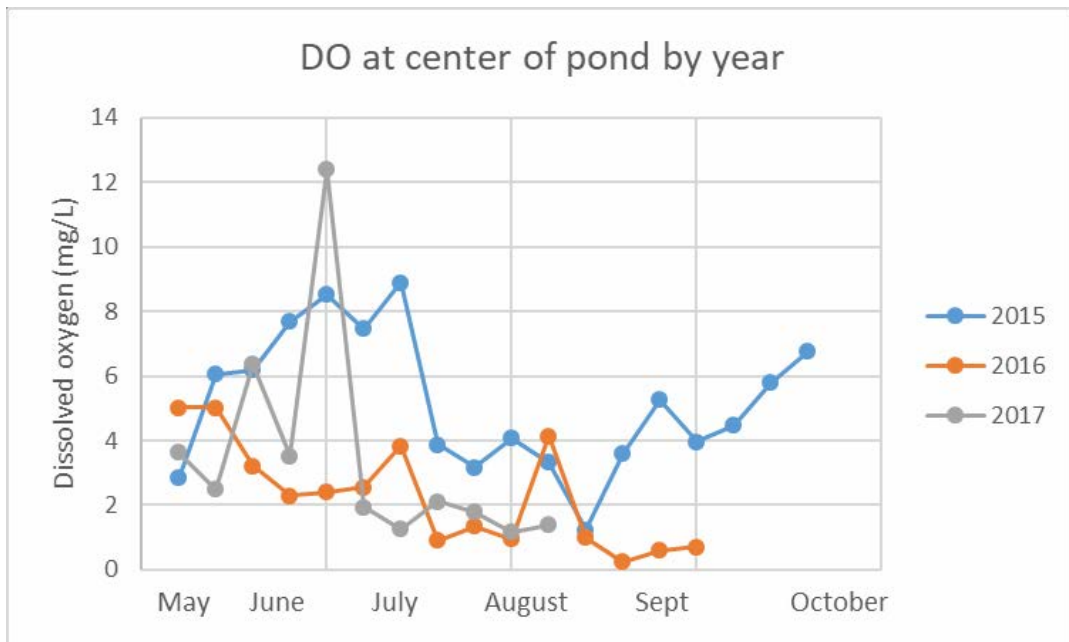


Figure 18: Dissolved oxygen in the center of pond by year of study (2015 is pre-FTW and 2016 and 2017 are post-FTW)

The pH at the center of the pond fluctuated throughout the year and is slightly lower overall in the years with the FTW installed (Figure 19). The direction of the pH change is surprising, as the addition of plants, which take up CO_2 from the water and respire O_2 , is associated with a slight increase in pH of water. This opposite effect may be a result of the FTW replacing floating submerged aquatic plant species that were shaded and could not compete. Chara, a type observed in abundance throughout the Quarry Ridge pond in 2015, is associated with calcium nodules in the plant cells. An abundance of this species in a pond may cause an increase in pH due to the calcium cation providing charge balance to buffer against increasing acidic conditions. Hence, where FTW displace a species that would otherwise be present, unexpected influences on pond water quality are possible.

