Stormwater subsurface gravel wetlands in Vermont

Permitting, performance, and chloride concerns

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Introduction

Subsurface gravel wetlands (SGW) are water treatment practices that utilize a saturated bed of gravel and (sometimes) wetland vegetation to filter incoming water and remove pollutants through a combination of physical filtration, adsorption, biological uptake, and microbial transformation (Center for Watershed Protection, 2007). Water level is controlled by an outlet structure to retain a permanent subsurface pool, providing retention of stormwater volume in addition to pollutant removal (Figure 1). SGW are becoming increasingly popular tools for stormwater treatment in Vermont.

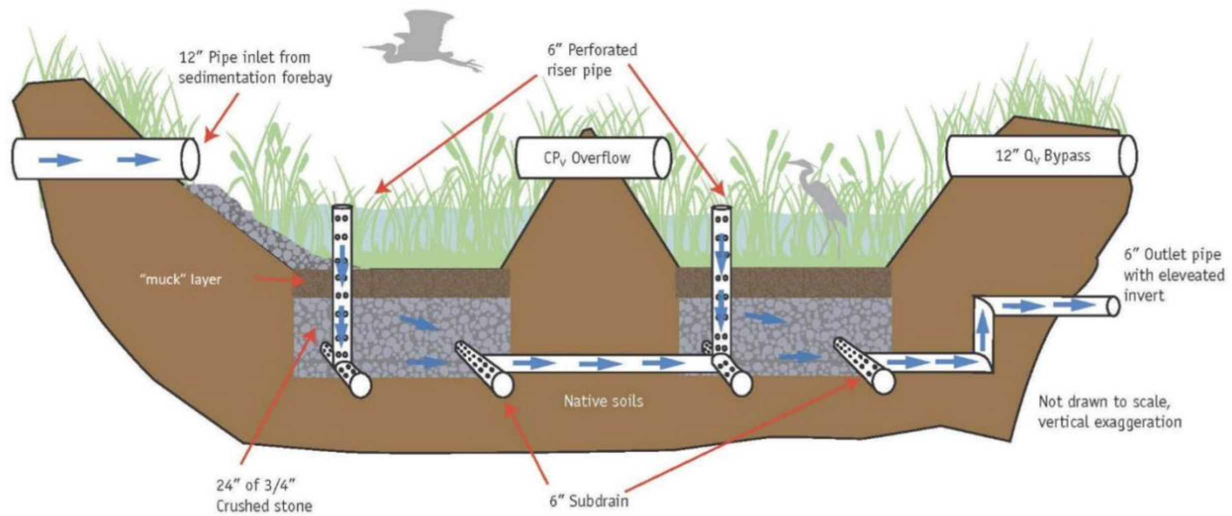


Figure 1. Cross sectional depiction of a subsurface gravel wetland. Note the "muck" layer which serves as an impermeable liner. Water enters the subsurface gravel layer through perforated riser pipes and moves from inlet to outlet through the gravel media. (Image adapted from: Stormwater Report: Water Environment Federation.)

Their modeled capacity to remove fine particles and nutrients of concern indicates that they have one of the highest capacities for phosphorus (P) removal of any passive stormwater treatment practice (Ballestero et al., 2016; Roseen et al., 2009; Houle & Ballestero, 2020). With the promise of impressive P removal, Vermont municipalities planning and managing for impending phosphorus control requirements have focused state stormwater permit applications on these practices. In large part, the recent surge in SGW permit applications Vermont is also influenced by the 2017 Vermont Stormwater Management Manual (VSMM), which identifies them as a preferred ("Tier 2") practice.

However, the enthusiasm with which SGWs are being embraced by the regulatory community may be premature. The range of design details for SGW state permit applications is wide – including varying soil and gravel media and physical configurations, like the inclusion of one or two cells. The influence of these design nuances on practice performance is not well described by research, including the decade-long investigations of those practices from the University of New Hampshire (UNH) Stormwater Center upon which much of the 2017 VSMM relies for performance metrics (Ballestero et al., 2016).

Challenges with premature adoption of stormwater controls have been documented. Based on modeled suppositions of the role of peak flow control, stormwater ponds became commonplace as a standard control structure for over two decades all over North America and Europe (Ballestero et al., 2016; Center for Watershed Protection, 2007; Schueler, 2000). In recent years, the body of evidence questioning ponds' capacity to effectively mitigate the negative impact of urban development on waterways simply by controlling peak discharge has resulted in changes to standard procedures and a rethinking of the basis of urban hydrology and stream ecology originally forming the backbone of urban hydrology developed by Thomas Schueller in the 1980s (Schueler et al., 2009). In addition to the now questionable theory of pond's peak discharge control as the most significant driver of urban watershed damage, wet detention basins have also been linked to internal release of dissolved nutrients from pond sediments (Chiandet and Xenopoulos, 2011; Duan et al., 2016; McEnroe et al., 2013; Song et al., 2015, 2013), accumulation and release of chemical pollutants (like metals, salts, and hydrocarbons), incubation and harboring of toxic algal species (Van Meter et al., 2011), and possible "ecological traps" for amphibians (Clevenot et al., 2018). Given what is now understood about the limitations of wet ponds as stormwater control structures, it is with caution that we should embrace a different and similarly poorly characterized alternative without careful study that includes field monitoring and evaluation of design as a significant contributor to practice performance.

While the State (and permittees) seek to allocate accurate P removal performance projections to gravel wetlands, they are limited in their ability to do so by a lack of performance data from field installations. Further, emerging concerns with the impact of chloride (Cl^-) on natural waters and roadside soils raises questions regarding the impact of road salt-laden runoff entering vegetated treatment practices that rely on the consistent hydraulic capacity of a soil and gravel media coupled with a robust plant community for pollutant removal performance (Kakuturu and Clark, 2015). In areas where salt application is significant (such as highways and state roadways) chloride loading to stormwater practices may dramatically change the hydraulic conductivity and/or vegetation health and survival – rendering practice performance different than what models predict (Hintz and Relyea, 2019; Richburg et al., 2001; White and Broadley, 2001).

A varied group of partners including academic researchers, municipal stormwater managers, and consulting designers and engineers, have identified questions around stormwater gravel wetland performance as significant in the goal of attenuating the impacts of urban stormwater pollution on Lake Champlain and its subwatersheds. We hypothesized that design variations such as media sourcing, and type of planting media would have significant influence on gravel wetland performance, and guidance on these points should therefore be included in the VSMM. Recommendations for additional information to be included in the VSMM are explained below. Additionally, we suspected that field conditions where chloride loading is highest will result in poor vegetation performance and therefore reduced pollutant removal, particularly as the SGWs age. A thorough assessment of the influence of design variables on treatment practice performance requires control that is only possible in a lab setting. Therefore, we pursued a complementary combination of field monitoring and lab studies in this project. The research proposed in this study aimed to investigate the following questions:

Part 1 – SGW Hydraulics and Phosphorus Capture

Field Investigation: Do the SGW that are being permitted under the VSMM perform as expected for flow attenuation and phosphorus capture?

Lab-scale Investigation: How do design variables influence SGW flow attenuation and phosphorus capture performance? Design characteristics to be considered include: (a) gravel media sourcing and (b) impermeable wetland "muck" material sourcing.

Part 2 – Effects of Road Salt on SGW Systems

Field Investigation: How is chloride moving through (and being stored) within SGW? Are plants taking up and storing Cl- in the above ground biomass?

Lab-scale Investigation: Is plant productivity and survival impacted by chloride? Do plants assimilate substantial chloride into their biomass?

Based on the findings of this preliminary phase of research, additional foci in subsequent years may include field verification of specific design variable influence, role of SGW placement on the landscape, and media sourcing - using Phase I results as a guide. These questions will be addressed through thorough explanations of methodologies, results, and conclusions over the course of this report.

Methodologies

Wetland Site Selection

A compilation of the local gravel wetlands was considered to determine feasible wetlands for this study. Two permitted and installed subsurface gravel wetlands of similar age and drainage area characteristics that were accessible for monitoring were selected to monitor performance over two growing seasons. Assuming that the modeled SGW performance was accurate, peak flow attenuation and target pollutant removal of the two selected installations was:

1. Within the range identified in permitting documents and modeling outputs, and
2. Similar to one another.

Simultaneously, lab-scale investigations focused on the influence of gravel and wetland muck media characteristics on performance.

Field performance was determined by monitoring flow, pollutant removal capacity (total suspended solids (TSS), total phosphorus (TP), total dissolved phosphorus (TDP)) and concurrent measures of chloride movement and storage within the SGWs.

Fairview Drive

The Fairview Drive constructed gravel wetland is located at the intersection of Fairview and State Route 15, Essex Junction, Vermont (44.49938, -73.09793) (Figure 2, right), on the northeastern corner of the intersection. It has a drainage area of 23.27 acres, 3.92 of which are impervious, 13.10 are grassed and 6.10 are wooded.

The site consists of two bays, a pretreatment forebay and a treatment bay. The forebay is significantly elevated from the treatment bay and they are connected via a pipe and a rock lined emergency spillway for high flow events that exceed the capacity of the forebay. Pretreated water leaves the forebay via an outlet structure that discharges to a 12” solid high-density polyethylene (HDPE) pipe that delivers runoff to 12” perforated underdrains within the subsurface gravel. The pretreated water then flows horizontally through the saturated microbe rich gravel media. A series of 12” perforated PVC underdrains are located on the southern side of the treatment bay and collect the treated water and convey it to the outlet structure. Treated water then enters the outlet structure and is discharged via a 24” HDPE that connects to existing drainage structures that pass under Route 15 and enters a small stream on the far side of the road. Construction was completed in the fall of 2019 and seeded with wetland seed mix. However, wetland plants were beginning to establish root structures by the end of the 2020 growing season.

The Fairview Drive SGW has two main inlets feeding into the forebay. There are also two inlets feeding directly into the treatment bay. The first is a 12" culvert bringing drainage from Route 15. It has a drainage area of 0.21 acres, 0.01 of which is grassed, and the rest is impervious area of the Route 15 road surface. The other inlet is a 15" culvert bringing drainage from both Fairview Drive and Route 15. It has a drainage area of 1.50 acres, 0.55 of which is impervious, 0.53 is grassed, and 0.42 is wooded.

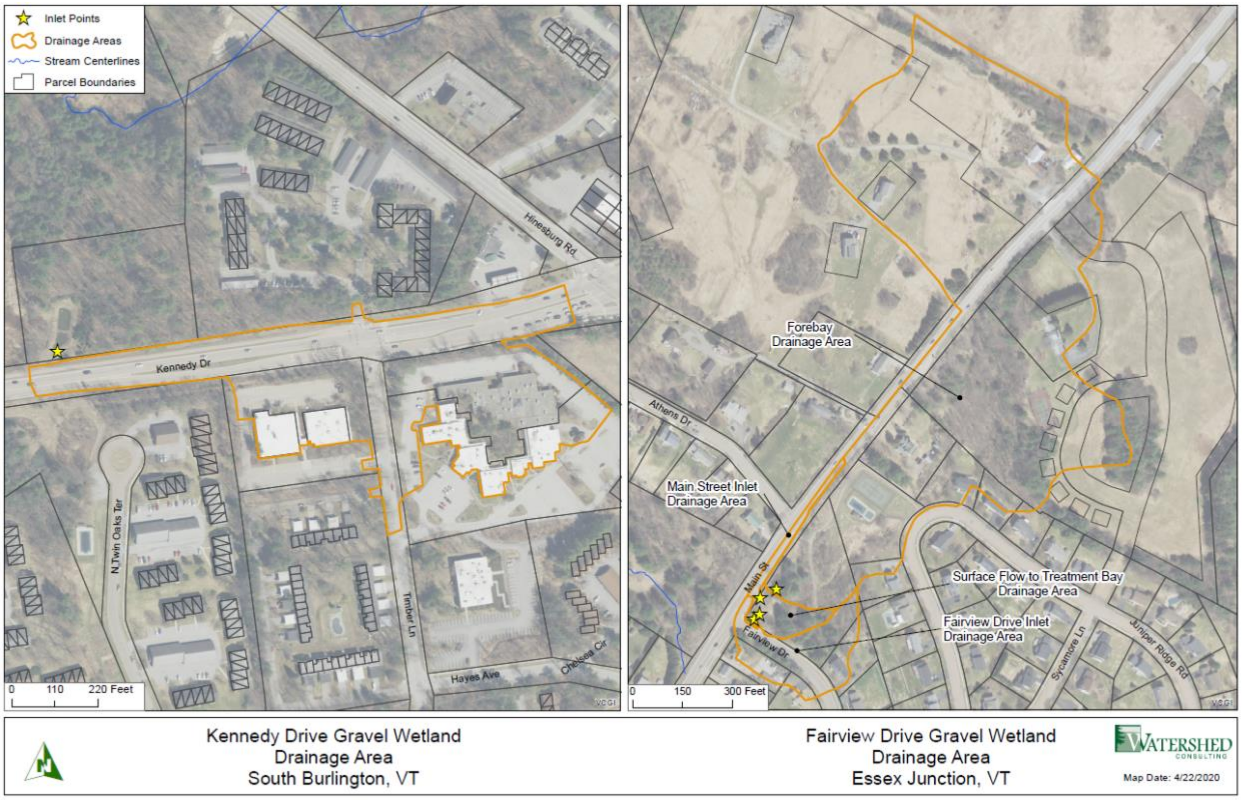


Figure 2. The drainage areas of each gravel wetland. Kennedy Drive is on the left. Fairview Drive is on the right.

Figure 3. Fairview Drive wetland.

Kennedy Drive

The Kennedy Drive constructed gravel wetland is located approximately at 87 Kennedy Drive, South Burlington, VT (44.45365, -73.16999), on the downhill, southern side of Kennedy Drive. It has a drainage area of 8.58 acres, 6.12 of which are impervious and 2.46 are grassed (Figure 2, left).

This site consists of three bays (one forebay and two treatment bays) separated by berms. Influent discharges into the wetland via a drainage structure that collects stormwater from two sources: a stone-lined swale that runs west along the north side of Kennedy Drive and a storm drain crossing south to north under Kennedy Drive. Influent enters the pretreatment forebay via a 24” HDPE solid pipe, allowing for large particles to settle. Influent overtops the berm and flows into the first treatment bay. During moderate to larger storms, influent can overtop the berm and access the first treatment bay via a spillway. At the near end of the first treatment bay, influent enters subsurface perforated pipes for passage to the second treatment bay via a 24” HDPE pipe. At the near end of the second treatment bay, influent runoff enters the subsurface perforated pipes for passage through the gravel medium to the far end of the treatment bay. Effluent departs the final treatment bay through a solid pipe and is discharged into a natural wetland draining to Potash Brook. A stone-lined emergency spillway is located along the western edge of the second treatment bay.

Figure 4. Kennedy Drive wetland. This photo is taken on the outlet side of the system and faces the inlet pipe coming in from Kennedy Drive.

Sampling Design

A Teledyne 6712 ISCO Sampler was placed at each inflow and outflow riser, along with a specific conductance logger. An additional specific conductance logger was placed in a riser pipe in the center of each treatment bay. Probes and strainers for the samplers/loggers were dropped to the bottom of the riser. ISCOs flow modules were calibrated to either Manning's Equation (roughness coefficient) of the culvert coming into the riser or the weir within the riser pipe itself, as needed. Sampling was initiated when a water level rise was detected and the ISCOs continued to sample over a 24-hour period at 100 milliliter (mL) added to the composite sample on a flow-weighted interval, for a total volume of 18,000 mL. For larger storms, the ISCO samplers operated for a 48-hour period. The flow volume was based upon predicted rainfall and modeled flow volume for each outlet, thus adjusted for each storm. This can be seen in Appendix A. All containers were washed and tripled rinsed with deionized water prior to sampling. The configuration of all the water quality sampling instruments and sensors are displayed in Figure 6, for the Kennedy wetland, and Figure 7 for the Fairview Drive wetland. An example set up is in Figure 5.

Figure 5. Example of the ISCO set up at the Fairview Outlet with a battery box adjacent.

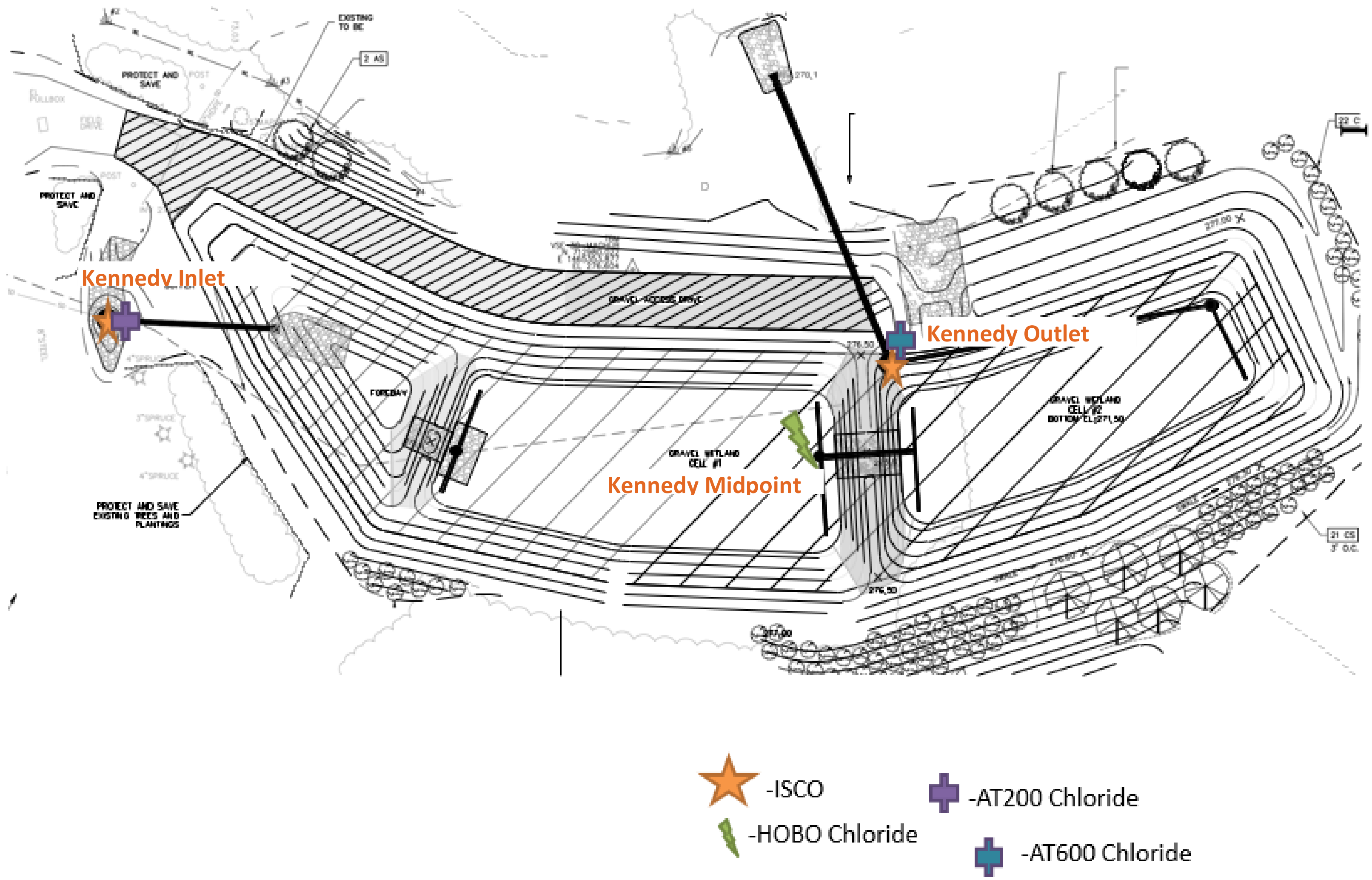


Figure 6. A plan view of the Kennedy Drive gravel wetland final design schematic.

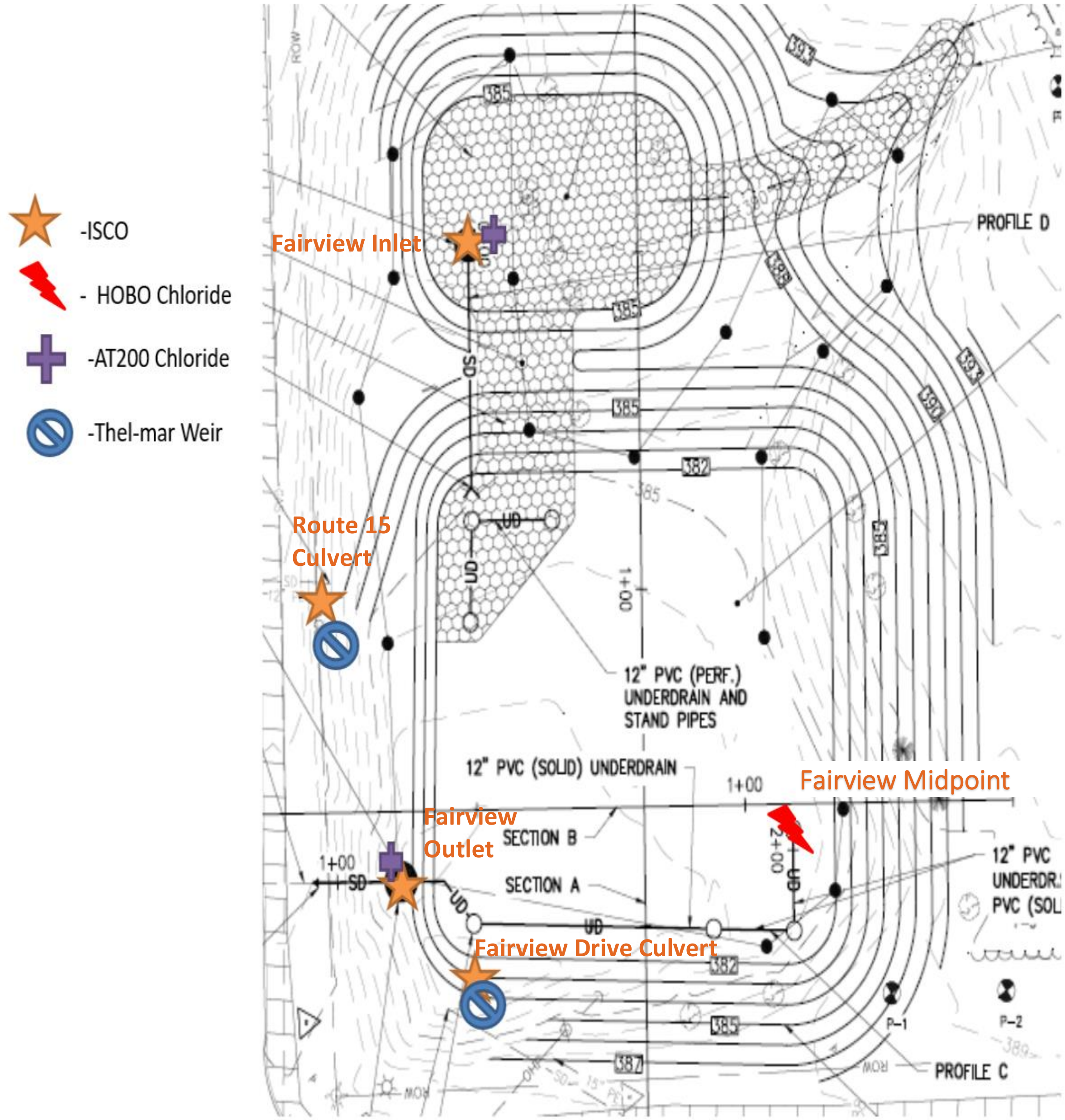


Figure 7. A plan view of the Fairview Drive gravel wetland final design schematic.

Fairview Additional Inlets (Fairview Drive Culvert and Route 15 Culvert)

Thel-mar weirs were installed at the ends of both culverts entering the treatment bay directly, as seen in Figure 8 below. These weirs allowed for calibration of the ISCO for flow measurements as well as creating a small pool from which to collect the sample. An ISCO sensor and sieve was affixed and placed in the mouth of the culvert just behind the Thel-mar weir. The Fairview Drive inlet pipe invert at the gravel wetland was surveyed as being at the elevation of the wetland surface, but visual inspection confirmed it was higher than the wetland surface, indicating that ponding was feasible within the wetland without backflowing the inlet pipe.

Figure 8. Thel-Mar weirs were installed at the two inlet culverts at the Fairview Wetland. Fairview Drive culvert is on the left, and Route 15 culvert on the right.

Field Sampling Set Up

HOBO Loggers

HOBO level loggers continuously logged inflow depth and temperature during each storm event. Watershed Consulting field staff checked their activity before each storm using a mobile application. The water level depth was used to cross reference the depth the ISCO flow-velocity probes read.

ISCO Auto-Samplers

Teledyne ISCO 6712 full size portable samplers were powered by 12 Volt batteries, calibrated prior to each sampling event and contained a triple rinsed 18 L bottle and packed with ice packs. ISCOs were programmed according to the current depth, predicted rainfall and associated flow volume. The current water level was cross referenced with the HOBO water level readings where HOBO probes had been deployed. The Flow Pacing Charts can be seen in Appendix A. The ½ Max flow was used to determine the correct volume based off of the predicted rainfall accumulation acquired from Weather Underground weather stations close to the respective wetlands. Station, KVTESSEX26 for the Five Corners was used for rainfall accumulations at the Fairview Drive wetland. The South Burlington weather station used for Kennedy Drive was for Golf Course Road, KVTSOUTH78. These values were recorded in a mobile application.

The ISCOs were programmed to begin sampling (100 mL) every 1 minute when the water level increased to 0.1 feet above the current depth.

Figure 9. A field technician programming the ISCO.

YSI Probe Readings

A YSI ProDSS multiparameter digital water quality meter was used to collect temperature, DO, pH and specific conductivity measurements at each sampling location, where water was present. Readings were also taken at the midpoint risers of each wetland. A YSI Professional Plus Multiparameter instrument was used to collect chloride concentration measurements at the same locations. All readings were recorded on an online platform for data storage.

Field Sampling Collection

Collection occurred on a variable timescale, between 6-8 hours after a smaller storm (less than 0.5 inches) or up to 24 hours after a larger storm to allow for the system to return to base flow conditions.

Hobo Loggers

Upon arrival. Data was collected from HOBO level loggers, at the inlets, outlets and midpoints of each of the wetland systems, and rain gauges. This data was collected using either a mobile application or tablet computer equipped with HOBOware Pro software. Data was sent to Watershed Consulting office computers.

ISCO Auto-Samplers

Flow Data

Teledyne ISCO hardware program Flowlink was used to download flow data from each ISCO onto a field tablet and saved to Watershed Consulting's Box drive. Data could then be analyzed for flow volumes.

Figure 10. A field technician collecting flow rate data from the ISCO autosampler.

Composite Water Quality Samples

Field technicians collected composite samples from the ISCO autosamplers for analysis of the Total Suspended Solids (TSS), Chloride (Cl^-) and Total Phosphorus (TP) and Total Dissolved Phosphorus (TDP) at each monitored location. The plastic bottles for TSS and Cl^- were triple rinsed, while the glass jars for TP/TDP were not. Samples were kept in a dark, iced cooler until transport to Endyne Laboratory in Williston, VT for analysis. Field blanks were collected every third sampling event for one analyte and duplicates were taken every fourth sampling event of all of the analytes for one sampling location.

Figure 11. A field technician subsampling the composite water sample collected by an ISCO autosampler.

YSI Probe Readings

Two YSI probes were used to collect temperature, DO, pH, specific conductance, and chloride measurements at each inlet, outlet, and midpoint at each of the wetland systems. After subsampling was complete, measurements for these parameters were also taken within the ISCO sample bottles in the 2021 sampling season. An example of sampling can be seen in the figure below.

Figure 12. A field technician collecting water quality readings using the YSI multiparameter probe at the outlet of the Kennedy Drive wetland.

Plant Tissue Harvesting

Destructive harvesting of herbaceous biomass was conducted twice in October of 2020 for peak standing dead and fresh litter and in August of 2021 for peak live biomass. These harvests began with establishing randomly selected cross-sections at the inlet, midpoint, and outlet of the two gravel wetlands (Figure 13 & Figure 14). Cross-sections were randomly selected prior to sampling using the ArcGIS platform. Along each cross section, plant biomass was collected from three 0.25m^2 quadrants in the form of stem clippings to within 1-2 cm of the sediment surface. Stems from the three quadrants along each cross-section were placed in a composite sampling bag to homogenize the sample per cross-section and then placed in a cooler for transport to the lab. All sampling of plant biomass was conducted on dry days as samples preserve better when moisture is low. The cut stems from each cross-section sampling bag were placed into distinct large paper bags and set in a drying room at 60°C (140°F) until constant weight was achieved (~1 week). Dry weight was recorded and then subsamples were sent to the University of Maine to be analyzed for chloride via ion chromatography.

Figure 13. Vegetation and soil sampling cross sections at Kennedy Drive.

Figure 14. Vegetation and soil sampling cross sections at the Fairview Drive wetland and an example of 0.25m^2 quadrat along cross section.

Figure 15. A field technician taking geographic coordinates of the quadrants for plant biomass harvesting in Fall 2020.

Figure 16. Two field technicians measuring the cross section along the midpoint of the Fairview Drive wetland to perform plant tissue and soil sampling in August 2021.