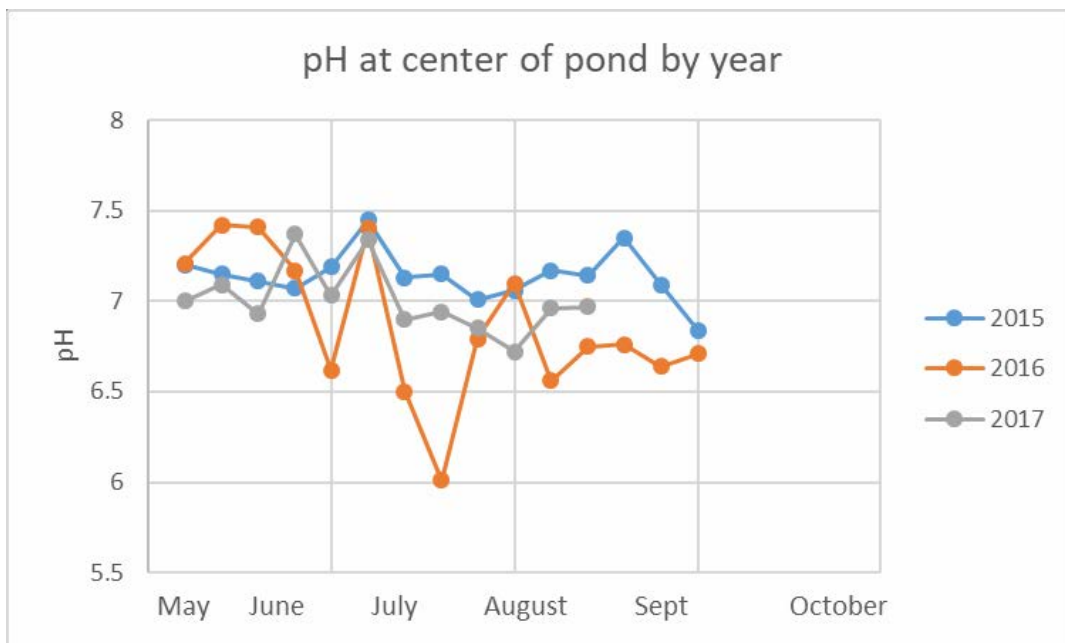


Figure 19: pH at center of pond in each study year (with and without FTW present)

Composite water quality (TSS, N, and P removal)

Concentration and loading of nitrogen, phosphorus (total and dissolved), and total suspended solids was measured for eight storms in 2015, five storms in 2016, and nine storms in 2017. One storm in 2017 was eliminated from analysis due to incomplete sampling throughout the full storm duration.

Percent difference in concentration was calculated by:

$$\% \text{ Concentration Difference} = ((\text{Concentration}_{\text{in}} - \text{Concentration}_{\text{out}}) / (\text{Concentration}_{\text{in}})) * 100.$$

Previous FTW studies included a plant establishment period prior to water quality analysis. In this study we began monitoring immediately following installation in 2016. The 2016 season was much drier than 2015 or 2017 (Table 3). Due to the different weather conditions and the fact that the plants were establishing throughout the 2016 season, the influent and effluent water quality data that follow compare 2015 and 2017 as the pre- and post-FTW periods. A total of 8 storms in each year (2015 & 2017) serve as the basis for pond performance comparison.

Table 4: Weather conditions during each study year. The dry conditions in 2016 coupled with the fact that the FTW plants were establishing in this period lead to the removal of those storm data from analysis. 2015 and 2017 storm events are analyzed as pre- and post-FTW periods. Eight storms in pre- and post-FTW period served as basis for the analysis.

	2015	2016	2017
Min temp (°C)	24	23	22
Avg temp (°C)	28	29	28
Max temp (°C)	34	36	33
Total Rain Fall (cm)	5.2	3.7	4.5
Avg antecedent dry days for collected storm events	2	4	2

Antecedent dry days preceding captured storms and storm size (depth) were compared between years to determine if conditions of the tested water samples varied. Both were found not to differ between years. Storm intensity can influence pollutant transport, as rainfall over a short period of time can result in erosive forces along the ground surface. To account for potential influence of that factor, storm intensity was calculated by:

$$\text{Storm intensity} = \text{Storm Depth (cm)} / \text{Storm Duration (hours)}$$

Storm intensity did differ between 2015 and 2017 (Figure 20). Sampled storms in 2015 were less intense than in 2017 ($p=0.008$).

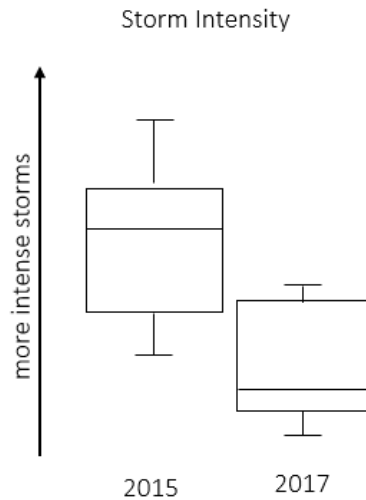


Figure 20: Captured storms were more intense in 2015 than 2017 ($p=0.008$) as determined by Mann Whitney U test.

As a result of increased storm intensity in 2015, we would expect to see higher influent particulate pollutant loading. However, other factors will influence this, including volume of built up sediments on roadways and particle size distribution of stored sediments in catch basins.

Influent concentrations of each pollutant were compared by year to determine variability in influent water quality and inform methodology for the determination of pond performance in differing influent conditions.

Both TN and TSS influent concentration distributions were the same between years (as measured by Mann-Whitney U test). TP and TDP influent concentrations are non-normally distributed and differ between years (Figure 21). There was more TP and TDP coming in to the pond in 2017 than 2015 ($p=0.035$, 0.037 respectively).

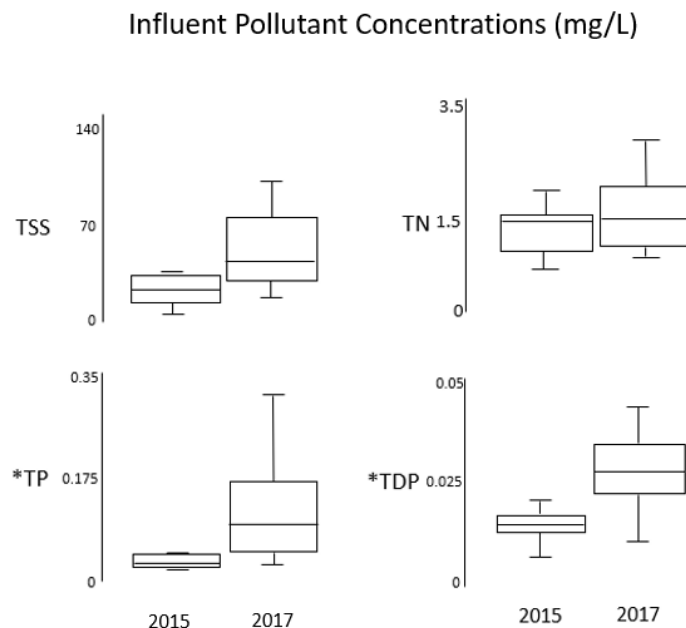


Figure 21: Influent pollutant values between pre- and post-FTW (units in y-axis are mg/L). While TSS influent concentration distributions are not statistically different, the graph indicates a greater spread in the influent TSS concentrations in the post-FTW year (2017) as compared to the pre-FTW period (2015). Influent TN values overlap much more and are not statistically different. Conversely, TP and TDP influent concentration values are different between pre- and post-FTW years. As a result, pond performance in the removal of those parameters are determined by % concentration difference between inlet and outlet.

Where the influent concentrations did not differ (TN and TSS), effluent concentrations were compared as absolute values. Where they do differ (as with TP and TDP), percent difference between inlet and outlet concentrations were used to calculate removal performance.

TN effluent values did not differ between pre- and post-FTW years. TSS effluent values did differ ($p=0.025$) between years with greater TSS concentration in the effluent in 2017 (post-FTW) than in the pre-FTW period (Figure 22).

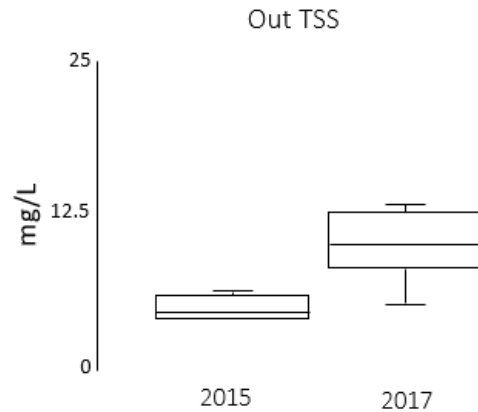


Figure 22: TSS concentration in the effluent of the pond by pre- and post-FTW period. 2015 was characterized by a lower concentration of TSS in the effluent while influent concentration distribution did not differ. The 2015 effluent concentration values were consistently low. The influent values that year also did not vary as much as the post-FTW period.