Soil Core Sampling

Soil core sampling was performed on the eight-inch wetland soil muck layer at the Kennedy Drive wetland and the Fairview Drive Wetland in October of 2020 and in August of 2021. Sampling began with establishing randomly selected cross-sections at the inlet, midpoint, and outlet of the two gravel wetlands (Figure 13 & Figure 14). Cross-sections were randomly selected prior to sampling using the ArcGIS platform. Each cross section was split into three equidistant segments to collect composited soil samples within three 0.25m^2 quadrants. A 60 mL plastic syringe was pressed into the soil layer using a wooden weight and a rubber mallet until it was filled completely with soil. Due to additional weight applied on the syringe, the soil compressed within the syringe and produced approximately 50 mL of sample. Four syringes of soil were cored per transect and collected into a composite sampling bag to homogenize the sample per cross-section and then placed in a cooler for transport to the lab. Samples were submitted to Endyne Laboratory for chloride and conductivity analysis. The EPA 9056A Method was used to test chloride and the modified EPA9050A Method was used to test conductivity (Table 1).

Figure 17. A field technician providing a tutorial on soil core sampling at an adjacent upland site using a 60 mL plastic syringe and a wooden weight.

Laboratory Analyses for Field Samples

Table 1. Laboratory methodologies for chemical analytes performed by Endyne Lab, UMaine, and UVM.

Analyte	Substrate	Laboratory Methodology
TSS	Surface water	SM2540 D-11
TP	Surface water	SM20 4500 P-F
TDP	Surface water	SM20 4500 P-F
Cl^-	Surface water	EPA 300.0
Electrical Conductivity	Soil/Muck	mod. EPA 9050A
Cl^-	Soil/Muck	EPA 9056A
Cl^-	Vegetation	EPA 9251 (after $CaSO_4$ extraction)

Statistical Analyses for Field Samples

Table 2. Statistical analyses for the field sample analytes.

Analyte	Substrate
Flow Volume	Measured peak flow volume comparison to modeled values
TSS, TP, TDP, Cl^-	Reduction efficiencies (influent – effluent)
EC & Cl- SGW media	Plot and visual inspection of spatial and temporal distribution
Cl^- in vegetation	Graphical comparison to published literature by species and comparison of lab controls to test units.

Data Acquisition and Analysis for Flow

The Manning's Equation was used to calculate the average velocity and total flow volume passing through each monitored inlet and outlet. The roughness coefficient, slope, and diameter of each pipe are taken into account in this calculation. These parameters can be viewed in Table 3 below.

Table 3. Roughness, slope, and diameter of the inlet pipes for the inlet and outlet at Fairview Drive and Kennedy Drive. These parameters are applied in the Manning's Equation to produce a flow volume at each site.

Site	Riser	Roughness	Slope	Diameter
Fairview Drive	Inlet	0.013	0.0186	1'
	Outlet	0.013	0.0489	2'
Kennedy Drive	Inlet	0.013	0.0033	2'
	Outlet	0.013	0.0020	2'

Area-velocity sensors were installed at the main inlet and outlet of each wetland. The sensor was mounted on a metal ring plate that was secured to the bottom of the HDPE culvert pipe entrance to accurately measure water level and velocity through the culvert. Bubbler flow modules were installed at the two additional inlets at the Fairview Drive wetland. These modules record water level readings by feeding an air bubble through the 90°, V-notch weir installed at the two additional inlets. The flow of air bubbles through the weir records absolute pressure readings that are converted to water level readings in real time. The Manning's Equation is applied on the water level datasets to calculate the total flow volume passing through the monitored location.

Lab-scale experimentation

In order to clarify the impacts of design materials and road salts on SGW performance, MS student Marcos Kubow and undergraduate ecological design students at UVM conducted a sequence of tests under the direction of Dr. Roy. Testing was focused on three engineered mucks (em) provided by different local suppliers, a version of one of the engineered mucks that had been installed in one of the field systems monitored in this study for approximately 1 year before being collected (em1_f), and three gravel materials available locally (Figure 18). Muck em1 was the material installed at both field sites included in this study.

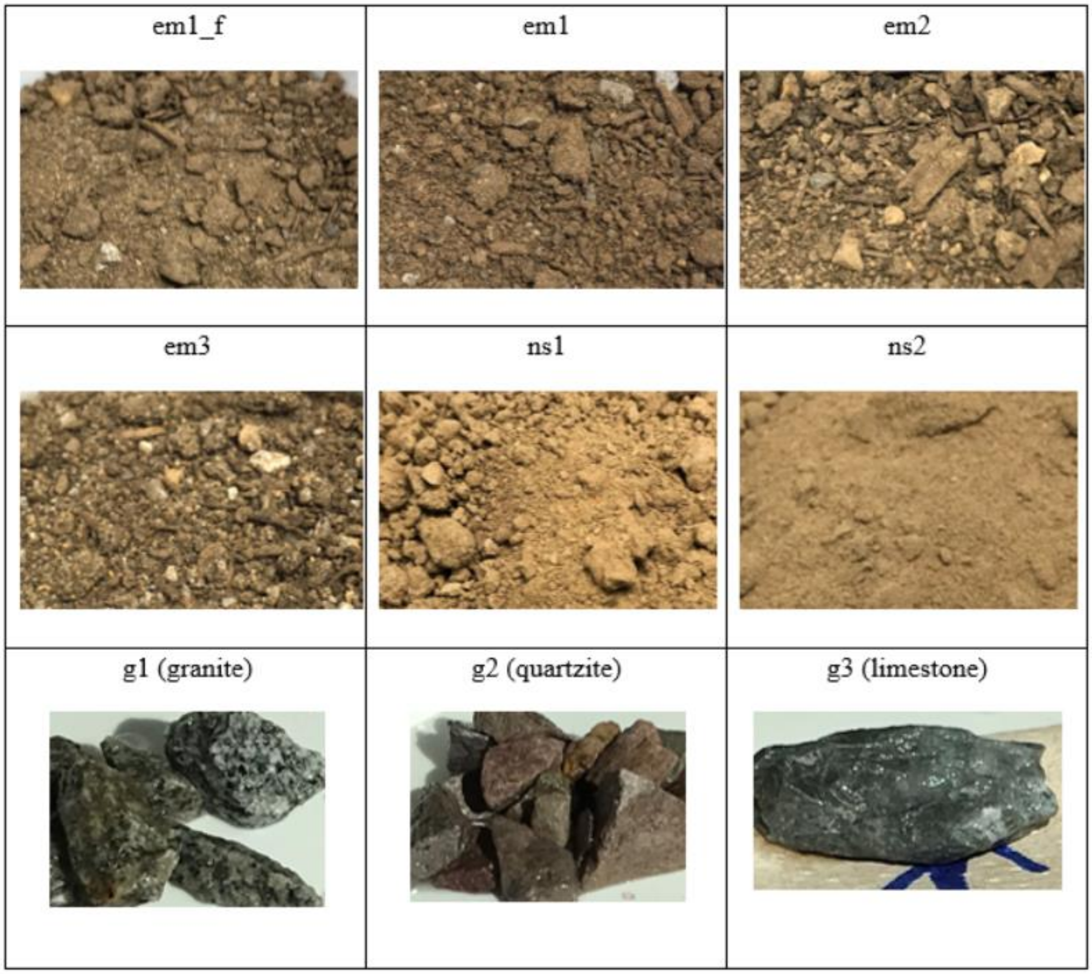


Figure 18. Muck materials (top two rows) and gravels (bottom row) tested in the laboratory. em = engineered muck. ns = native soil.

A subsample of raw sieved (200-millimeter (mm)) muck material from each source was sent to University of Maine Soil Testing lab for the following analyses:

Basic compost test – Includes total carbon (%), total nitrogen (%), total phosphorus (%), total potassium (%), total calcium (%), bulk density, pH, electrical conductivity, and micronutrients.

Modified Morgan extraction – Air-dry, 2 mm sieved soil samples are extracted with modified Morgan extractant (0.62 N NH_4OH + 1.25 N CH_3COOH) by shaking a soil-solution suspension for 15 minutes at a 1:5 (soil mass:solution) ratio followed by filtering to remove particles above 8 micrometers (µm) in size. Extracts from the Modified Morgan procedure are to be analyzed for P, Iron (Fe), and Aluminum (Al) by ICP-OES.

Mehlich-3 extraction – Air-dry, 2 mm sieved soil samples are extracted with the Mehlich-3 solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M EDTA) by shaking a soil-solution suspension for 5 minutes at a 1:10 (soil mass:solution) ratio, followed by filtering to remove particles above 2 µm in size (0.45 µm pore size is also acceptable). Extracts from the Mehlich-3 procedure are to be analyzed for P, Fe, and Al by ICP-OES.

In this report, we focus on the results from measures above most directly associated with P dynamics. Any of the above information omitted from this report is available upon request. The Phosphorus Saturation Ratio (PSR), an important metric for gauging whether a soil will be a source or sink of P (Kleinman and Sharpley, 2002; Dari et al. 2018), was calculated for mucks as follows:

$$PSR = \frac{\left(\frac{P_{M3}}{31}\right)}{\left(\frac{Fe_{M3}}{56}\right) + \left(\frac{Al_{M3}}{27}\right)}$$

where, PM3 = Mehlich-3 P in milligrams (mg) P per kilogram (kg) dry soil, FeM3 = Mehlich-3 Fe in mg Fe per kg dry soil, and AlM3 = Mehlich-3 Al in mg Al per kg dry soil.

Each muck material was also tested for water extractable P (WEP) to assess P leaching potential. WEP was measured at UVM using methods adapted from Kleinman et al. (2007), including a 1:100 solid:solution ratio. Hydraulic conductivities of mucks were measured at UVM with a K_{sat} meter from Meter Group™ (n=4). Soils were gently packed in the K_{sat} meter to imitate field conditions at time of SGW construction. All other sample preparation was carried out as per Meter Group instructions.

Column testing in the laboratory is an effective method for isolating the effects of a substrate in a controlled environment over the course of repeated events (Okaikue-Woodi, Cherukumilli, & Ray, 2020), and can complement field monitoring. To isolate the performance of wetland muck materials and gravels, we designed a sequential testing procedure that first simulates flooding and infiltration for muck materials, and then uses effluent from these tests as influent for column testing of gravels (Figure 19). Experiment 1 tested three engineered wetland mucks acquired in the northeastern US (labeled em1, em2, and em3), one of which (em1) was installed in both field sites. After sampling, all remaining effluent from the 3 engineered mucks were composited and fed to the 3 gravels, granite (g1), quartzite (g2), and limestone (g3).

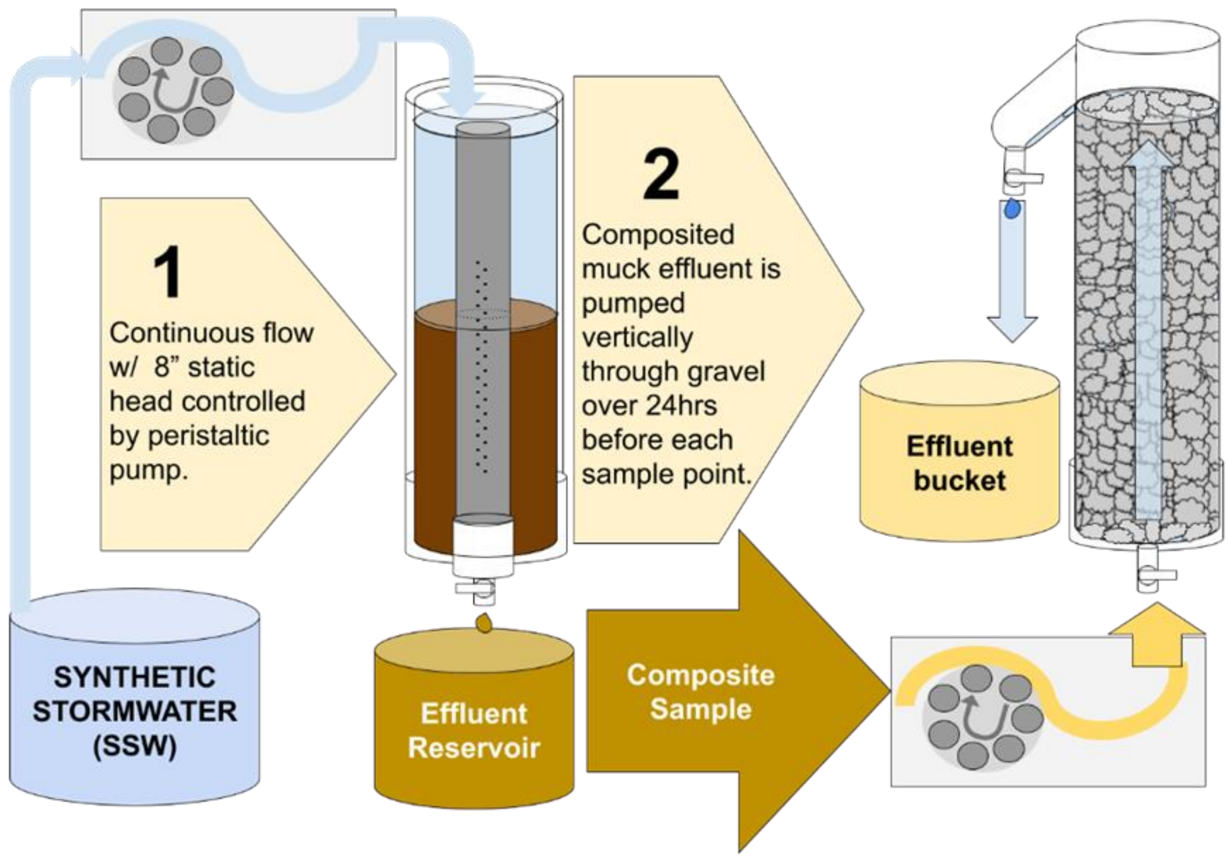


Figure 19. Workflow for column Experiment 1. All 3 engineered mucks were exposed to 6 sequential "storm" events using a synthetic stormwater with effluents measured for soluble reactive P (SRP) and Cl- (all 6 events), as well as total P (TP) and total suspended solids (TSS) (events 1, 3, and 6). All remaining effluents from treatment columns were composited into a single container and used as the influent for the gravel column testing. Gravel columns continuously received the influent mixture with a 24 hour hydraulic residence time and vertical upflow conditions. SRP and Cl- were measured at each 24 hour period for 6 days, while TP and TSS were measured on days 1, 3 and 6 for gravel columns. pH was also monitored (data not shown in this report but available upon request).

Experiment 2 explored the feasibility of using soils native to the SGW construction sites as a cost-effective and environmentally friendly alternative to importing engineered muck materials. Additionally, Experiment 2 considered P and Cl^- dynamics for an engineered soil that was installed in a SGW field site for ~1 year prior collection and testing (em1_f). Muck effluents were again analyzed using the same approach as Experiment 1. Muck effluents from Experiment 2 were not used in the gravel column testing.

For muck columns, an 8" uncompacted muck layer was placed in each column – 3 replicates per muck material (Figure 20). Synthetic stormwater (SSW) was then added from a 3-gallon food grade plastic bucket through a peristaltic pump, down the drainpipe, all while the outlet valve was closed. Once the column reaches an 8" ponding depth on top of the muck the SSW was incubated in the column for 1 hour to reach a chemical equilibrium with the soil. After 1 hour, the outlet valve at the bottom of the column was slightly opened, allowing stormwater to move through the perforated pipe and drain into a collection bucket underneath the column at a flow rate ranging from 3 - 6 $cm^3\ s^{-1}$. The total volume of each simulated storm was 3 L. The effluent was mixed before collecting each sample for analysis. This process (i.e., test "storm event") was repeated 6 times for each column (n=3 columns per muck). During each experimental run, a control column was included that was empty, but otherwise under the same conditions as the 3 treatment columns. For Experiment 1 all effluent not used for water quality sampling was composited and preserved at 4°C for ≤ 1 week for the subsequent gravel-column testing.