Because TP and TDP influent concentrations differed between years, comparison of pond performance was determined as a ratio with influent and expressed as percent concentration difference between influent and effluent. Both TP and TDP concentration differences from influent to effluent did not vary between years (Figure 23.)

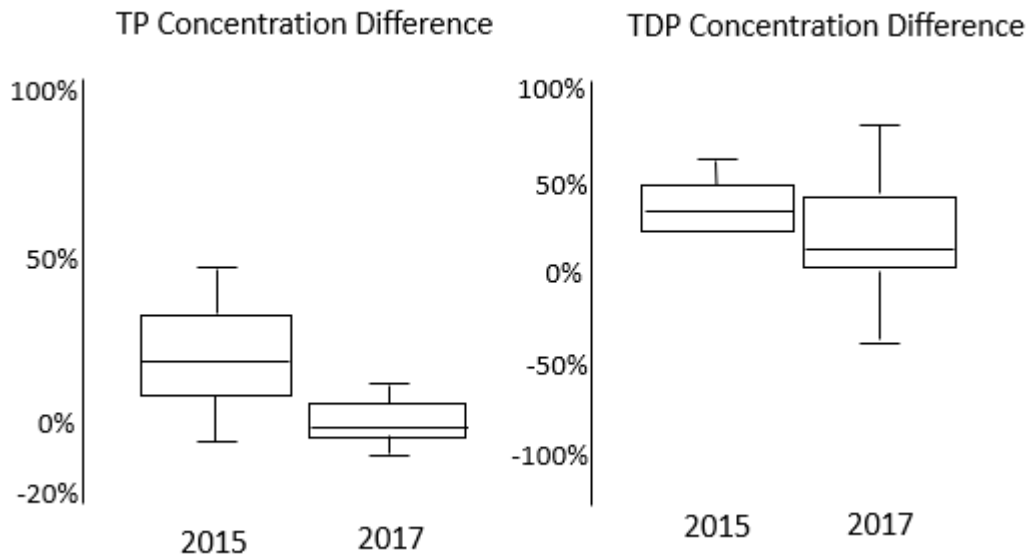


Figure 23: TP and TDP concentration difference between in and out by year. No difference is detected between years in percent concentration reduction pre- and post-FTW. Note that unlike the previous graphs, this figure represents pollutant removal performance where higher values denote greater removal of the pollutant (better performance).

A table of results from all water quality analyses are in Appendix III.

A catalogue of high resolution photos of FTW installation and growth over two years can be viewed in Appendix IV.

6 Conclusions

This project accomplished the first full-scale, in situ study of floating treatment wetland technology in cold northern climate conditions. The study resulted in a design and method for building and installation of FTW units that showed positive results for withstanding the range of temperatures in a stormwater pond in the Northeast.

The plant investigation clearly indicates the superior status of the Longhair sedge for tolerating winter conditions and producing significantly more biomass than any other studied species. While Bulrush tolerated the winter conditions well, their biomass production was not as robust as the sedge. Pickerelweed was a poor performer and was challenged in this setting resulting in almost complete failure. The project team recommends omitting Pickerelweed from a list of plants suitable for FTW application in Vermont and promotion of Longhair sedge for its hardiness and biomass performance.

The water quality data is more complex and presents some unexpected results. The data indicate that overall, FTW did not have a positive impact on stormwater pond performance. No difference was noted in pond effluent concentrations of TN or in percent concentration difference between in and out of TP or TDP. TSS effluent concentration increased slightly between pre- and post-FTW periods even while the storms were less intense in 2017 as compared to 2015. Temperature of the pond was not impacted and DO levels at the center of the pond were depressed in the FTW period.

Reduced DO levels after FTW installation is likely a result of reduced mixing from wind action with mats covering the surface of the pond. Lower DO may have influenced internal nutrient cycling, causing greater

release of bound P from sediments and an overall alteration of pond functioning. However, the same reasoning does not explain the reduced capacity of the pond in the post-FTW to manage TSS. Where other studies found particulate entrapment in root networks a major removal pathway and FTWs most promising trait, this study found a reduced capacity of the pond to perform this function following FTW installation. The study team posits that some of the increased effluent TSS concentrations may also be related to the marginally (though not statistically) greater influent TSS concentration in the post-FTW period coupled with sediment disturbance in the pond from study activities (ie installing FTW rafts, counting and harvesting plants at the end of 2016 season, counting survival in early 2017, and mat repair in early 2017).