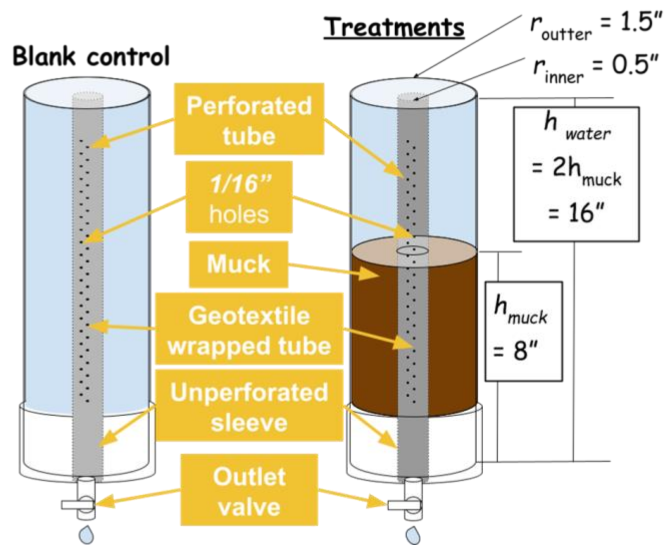


Figure 20. Design of muck columns.

For the gravel column experiment, we tested 3 locally abundant angular gravels (1/2" – 3/4") and their ability to remove Cl^-, TSS, SRP, & TP (Figure 21). Effluent collected from the three engineered mucks in Experiment 1 were peristaltically pumped at a rate 2.5 rpm to approximate an hydraulic retention time (HRT) of 24 hours (+/- 30 min) for all 3 gravels for 6 days (144 hours) in triplicate. Each column contained the minimum elevation of 24" recommended by VSMM (2017). Every 24 hours 200 mL was sampled from inflow and outflow of each column. SRP, Cl-, and pH was measured for each 200 mL sample while all 6-inflow samples and outflow samples from each column were composited for one composite inflow TP and TSS sample and one outflow TP and TSS sample for each column. During each experimental run, a control column was included that was empty, but otherwise under the same conditions as the 3 treatment columns.

Subsamples of 5-10 mL volume were filtered (0.45 µm) and frozen until analysis for SRP, while subsamples of 20 mL volume were pipetted into pre-cleaned (acid washed, and 3x rinsed with DDI H2O) 60 mL borosilicate glass digestion vials and stored in the dark at room temperature for digestion and analysis of total P (TP). SRP was analyzed at 660 nm using a microplate reader (BioTek Synergy HT) following the malachite green method for colorimetric orthophosphate analysis (D'Angelo et al. 2001; Ringuet et al. 2011). TP samples were digested following the alkaline persulfate digestion (Patton & Kryskalla, 2003), and analyzed using colorimetric orthophosphate analysis at 880 nm on a Lachat QuickChem 8500 using the ascorbic acid method for molybdenum blue (Murphy & Riley, 1962). ~1 L water samples were analyzed for total suspended solids (TSS) following methods described in Roy et al. (2016).

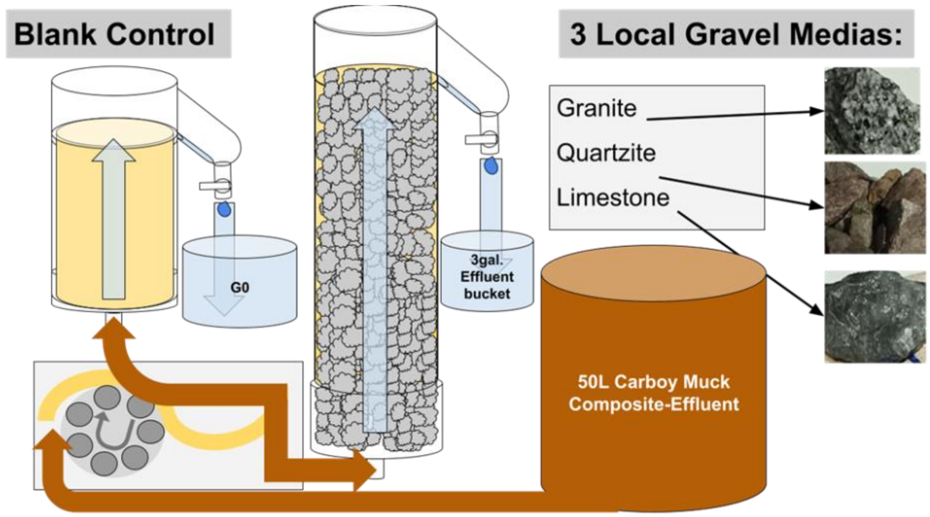


Figure 21. Design of gravel columns.

Muck column effluent data were log-transformed prior to statistical analysis to meet the assumptions of linear regression. For muck effluents, linear models predicting log10(SRP), log10(TP), or log10(TSS+1) were fit for each experiment including muck type, storm number (1-6), and an interaction term for muck × storm. A simpler model only including muck type was also fit (as well as a medium complexity model including muck type and storm number as predictors if appropriate), and AICc along with whether or not the storm and/or interaction terms were significant were used to determine the most appropriate model for each experiment-water quality dependent variable combination. In these models, muck types were dummy variables that could be assessed for significant effects relative to the reference level (i.e., blank control cores). In cases where only muck was included as a predictor, ANOVA with post-hoc Tukey HSD (or a suitable nonparametric alternative) was used to determine differences between treatments. Analysis of effluent data from the gravel columns followed a similar approach, with the exception that log10(TSS) was used instead of log10(TSS + 1) because all effluents contained measurable TSS.

In a third lab experiment, we evaluated the effects of road salt on gravel wetland plant species using a bioassay approach (Powell et al., 1996). Plants tested included species common in Vermont wetland seed mixes such as Broadfruit bur-reed (*Sparganium eurycarpum*) and Shallow sedge (*Carex lurida*). All plants were acquired as plugs from Vermont Wetland Plant supply with an average plant height of 6-12" tall. 32 plugs of each species were transplanted into 4" pots with Gardener's Supply Garden Mix (20% silt, 15% sand, 10% peat moss, and 55 % compost) and cultured with tap water for 7 days prior to exposure of Cl^- treatment period. During the culturing process all pots were kept moist in randomized block pattern trays (18" x 12" x 3.5") organized in a 36" x 48" area in the UVM Main Campus Greenhouse under grow lights (average photosynthetically-active radiation (PAR) of 90 µmol m^{-2} s^{-1}) for a 16-hour photoperiod and sub-irrigated from the trays. Trays received water containing NaCl to produce Cl^- levels equal to 0%, 50%, and 100% of a level observed in Vermont stormwater, 650 mg Cl^- L^{-1}) (n = 5 per species-treatment combination). Every three days tray water was completely replaced (Powell et al., 1996). Chloride treatment continued for 8 weeks, at which time aboveground biomass was destructively harvested by clipping at the soil surface.

Upon harvest, biomass samples were placed in brown paper bags and dried at 65°C for 24 hours or until dry and then weighed to determine dry biomass. Biomass was compared across treatments for each species using ANOVA and (if appropriate) post-hoc TukeyHSD tests or suitable nonparametric alternatives when data were non-normal. Duplicate subsamples per species-treatment combination were analyzed for chlorophyll *a* and chloride at Endyne, Inc. Chlorophyll *a* was measured by extracting the chlorophyll from the frozen blended plant tissue and analyzing the extract with high-performance liquid chromatography (HPLC) at a wavelength of 669 nm. Duplicate soil samples from each plot were analyzed for electrical conductivity and chloride. Additional replicates for biomass chloride and soil chloride are currently being analyzed at Endyne, Inc. and results were not available in time for this final report. While we do not expect these additional forthcoming data to change any conclusions offered herein, we will submit an amendment to LCSG describing the additional data once available.

Quality Assurance Tasks Completed

Field Sampling

Data quality was measured in terms of accuracy and precision, completeness, representativeness, comparability, and the required detection limits for the analytical methods.

Data acceptance was based on adherence to field sampling, recording, transport, and lab analytical procedures and the use of field and lab blanks and duplicates.

Sensitivity was assessed with field blanks. Staff prepared blanks in the field by filling vials directly with distilled water. Blanks were then handled and transported to the laboratory in the same manner as the rest of the samples. A field blank was taken every third sampling event on one analyte and duplicate sampling was completed every fourth event for all the analytes at one sampling location.

Field data, including conditions, date, time of sample collection, and photo documentation of the site were collected using the Fulcrum application for smartphones. Files were stored both in the Fulcrum application software (under a license held by Watershed Consulting) and in exported format on the Watershed Consulting file network (using Box Drive). Watershed Consulting's complete file database is backed up daily to an on-site hard drive.

Lab Experiments

Lab experiments were all run in triplicate (column studies) or with n=5 (bioassay) during this study. For column studies, every experimental run (1 run = 1 control and 3 treatment columns) included a control column subjected to identical conditions as treatment columns, including identical influent water, residence time, column and tubing materials, and environmental conditions. This enabled isolation of the effects of the treatment materials (i.e., mucks and gravels) versus other nuisance factors: data analysis for columns focused on comparisons of treatment effluents with those of the control. For SRP analysis of samples at UVM, every sample was analyzed in triplicate, with concentrations estimated using a standard curve developed with known standards in the same background matrix as the unknown samples. Every plate run included a quality control sample equal to ½ the high standard and prepared using a certified standard obtained from a third party (as opposed to the same chemical stock used to develop the standard curve in the lab). QC acceptance criteria was percent difference +/- 10% compared to a known or "true" value. For chloride measurements, the YSI probe was calibrated before use following the instructions provided by YSI. In the gravel columns studies, flow rate was measured periodically to ensure the target residence time. K_{sat} was measured in four replicates for all mucks. Chlorophyll a, electrical conductivity, soil/biomass chloride, total phosphorus, Modified Morgan P, and Mehlich-3 P, Al, and Fe were run by outside labs (Endyne, UVM AETL, and Umaine Soil Testing Lab), following their standard QC guidelines. All laboratory data were reviewed by multiple project team members and are backed up on multiple hard drives and the cloud. One out of 143 SRP samples in the muck column testing (a control column sample) was determined to be an outlier by UVM PI Roy based on testing of assumptions for linear models (normality of residuals and homogeneity of variance) and a highly suspect value that indicates student error. This sample was omitted from the data analysis. There was also one missing SRP sample for the muck column test and two missing data for the gravel SRP dataset due to student error – these missing values were not filled, and data analysis was conducted without them.

Results and Discussion

Flow and Rainfall

Kennedy Drive Wetland

Flow sampling was attempted for twenty-eight storm events between June 2020 and November 2021, twenty of which produced a complete dataset of one total inlet volume and one total outlet volume (Table 4). The inlet and outlet volumes were calculated using the Manning's Equation:

$Q = VA = (1.49/n)*AR^{2/3}\sqrt{S}$

where,

n = pipe's roughness coefficient

A = pipe's cross-sectional area

R = hydraulic radius (cross sectional area divided by the wetted perimeter)

S = slope of the hydraulic gradient.

The inlet and outlet pipes' diameter, roughness coefficient, and slope was measured in the field. These measurements are displayed in Table 3.

Table 4. The total number of storms that sampling was attempted for and the subset of storms that were successfully sampled at the Kennedy Drive wetland in 2020 and 2021.

	Kennedy 2020	Kennedy 2021
Storms Attempted	16	12
Storms Completed	12	8

The inlet and outlet volumes measured during the twenty storm events over the two-year monitoring period and the associated rainfall for each event are displayed below in Table 5. The inlet and outlet volumes measured in the field are displayed alongside the modeled inlet and outlet volumes. For each storm event, a modeled flow volume was developed from HydroCAD based on the site's land use, drainage area, and soil types. The model assumed that the inlet volume equals the outlet volume. However, field results demonstrated variable inlet and outlet volumes during every monitored storm event.

Table 5. Inflow and outflow volumes were measured during 20 storm events at the Kennedy Drive Wetland. The modeled volume (inlet = outlet) is displayed between the measured inlet and outlet volumes. Abbreviations: CF= cubic feet.

Storm	DATE	Rainfall (in)	Kennedy Inlet Volume (CF)		Kennedy Outlet Volume (CF)
			Field	Modeled (CF)	Field
1	6/25/2020	0.32			
2	7/10/2020	0.28	1,385.08	2,831.39	1,963.25
3	7/12/2020	0.31	2,698.28	3,441.23	2,074.99
4	7/17/2020	0.2	1,524.28	1,350.36	1,873.24
5	7/24/2020	0.32	3,242.38	3,659.03	2,003.16
6	8/5/2020	2.44	44,784.70	49,135.57	37,328.27
7	8/18/2020	0.1			
8	8/26/2020	0.32	4,390.94	3,659.03	3,030.68
9	8/29/2020	0.60	10,614.40	10,628.62	9857.13
10	9/14/2020	0.21	1,229.97	1,481.04	1,248.15
11	10/1/2020	2.16	40,133.95	42,950.06	35,348.53
12	10/8/2020	0.29	3,654.41	3,005.63	3,320.03
13	10/15/2020	0.1			
14	10/16/2020	0.86	17,264.12	17,903.12	12,849.07
15	10/22/2020	0.47	6,433.23	7,230.94	4,043.70
16	10/27/2020	0.08			
1	6/23/2021	0.17			
2	7/1/2021	0.49			
3	7/9/2021	0.49	10,314.54	7,753.66	3,477.27
4	7/19/2021	2.24	33,133.18	44,692.46	30,571.30
5	7/22/2021	0.97	22,010.13	21,082.99	18,777.78
6	7/30/2021	0.75	11,216.87	14,766.81	10,494.43
7	8/2/2021	0.71	13,910.72	13,677.81	12,927.75
8	8/20/2021	1.21	19,083.98	22,128.43	18,764.38
9	9/10/2021	1.27	23,650.25	23,435.23	23,230.21
10	9/24/2021	1.02	18,404.86	17,990.24	15,152.83
11	10/26/2021	0.47			
12	11/1/2021	2.19			

The following Kennedy Drive wetland flow volume results are organized within four storm size categories:

- 0.0-0.3 inches
- 0.3-1.0 inches
- 1.0-2.0 inches
- greater than 2.0 inches

0.0-0.3 Inch Storm

Out of the twenty monitored storm events during the two-year monitoring period, four events fell within the 0.0-0.3 inch rainfall range, all of which occurred in 2020. For this storm size, the inlet volume ranged from 1,230 cubic feet (cf) to 3,654 cf with an average volume of 1,948 cf. The outlet volume ranged from 1,248 cf to 3,320 cf with an average volume of 2,101 cf. The average volume reduction efficiency between the measured inlet volume and measured outlet volume during the four storm events was -14.2% (Table 6). This result demonstrates an increase in the outlet volume from the inlet volume. At the end of each twenty-four-hour storm event, the outlet was observed to have a constant rate of base flow. It is anticipated that there is a source of base flow further upstream within the site's drainage area that continually enters the wetland system. Further investigation of the source(s) of additional base flow is required to understand the varying magnitude of this volume for individual events. However, even with the additional base flow volume after peak storm flow, the average outlet volume was 2.7% lower than the average modeled outlet volume (Table 6). Additionally, the average inlet volume was 13.9% lower than the average modeled inlet volume (Table 6). These results demonstrate that the model overestimated the volume entering and exiting the system (Relative Percent Difference (RPD) > 10%). With the measured inlet and outlet flow volumes being lower than their modeled value, the system is highly effective at mitigating peak storm flows during a 0.0-0.3-inch storm. Due to the design of the controlled outlet orifice, the outlet volume with additional base flow is released more slowly over an extended detention period than if it was discharged directly to the adjacent natural wetlands surrounding Potash Brook. Figure 22 displays a typical hydrograph for a storm event that produced between 0.0 and 0.3 inches of rainfall. The peak outlet flow rate displayed (brown) is significantly reduced relative to the peak inlet flow rate (blue).

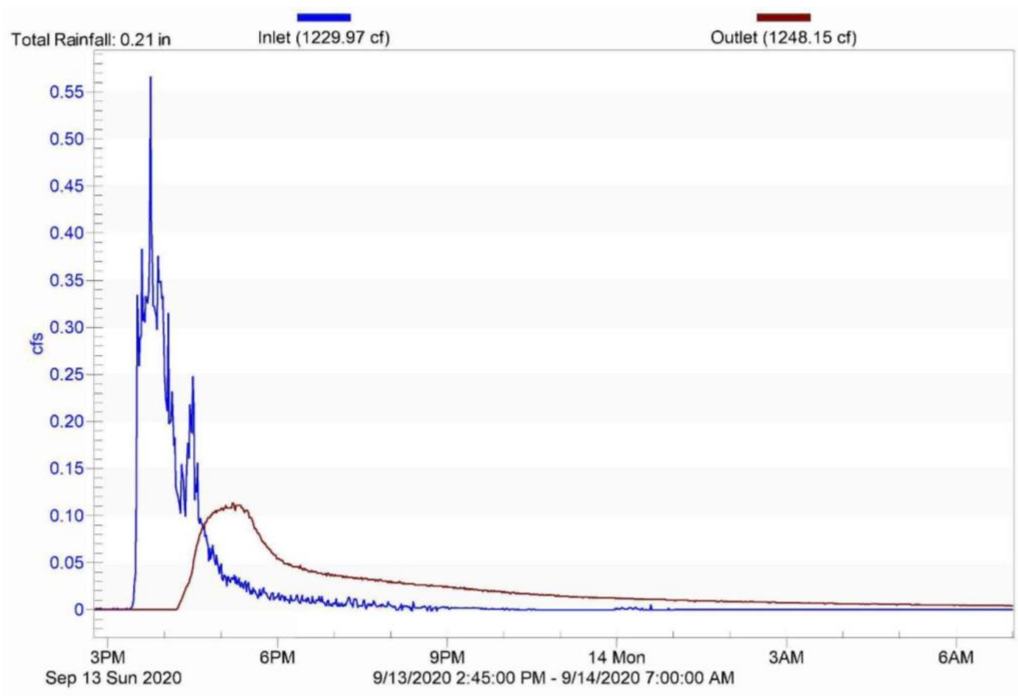


Figure 22. In 2020, Storm 10 took place on September 13th with a total rainfall of 0.21 inches. The peak inlet flow rate was 0.56 cubic feet per second (cfs) and the peak outflow rate was 0.11 cfs.

0.3-1.0 Inch Storm

Out of the twenty monitored storm events during the two-year monitoring period, ten events fell within the 0.3-1.0 inch rainfall range. For this storm size, the inlet volume ranged from 2,698 cf to 22,010 cf with an average volume of 10,210 cf. The outlet volume ranged from 2,003 cf to 18,778 cf with an average of 7,954 cf. The average volume reduction efficiency between the measured inlet volume and outlet volume during the ten storm events was 25.7% (Table 6). This result demonstrates a strong reduction in the outlet volume relative to the inlet volume. In terms of the field performance compared to the modeled performance, the average outlet volume was 35% less than the average modeled volume (Table XYZ). Additionally, the average inlet volume was 2.7% lower than the average modeled inlet volume (Table 6). These results demonstrate that the model was fairly accurate in estimating the inlet volume (RPD < 10%). However, the model overestimated the outlet volume (RPD > 10%). With the measured inlet and outlet flow volumes being lower than the modeled values, the wetland system is highly effective at mitigating peak storm flow rate during storms with under 1.0 inches of rainfall. Figure 23 displays a typical hydrograph for a storm event that produced between 0.3 and 1.0 inches of rainfall. The peak outlet flow rate (brown) is significantly reduced relative to the peak inlet flow rate (blue).

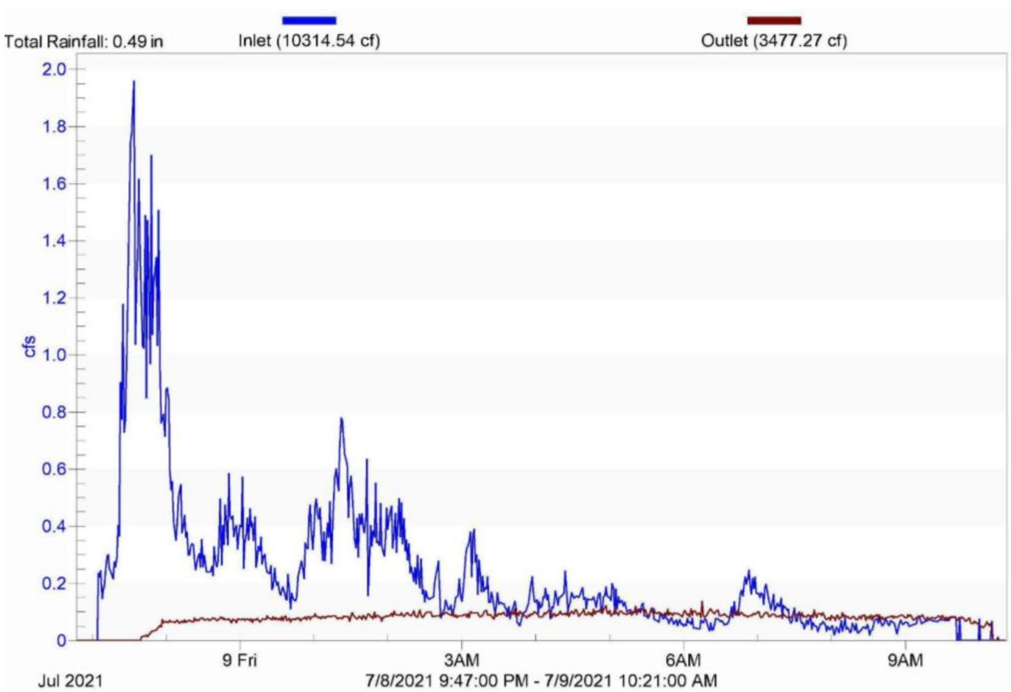


Figure 23. In 2021, Storm 3 took place from July 8th to July 9th with a total rainfall of 0.49 inches. The peak inlet flow rate was approximately 2.0 cfs and the peak outflow rate was approximately 0.1 cfs.

1.0-2.0 Inch Storm

Three storm events fell within the 1.0-2.0-inch storm category out of the twenty events during the two year monitoring period. For this storm size, the inlet volume ranged from 18,405 cf to 23,650 cf with an average of 20,380 cf. The outlet volume ranged from 15,153 cf to 23,230 cf with an average of 19,049 cf. The average volume reduction efficiency between the measured inlet volume and measured outlet volume during the three storm events was 7.0% (Table 6). This result demonstrates a small, but notable reduction in the outlet volume relative to the inlet volume. In terms of the field performance compared to the modeled performance, the average outlet volume was 11.5% less than the average modeled volume (Table 6). Additionally, the average inlet volume was 3.9% lower than the average modeled inlet volume (Table 6). These results demonstrate that the model was fairly accurate in estimating the inlet volume (RPD < 10%). However, the model overestimated the outlet volume (RPD > 10%). With the measured inlet and outlet flow volumes being lower than the modeled values, the wetland system is effective at mitigating peak storm flow rate during storms with under 1.0 inches of rainfall. Figure 24 displays a typical hydrograph for a storm event that produced between 1.0 and 2.0 inches of rainfall. The peak outlet flow rate displayed in brown is significantly reduced relative to the peak inlet flow rate displayed in blue.

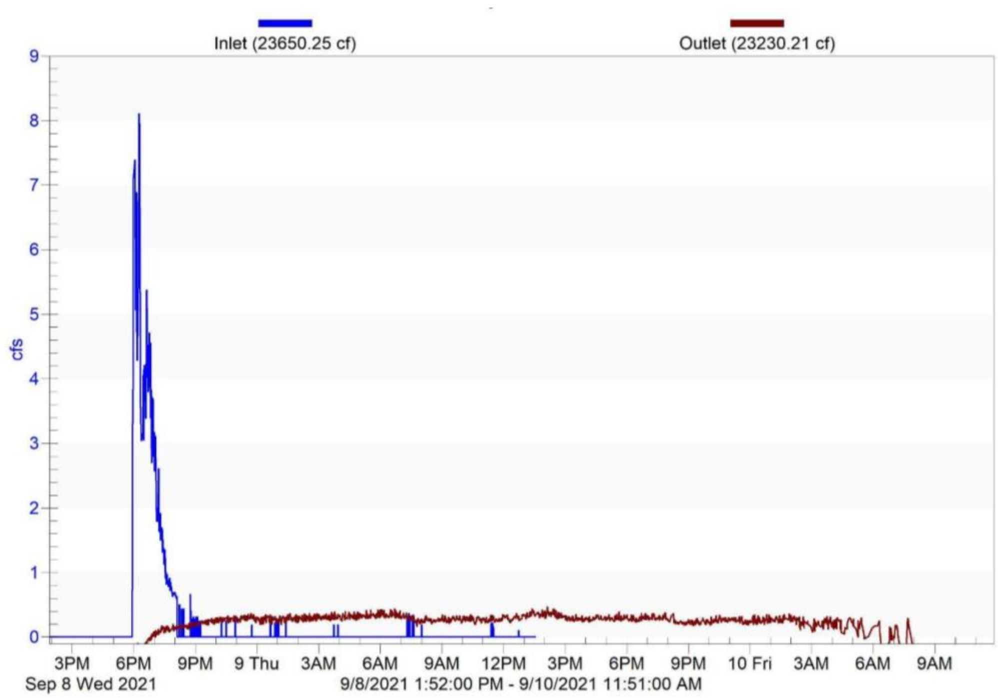


Figure 24. In 2021, Storm 9 took place from September 8th to September 10th with a total rainfall of 1.27 inches. The peak inlet flow rate was approximately 8.0 cfs and the peak outflow rate was approximately 0.2 cfs.

2.0 Inch Storm

Three storm events fell within the 2.0-inch storm category out of the twenty monitored events during the two-year monitoring period. For this storm size, the inlet volume ranged from 33,133 cf to 44,785 cf with an average of 39,351 cf. The outlet volume ranged from 30,571 cf to 37,328 cf with an average of 34,416 cf. The average volume reduction efficiency between the measured inlet volume and measured outlet volume during the three storm events was 12.1% (Table 6). Due to the larger magnitude of inlet and outlet flow volumes generated from storms larger than 2.0 inches, this result demonstrates a strong reduction in the outlet volume relative to the inlet volume. In terms of the field performance compared to the modeled performance, the average outlet volume was 28.1% less than the average modeled volume (Table 6). Additionally, the average inlet volume was 15.3% lower than the average modeled inlet volume (Table 6). These results demonstrate that the model overestimated both the volumes entering and exiting the system (RPD > 10%). With the three sets of measured inlet and outlet flow volumes being significantly lower than the modeled values, the wetland system demonstrated that it provided sufficient storage to reduce the volume of flow leaving the system within the twenty-four-hour storm event. Figure 25 provides a visual example of the flow attenuation provided by the treatment cells during a 2.16-inch storm. The peak outlet flow rate displayed in brown is significantly reduced relative to the peak inlet flow rate displayed in blue. See Appendix B for the complete set of hydrographs produced for all twenty completed storm events at the Kennedy Drive wetland between 2020 and 2021.

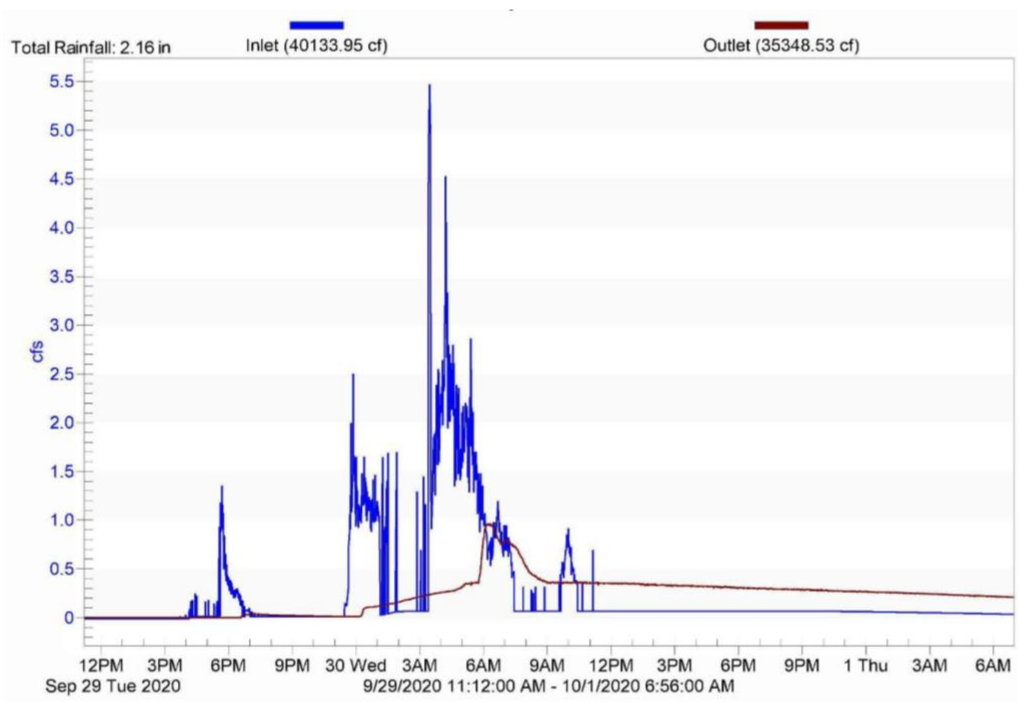


Figure 25. In 2020, Storm 11 took place from September 29th to October 1st with a total rainfall of 2.16 inches. The peak inlet flow rate was approximately 5.5 cfs and the peak outflow rate was approximately 0.9 cfs.