Collecting data simultaneously on paired basins would reduce the confounding factors that challenged this study and answer with more certainty how the FTW influence pond performance. Because displacement of floating algal species and alteration of internal pond nutrient cycling is a hypothesized influence of FTW in this study, future studies should seek to quantify this effect by measuring floating biomass, DO and temperature throughout the water column, and sediment nutrient flux. Further, a longer-term investigation of FTWs (5+ years) could address questions about mat integrity over multiple years as well as risk of root attachment into pond sediments, potentially causing damage to plants and resuspension of settled particulates.

Until such field data exist for this region to indicate pollutant reduction potential without concurrent deleterious effects (like DO suppression), the research team suggests that FTW not be employed as practices to improve stormwater pond performance in Vermont.

7 References

- Ballesterio, T., Houle, J., & Puls, T. (2016). Breaking Through UNH Stormwater Center 2016 Report.
- Borne, K. E. (2014). Floating treatment wetland influences on the fate and removal performance of phosphorus in stormwater retention ponds. *Ecological Engineering*, 69, 76–82. <https://doi.org/10.1016/j.ecoleng.2014.03.062>
- Borne, K. E., Fassman, E. a., & Tanner, C. C. (2013). Floating treatment wetland retrofit to improve stormwater pond performance for suspended solids, copper and zinc. *Ecological Engineering*, 54, 173–182. <https://doi.org/10.1016/j.ecoleng.2013.01.031>
- CWP. (2007). National Pollutant Removal Performance Database.
- Headley, T. R., & Tanner, C. . (2006). Application of Floating Wetlands for Enhanced Stormwater Treatment: A Review.
- Kalra, Y. P. (1998). Handbook of Reference Methods for Plant Analysis. *Crop Science* (Vol. 38). <https://doi.org/10.2135/cropsci1998.0011183X003800060050x>
- Ladislav, S., G  rente, C., Chazarenc, F., Brisson, J., & Andr  s, Y. (2014). Floating treatment wetlands for heavy metal removal in highway stormwater ponds. *Ecological Engineering*, 80,

- 85–91. <https://doi.org/10.1016/j.ecoleng.2014.09.115>
- Lane, C., Sample, D., Lazur, A., Winston, R., Streb, C., Ferrier, D., ... Brittingham, K. (2016). Recommendations of the expert panel to define removal rates for floating treatment wetlands in existing wet ponds.
- Nichols, P., Lucke, T., Drapper, D., & Walker, C. (2016). Performance Evaluation of a Floating Treatment Wetland in an Urban Catchment, 1–8. <https://doi.org/10.3390/w8060244>
- United States Environmental Protection Agency. (2009). Stormwater Wet Pond and Wetland Management Guidebook, 80.
- Wang, C., Sample, D. J., Day, S. D., & Grizzard, T. J. (2015). Floating treatment wetland nutrient removal through vegetation harvest and observations from a field study. *Ecological Engineering*, 78, 15–26. <https://doi.org/10.1016/j.ecoleng.2014.05.018>
- Wang, C. Y., & Sample, D. J. (2014). Assessment of the nutrient removal effectiveness of floating treatment wetlands applied to urban retention ponds. *Journal of Environmental Management*, 137, 23–35. <https://doi.org/10.1016/j.jenvman.2014.02.008>
- Winston, R. J., Hunt, W. F., Kennedy, S. G., Merriman, L. S., Chandler, J., & Brown, D. (2013). Evaluation of floating treatment wetlands as retrofits to existing stormwater retention ponds. *Ecological Engineering*, 54, 254–265. <https://doi.org/10.1016/j.ecoleng.2013.01.023>

8 Appendices

Appendix I: Digital field logs

Appendix II: Flow graphs for all storms sampled

Appendix III: Water quality results table

Appendix IV: High resolution photographs of project

Appendix V: List of acronyms