Table 6. The percent reduction between measured inflow and outflow volumes at the Kennedy Drive wetland was calculated within four storm size categories (% Reduction Efficiency). A negative value indicates that the outlet volume was higher than the inlet volume. The percent difference between the modeled inflow volume and field measured inflow volume was calculated for each storm size (% Difference, Modeled vs. Inlet). The percent difference between the modeled outflow volume and field measured outflow volume was calculated for each storm size (% Difference, Modeled vs. Outlet). A negative value indicates that the modeled value was higher than the field measured value. Values generated for each storm size category are based on the number of storm events displayed in the "Sample Size" row.

	Rainfall Accumulation (inches)			
	0-0.3	0.3-1	1.0-2.0	>2.0
% Reduction Efficiency	-14.2%	25.7%	7.0%	12.1%
% Difference, Modeled vs. Inlet	-13.9%	-2.7%	-3.9%	-15.2%
% Difference, Modeled vs. Outlet	-2.7%	-35.1%	-11.5%	-28.1%
Sample Size	4	10	3	3

Fairview Drive Wetland

Flow sampling was attempted for twenty-eight storm events between June 2020 and November 2021, twelve of which produced a complete dataset of three inlet volumes and one outlet volume (Table 7). The total combined inlet volume and the total outlet volume measured during the twelve storm events and the associated rainfall for each event are displayed below in Table 8. The inlet and outlet volumes were calculated using the Manning's Equation. The inlet and outlet pipes' diameter, roughness coefficient, and slope was measured in the field. These measurements are displayed in Table 3.

Table 7. The total number of storms that sampling was attempted for and the subset of storms that were successfully sampled at the Fairview Drive wetland in 2020 and 2021.

	Fairview 2020	Fairview 2021
Storms Attempted	16	12
Storms Completed	6	6

Table 8. Inflow and outflow volumes were measured during 12 storm events at the Fairview Drive Wetland. The modeled volume (inlet = outlet) is displayed between the measured inlet and outlet volumes. Abbreviations: CF= cubic feet.

Storm	DATE	Rainfall (in)	Fairview Inlet Volume (CF)		Fairview Outlet Volume (CF)
			Field	Modeled (cf)	Field
1	6/25/2020	0.26	2,436.37	130.68	0
2	7/10/2020	0.28			
3	7/13/2020	0.45			
4	7/17/2020	0.27			
5	7/24/2020	0.52			
6	8/5/2020	2.03	57,440.09	63,336.09	33,881.99
7	8/18/2020	0			
8	8/26/2020	0.13			
9	8/31/2020	0.8			
10	9/14/2020	0.01			
11	10/1/2020	1.87	34,999.82	54,667.67	26,175.81
12	10/8/2020	0.53	12,914.60	2,003.76	3,495.92
13	10/13/2020	0.22	2,148.58	87.12	42.24
14	10/19/2020	0.84			
15	10/22/2020	0.47	8,386.68	1,176.12	6,626.53
16	10/27/2020	0.15			
1	6/23/2021	0.01			
2	7/1/2021	0.7			
3	7/9/2021	0.5			
4	7/19/2021	1.93	26,491.59	57,847.55	6,372.64
5	7/22/2021	1.36	30,748.86	29,969.21	18,320.86
6	7/30/2021	0.18	9,624.18	87.12	0
7	8/2/2021	1.00	20,635.70	16,160.72	5,003.93
8	8/20/2021	0.81	15,619.09	9,104.02	3,105.60
9	9/10/2021	0.92			
10	9/24/2021	0.61			
11	10/27/2021	0.88	20,002.31	11,499.81	8,078.23
12	11/1/2021	2.12			

The following Fairview Drive wetland flow volume results are organized within four storm size categories:

- 0.0-0.3 inches
- 0.3-1.0 inches
- 1.0-2.0 inches
- greater than 2.0 inches

0.0-0.3 Inch Storm

Of the twelve monitored storm events during the two-year monitoring period, three events fell within the 0.0-0.3-inch rainfall range. For this storm size, the inlet volume ranged from 2,149 cf to 9,624 cf with an average volume of 4,736 cf. The outlet volume ranged from 0 cf to 42.2 cf with an average volume of 14.1 cf. The average volume reduction efficiency between the measured inlet volume and measured outlet volume during the three storm events was 99.3% (Table 9). This result demonstrates almost a complete attenuation of storm flow during the three 0.0-0.3-inch storm events. In terms of the field performance compared to the modeled performance, the average measured outlet volume was 156.5% lower than the average modeled outlet volume (Table 9). Additionally, the average measured inlet volume was 186.8% higher than the average modeled inlet volume (Table 9). These results demonstrate that the model highly underestimated the flow volume entering the system and highly overestimated the flow volume leaving the system (Relative Percent Difference (RPD) > 10%). The system is extremely effective at mitigating peak storm flows during a 0.0-0.3-inch storm. Figure 26 displays a typical hydrograph for a storm event that produced between 0.0 and 0.3 inches of rainfall. The Fairview Inlet did not receive any storm flow, while the two culvert inlets, the Route 15 Inlet and FV Drive Inlet, received storm flow immediately upon the start of the storm event. The combined volume of 2,436 cf from the Route 15 Inlet and FV Drive Inlet was completely attenuated in the wetland and there was no outlet volume produced from this event.

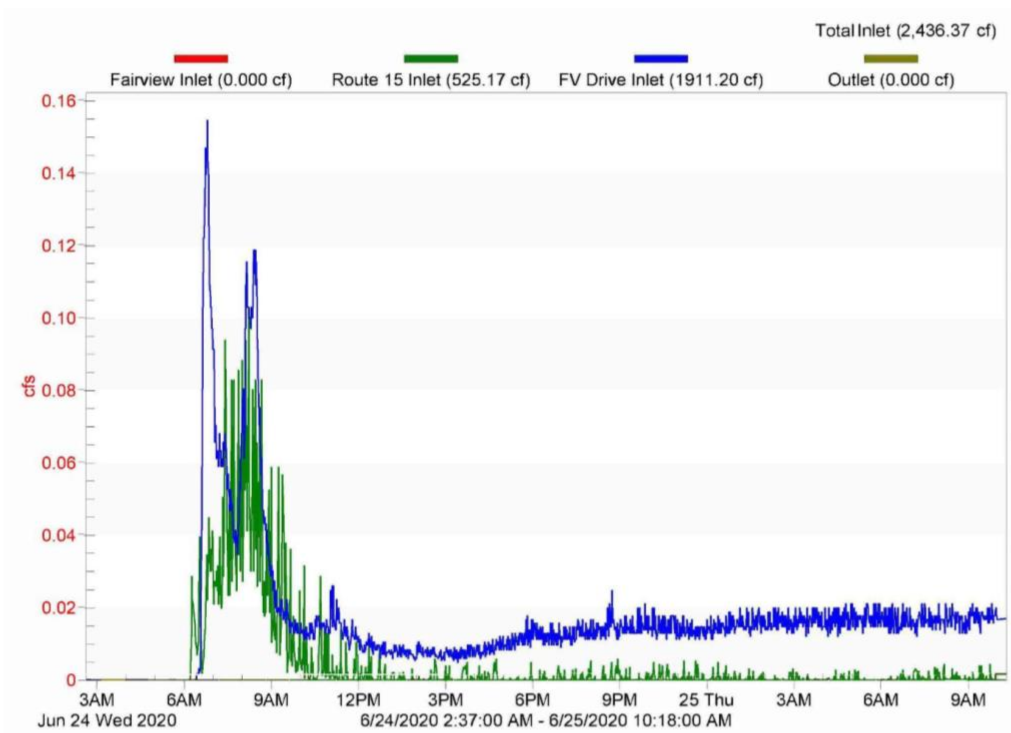


Figure 26. In 2020, Storm 1 took place from June 24th to June 25th with a total rainfall of 0.26 inches. The peak FV Drive inlet flow rate was approximately 0.16 cfs and the peak outflow rate was 0.0 cfs.

0.3-1.0 Inch Storm

There were four storm events during the two-year monitoring period that fell within the 0.3-1.0 inch storm. For this storm size, the inlet volume ranged from 8,387 cf to 20,002 cf with an average volume of 14,231 cf. The outlet volume ranged from 3,106 cf to 8,078 cf with an average volume of 5,327 cf. The average volume reduction efficiency between the measured inlet volume and measured outlet volume was 58.4% (Table 9). This result demonstrates that the wetland was highly effective at reducing the storm flow volume during the four monitored events. In terms of the field performance compared to the modeled performance, the average measured outlet volume was 15.2% higher than the average modeled outlet volume (Table 9). Additionally, the average measured inlet volume was 101.9% higher than the average modeled inlet volume (Table 9). These results demonstrate that the model highly overestimated the flow volume entering the system and moderately overestimated the flow volume leaving the system (RPD > 10%). The system is extremely effective at mitigating peak storm flows during a 0.3-1.0-inch storm. Figure 27 displays a typical hydrograph for a storm event that produced between 0.3 and 1.0 inches of rainfall. All three inlets – the Fairview Inlet, the Route 15 Inlet and FV Drive Inlet – received storm flow at varying times during the event. The wetland system attenuated 25.3% of the combined inlet volume of 8,387 cf and produced an outlet volume of 6,262 cf from this event.

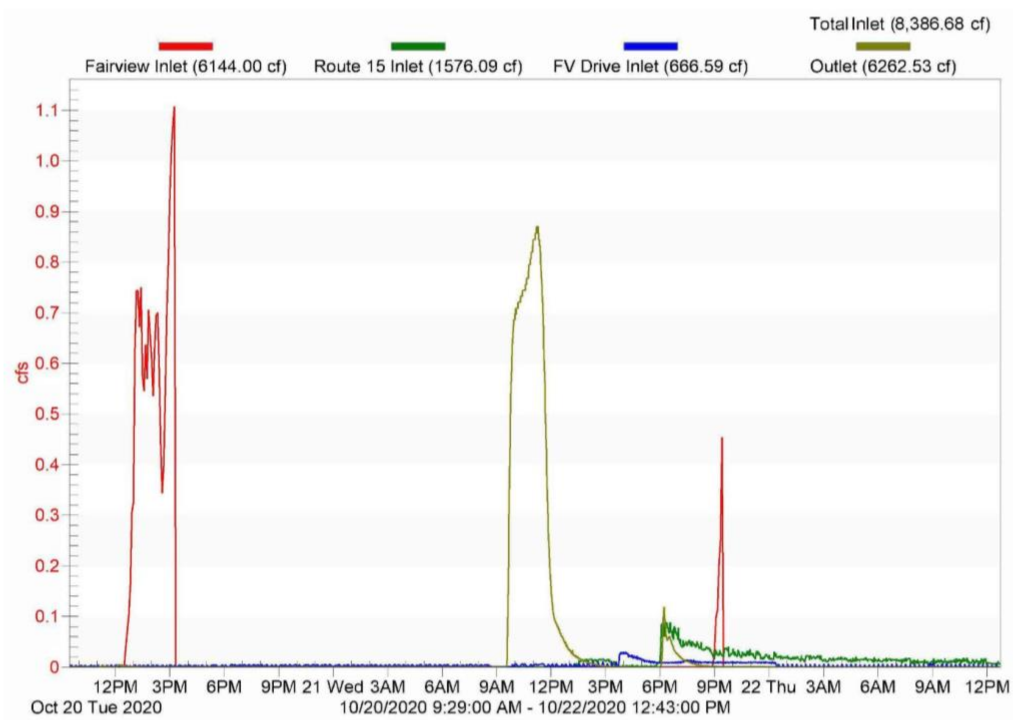


Figure 27. In 2020, Storm 15 took place from October 20th to October 22nd with a total rainfall of 0.47 inches. The peak Fairview inlet flow rate was approximately 1.1 cfs and the peak outflow rate was 0.88 cfs.

1.0-2.0 Inch Storm

There were four storm events during the two-year monitoring period that fell within the 1.0-2.0 inch storm. For this storm size, the measured inlet volume ranged from 20,635.7 cf to 34,999.8 cf with an average volume of 28,218.9 cf. The measured outlet volume ranged from 5,003.9 cf to 26,175.8 cf with an average volume of 13,968 cf. The average volume reduction efficiency between the measured inlet volume and outlet volume was 54.3% (Table 9). This result demonstrates that the wetland was highly effective at reducing the storm flow volume during the four monitored events. In terms of the field performance compared to the modeled performance, the average measured outlet volume was 96.1% lower than the average modeled outlet volume (Table 9). Additionally, the average measured inlet volume was 22.8% lower than the average modeled inlet volume (Table 9). These results demonstrate that the model moderately overestimated the flow volume entering the system and highly overestimated the flow volume leaving the system (RPD > 10%). Figure 28 shows a hydrograph produced from the 1.87-inch storm event that took place in September 2020. The wetland retained 25.2% of the combined inlet volume of 35,000 cf and produced an outlet volume of 26,176 cf. With both the measured inlet and outlet volumes being lower than their modeled volume (54,667.7 cf), this storm is an example of how effective the wetland system was at reducing the total flow volume exiting the system during the 1.87-inch storm event.

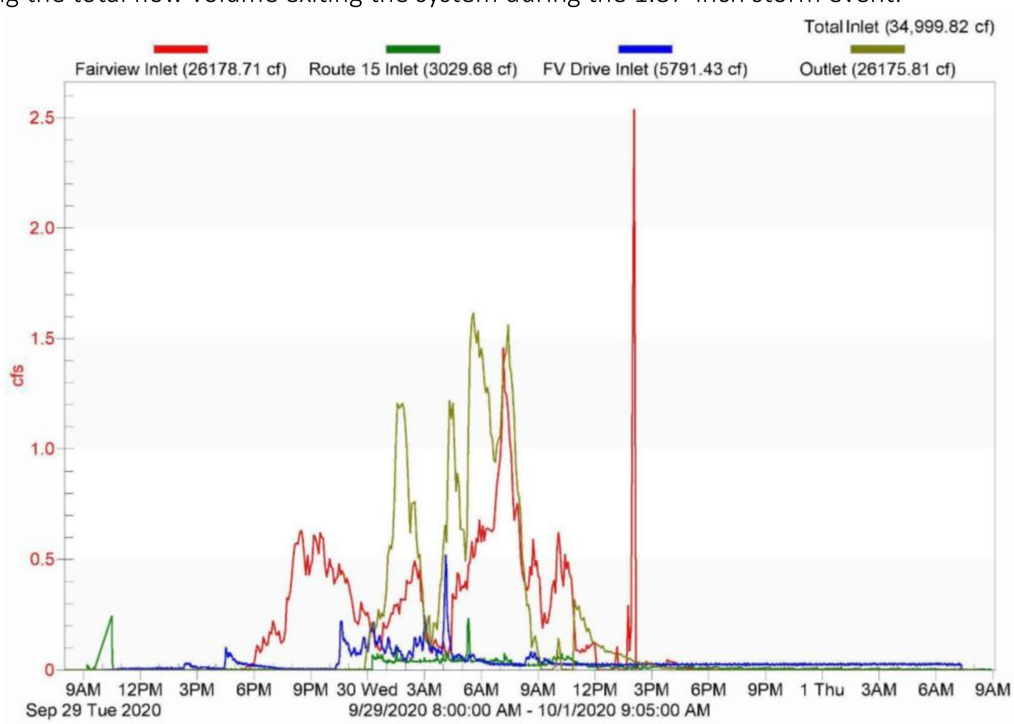


Figure 28. In 2020, Storm 11 took place from September 29th to October 1st with a total rainfall of 1.87 inches. The peak Fairview inlet flow rate was approximately 2.5 cfs and the peak outflow rate was 1.6 cfs.

2.0 Inch Storm

Out of the twelve monitored storm events during the two-year monitoring period, only one event fell within the 2.0-inch rainfall category. Storm 6 took place between August 3rd and August 6th of 2020 and produced 2.03 inches of rainfall. The measured inlet volume was 57,440.1 cf and the measured outlet volume was 33,882 cf. The percent reduction efficiency between the inlet volume and outlet volume of this storm was 41.0% (Table 9). This result demonstrates that the system was effective at reducing the storm flow exiting the system. In terms of this storm's field performance relative to its modeled performance, the measured outlet volume was 60.6% less than the modeled outlet volume (Table 9). The measured inlet volume was 9.8% less than the modeled inlet volume (Table 9). This performance demonstrates that the model was relatively accurate at estimating the combined inlet volume entering the system (RPD <10%), but highly overestimated the volume exiting the system (RPD > 10%). Figure 29 shows the hydrograph produced from the 2.03-inch storm event that took place from August 3rd to August 6th of 2020. All three inlets and the outlet recorded three peak flows within the event. While the peak Outlet flow rate (3.1 cfs) exceeded the peak Fairview Inlet flow rate (2.8 cfs), the system still performed effectively in reducing the total flow volume exiting the system during the 2.03-inch storm event. See Appendix B for the complete set of hydrographs produced for all twelve completed storm events at the Fairview Drive wetland between 2020 and 2021.

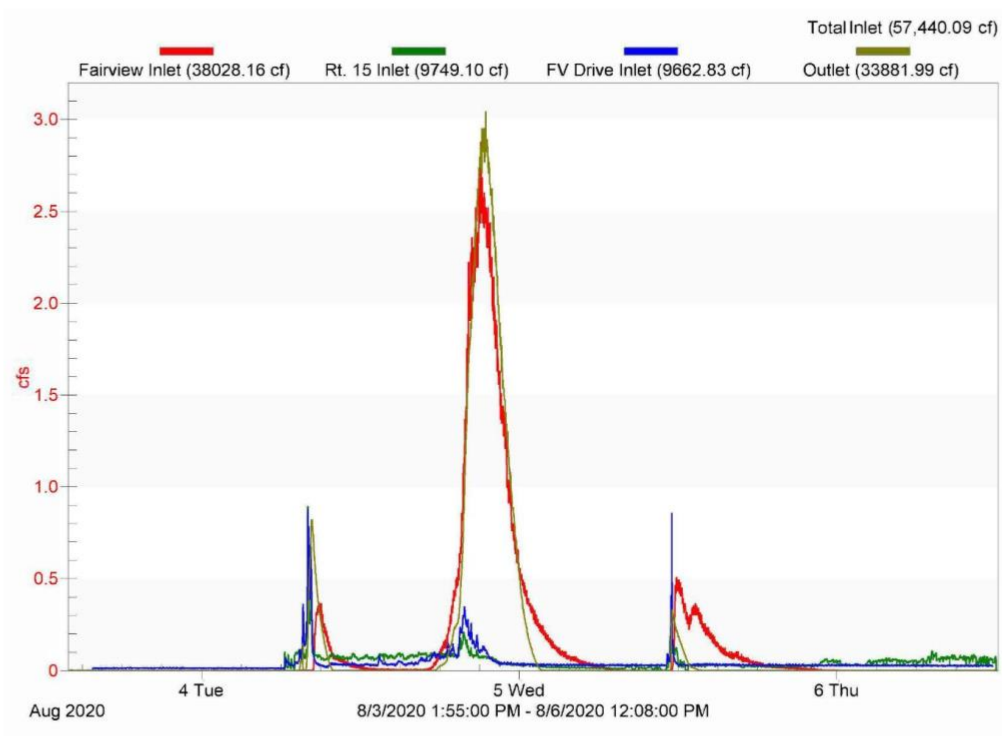


Figure 29. In 2020, Storm 6 took place from August 3rd to August 6th with a total rainfall of 2.03 inches. The peak Fairview inlet flow rate was approximately 2.8 cfs and the peak outflow rate was 3.1 cfs.

Table 9. The percent reduction between measured inflow and outflow volumes at the Fairview Drive wetland was calculated within four storm size categories (% Reduction Efficiency). A positive value indicates that the inlet volume was higher than the outlet volume. The percent difference between the modeled inflow volume and field measured inflow volume was calculated for each storm size (% Difference, Modeled vs. Inlet). The percent difference between the modeled outflow volume and field measured outflow volume was calculated for each storm size (% Difference, Modeled vs. Outlet). A negative value indicates that the modeled value was higher than the field measured value. Values generated for each storm size category are based on the number of storm events displayed in the "Sample Size" row.

	Rainfall Accumulation (inches)			
	0-0.3	0.3-1	1.0-2.0	>2.0
% Reduction Efficiency	99.3%	58.4%	54.3%	41.0%
% Difference, Modeled vs. Inlet	186.8%	100.9%	-22.8%	-9.8%
% Difference, Modeled vs. Outlet	-156.5%	15.2%	-96.1%	-60.6%
Sample Size	3	4	4	1

Pollutant Loading

The import and export of chloride (Cl-), total suspended solids (TSS), total dissolved phosphorus (TDP), and total phosphorus (TP) loads were calculated for twenty storm events at the Kennedy Drive wetland and twelve storm events at the Fairview Drive wetland over the two year monitoring period. Each wetland system's pollutant loading results are organized within Year 1 (2020) and Year 2 (2021). A Spearman's Rank-Order Correlation analysis was performed on each of the four analytes (Cl-, TSS, TDP, TP) to measure the strength and direction of the association between sets of pollutant loads. Additionally, the two systems' reduction efficiency for each analyte was calculated for Year 1 and Year 2. All pollutant loading results were calculated using raw concentration data analyzed by Endyne Laboratory and flow volumes measured by ISCO autosamplers in the field. Raw concentration data from both wetland systems can be viewed in Appendix C. Supplemental YSI data measuring dissolved oxygen, temperature, pH, specific conductance, and chloride can be viewed in Appendix D.

Kennedy Drive

Year 1 Results

Chloride loadings at the inlet and outlet of the Kennedy Drive wetland were collected from twelve storm events in Year 1. The reduction in Cl- loads between the inlet and outlet demonstrated to be highly variable across the twelve monitored storm events. Five storm events had a reduction in Cl- loads at the outlet while seven events had an increase in Cl- loads (Figure 30). There were no consistent positive or negative trends in chloride loads between the inlet and outlet over the duration of the season. However, there was a strong positive correlation between the rainfall amount and the chloride loads entering the inlet (Spearman's ρ = 0.83). Storms with higher rainfall amounts typically produced higher chloride loads at the inlet. Storm 6 had the highest rainfall accumulation of the season (2.44 inches) which subsequently produced the highest chloride load (391 kg) at the inlet that the wetland received out of all the monitored events in 2020 (Figure 30). With such a large volume of runoff entering the system during Storm 6, a dilution of the chloride load at the inlet produced a reduced chloride load of 98 kg at the outlet. In smaller storms (< 0.5 inch), the chloride load was typically variable between the inlet and outlet. Due to the highly impervious and commercialized land use within the wetland's drainage area, salt applications are a common practice in the winter months as a road deicing mechanism. With deicing salt being a direct source of chloride, the consistent application of salt on these surfaces led to varying influxes of chloride into the wetland system downstream.

TSS loadings at the inlet and outlet were collected from eleven storm events in Year 1. Ten out of the eleven storms demonstrated TSS load reductions between the inlet and outlet. TSS load between the inlet and outlet had a reduction efficiency of 47% during the Year 1 monitoring period (Figure 32). TSS loads entering the system were typically greatest in larger storm events. Storms 6 and 11 were the largest storms monitored in 2020 (> 1.0 inch). The highest TSS load that entered the system during the Year 1 monitoring period was 14 kg over the course of Storm 11. In this particular storm, the system provided sufficient detention time to reduce the TSS load to 8 kg at the outlet. For larger events such as Storm 11, the reduction of TSS loads between the inlet and outlet was greatest compared to TSS reductions during smaller storms (Figure 30).

TDP and TP loadings at the inlet and outlet were collected from twelve storm events in Year 1. There was a strong positive correlation between the TDP load at the inlet and the TDP load at the outlet (Spearman's ρ = 0.72). Additionally, there was a strong positive correlation between the TP load at the inlet and the TP load at the outlet (Spearman's ρ = 0.75). Eleven out of the twelve monitored storm events produced higher exports of both TP and TDP than imports into the system (Figure 30). There is also a strong positive correlation between rainfall and both TDP and TP loading (Spearman's ρ = 0.90 and Spearman's ρ = 0.88, respectively). This result demonstrates the system exported higher loads of phosphorus during storms that had greater rainfall. Both TDP and TP loadings were greatest at the inlet and outlet during storms greater than 1.0 inch (Storms 6 and 11). Phosphorus exports consistently exceeded imports throughout Year 1 due to net release of TDP, which (based on lab findings discussed below) was likely driven by SRP leaching out from the eight inch engineered soil layer above the gravel media in the treatment cells of the system. Expanded results and discussion on the wetland soil and its role in releasing phosphorus into the wetland are detailed in the "Wetland Soil Muck and Gravel Media" portion of this report.

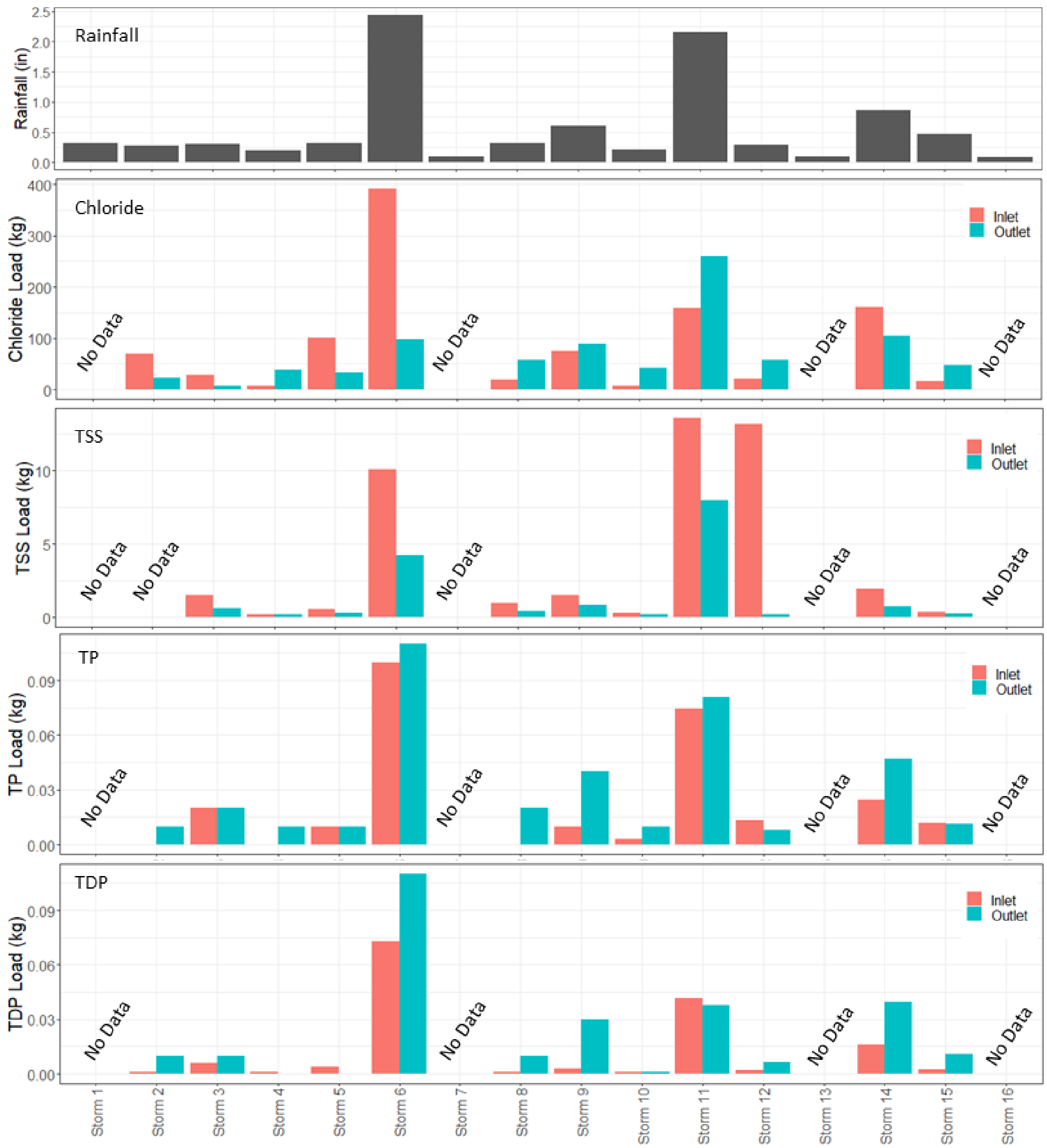


Figure 30. Kennedy Drive inlet and outlet Cl-, TSS, TP, and TDP loads in Year 1 (2020).

Year 2 Results

Chloride loadings at the inlet and outlet of the Kennedy Drive wetland were measured from eight storm events in Year 2. The reduction in Cl- loads between the inlet and outlet were variable across the eight monitored storm events. Four storm events had a reduction in Cl- loads at the outlet and four events had an increase in Cl- loads. There were no consistent positive or negative trends in chloride loads between the inlet and outlet over the duration of Year 2. Additionally, there was no strong correlation between the rainfall amount and the chloride loads entering the inlet (Spearman's $\rho = 0.57$). Across the eight monitored storms, at least 50 kg of chloride entered the system during an event. The maximum chloride load that entered the system in Year 2 was 487 kg during Storm 10 and its corresponding outlet load was 376 kg (Figure 31). The elevated chloride import and export during this storm relative to the other monitored storms may be attributed to sources of chloride from nearby road salt applications in the previous winter months. In a larger rain event such as Storm 10 (1.02 inches), the static source of chloride within the drainage area is anticipated to mobilize with runoff and influx the system. The chloride load that remained within the system across the two year monitoring period was investigated by analyzing the chloride uptake from the engineered soil layer and the wetland vegetation within the two treatment cells.

TSS loadings at the inlet and outlet were collected from eight storm events in Year 2. The average reduction of TSS loads from the inlet to the outlet was 90% over the duration of the Year 2 monitoring period. TSS reductions of at least 90% were observed for five out of the eight events (Figure 32). Storm 7 was the only event that demonstrated an increase in the TSS load at the outlet. This additional export of TSS between the inlet and outlet was 10 kg, which is an extremely small increase relative to the magnitude of TSS removed from effluent in all the remaining storm events (741 kg). The system's performance with TSS removal from effluent in Year 2 was highly effective, particularly during storms that had greater TSS loads entering the system.

TP loadings at the inlet and outlet were collected from eight storm events in Year 2. TDP loadings were calculated for seven storm events. TP loads increased in the effluent for five out of the eight storm events. TDP loads increased in the effluent during all seven storms (Figure 31). The reduction efficiency of both TP and TDP loads from effluent were extremely poor in Year 2. In fact, the TDP reduction efficiency decreased between Year 1 and Year 2. TP reduction efficiency increased slightly between Year 1 and Year 2. This small increase may be attributed to the fact that particulate phosphorus is bound to sediment within the system. Since TSS removal was highly effective in Year 2, it is likely that the particulate phosphorus bound to this sediment was retained in the system and contributed to slightly improved TP reduction efficiency, but not enough to offset losses of TDP. The fraction of TP that is in dissolved form was high during storm events with high rainfall (Spearman's $\rho = 0.75$). It is expected that removal of TP and TDP will continue to be poor at the Kennedy Drive system until there are enough storm events to flush out the more readily available P forms in the wetland muck material (see lab study results below). Extended monitoring of TP and TDP loading within the system will determine how long this "flushing" period will last until the wetland begins retaining enough phosphorus to observe the desired P load reductions.

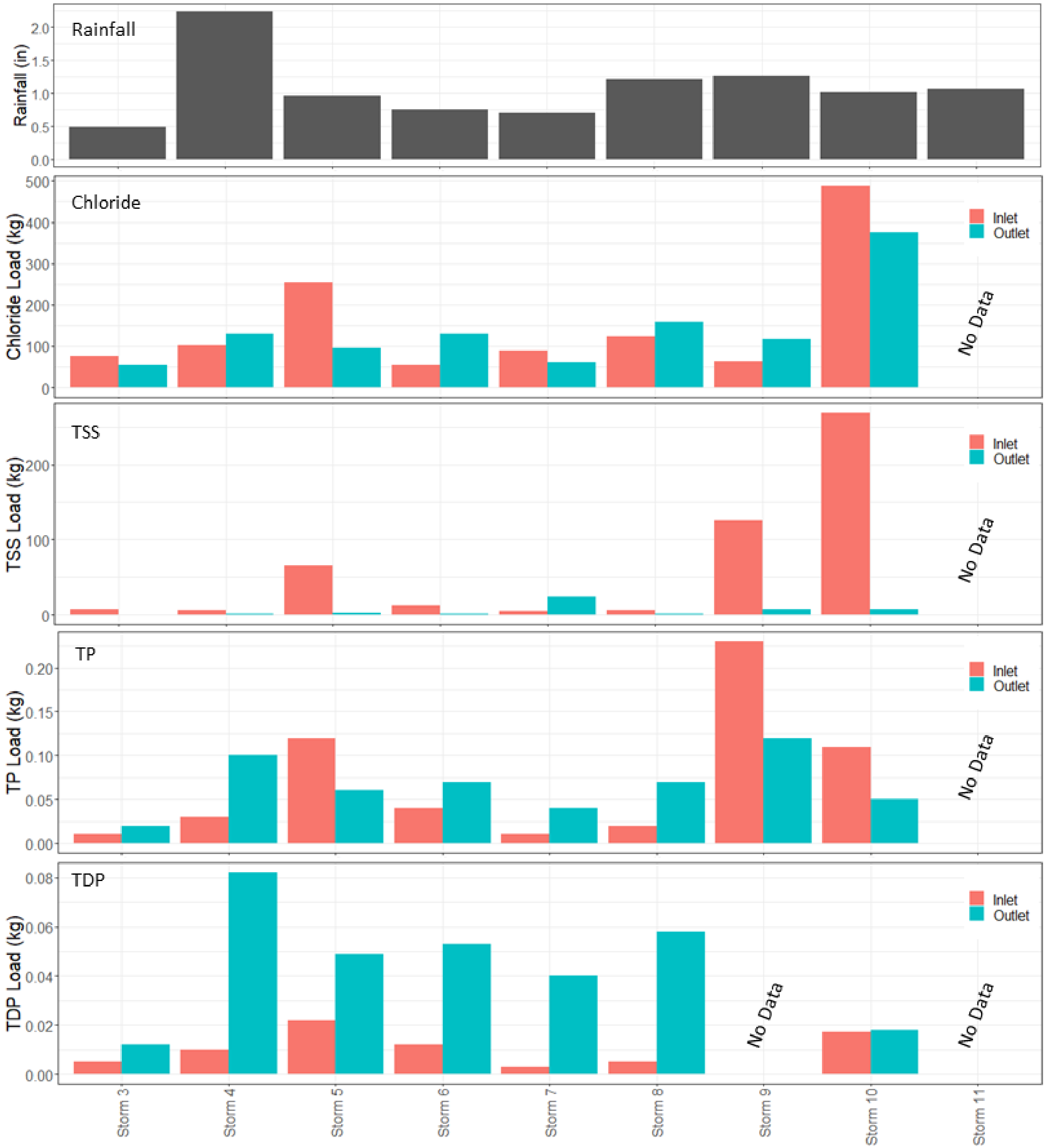


Figure 31. Kennedy Drive inlet and outlet Cl-, TSS, TP, and TDP loads in Year 2 (2021).

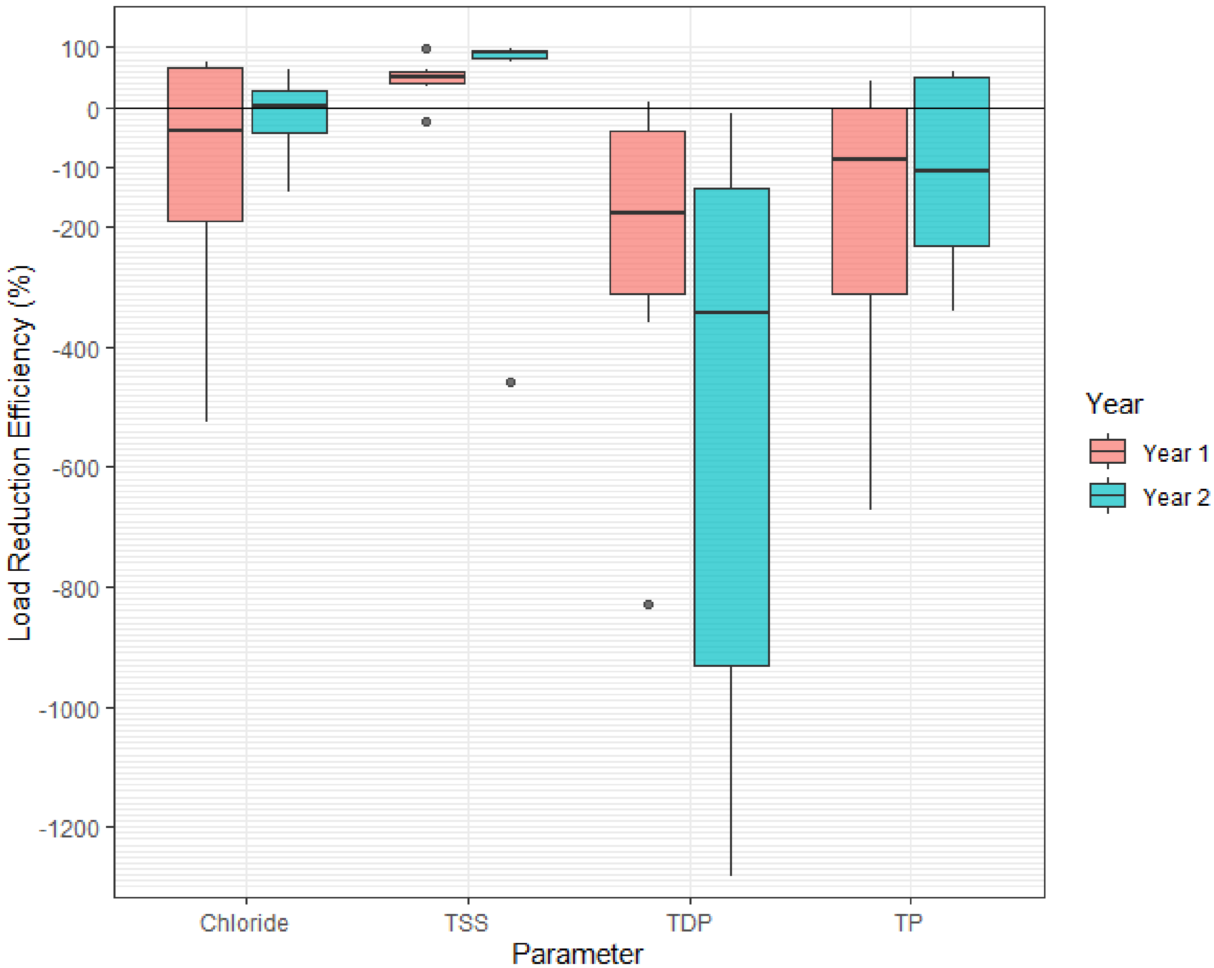


Figure 32. Load reduction efficiency of Chloride, TSS, TDP and TP in Years 1 & 2 at the Kennedy Drive gravel wetland.

Fairview Drive

Year 1 Results

Chloride loading at the inlets and outlet of the Fairview Drive gravel wetland were collected from 5 storm events in year 1. The total chloride inlet loading, as displayed in Figure 33 below, is the sum of the inlet loadings from the Fairview Inlet, the FV Drive Inlet and the Route 15 Inlet. Chloride loading into the system was greatest during the larger storm events, with a strong positive correlation identified between rainfall intensity and loading rate (Spearman's $\rho = 0.9$). There also appeared to be a relatively strong positive correlation between the outlet and rainfall intensity (Spearman's $\rho = 0.9$). In the two largest storm events, it was observed that roughly the same load entering the system was leaving. In the three smaller storm events, reductions in chloride content were observed across the board with an average load reduction in Year 1 of 44.23% (Figure 33).

TSS loading at the inlets and outlet of the Fairview Drive gravel wetland were collected from 6 storm events in Year 1. There was a relatively strong positive correlation between TSS and chloride inflow (Spearman's $\rho = 1$), as was expected considering the correlative nature of these two constituents. Unlike chloride however, the Fairview gravel wetland displayed significant reductions in TSS during every rainfall event, large or small with an average load reduction in Year 1 of 91.76% (Figure 33).

TP and TDP loadings were collected from the same 6 storm events as TSS. Similar to the other constituents, TP and TDP inlet loadings showed a strong positive correlation to rainfall intensity (Spearman's $\rho = 1$ and Spearman's $\rho = 1$, respectively). The most significant reductions in TP and TDP occurred during the two largest rain events, this is in stark contrast to chloride reductions, which as previously noted was worse during larger events. The average load reduction in Year 1 of TP and TDP were 57.26% and 55.28% respectively (Figure 37).

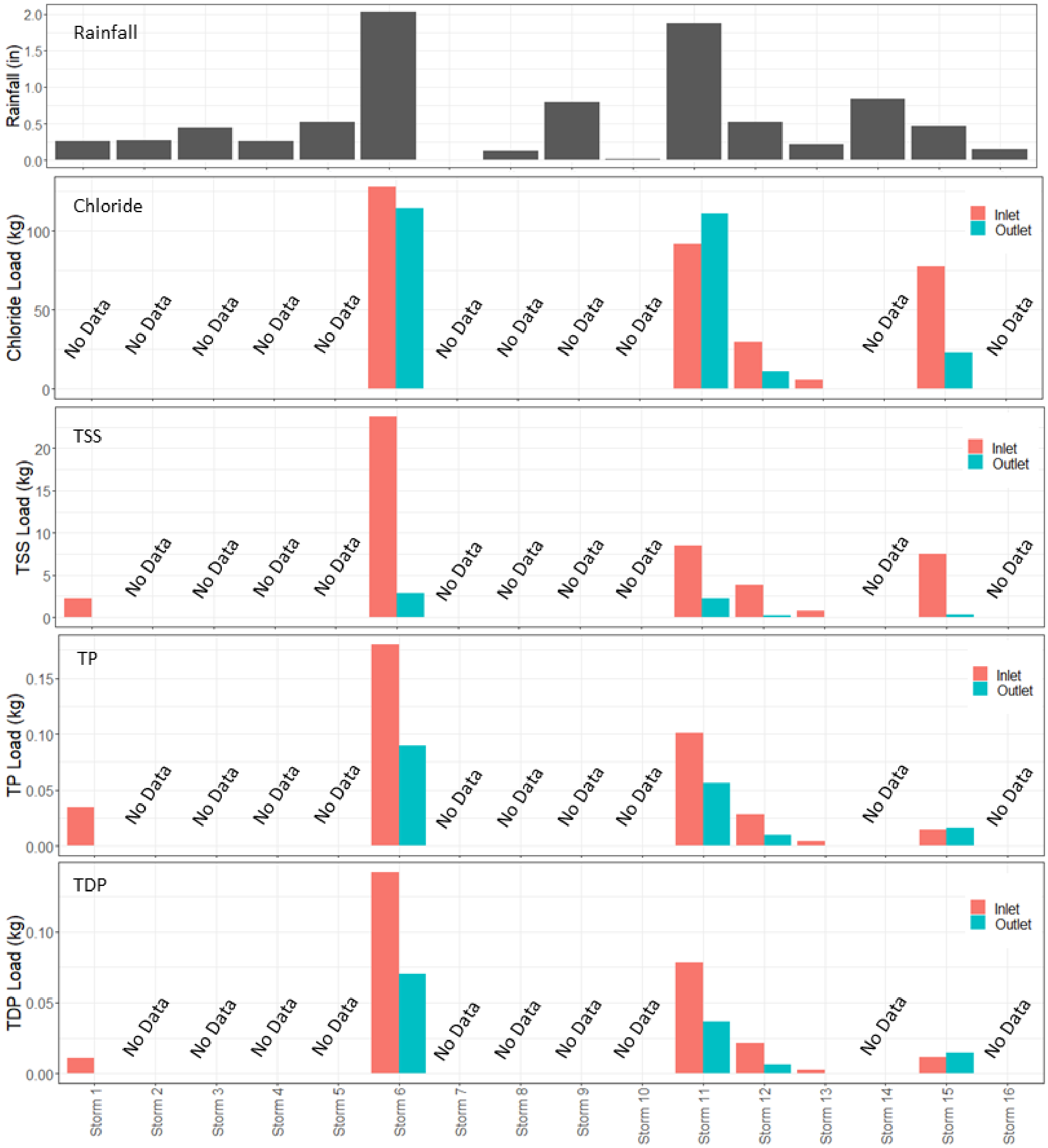


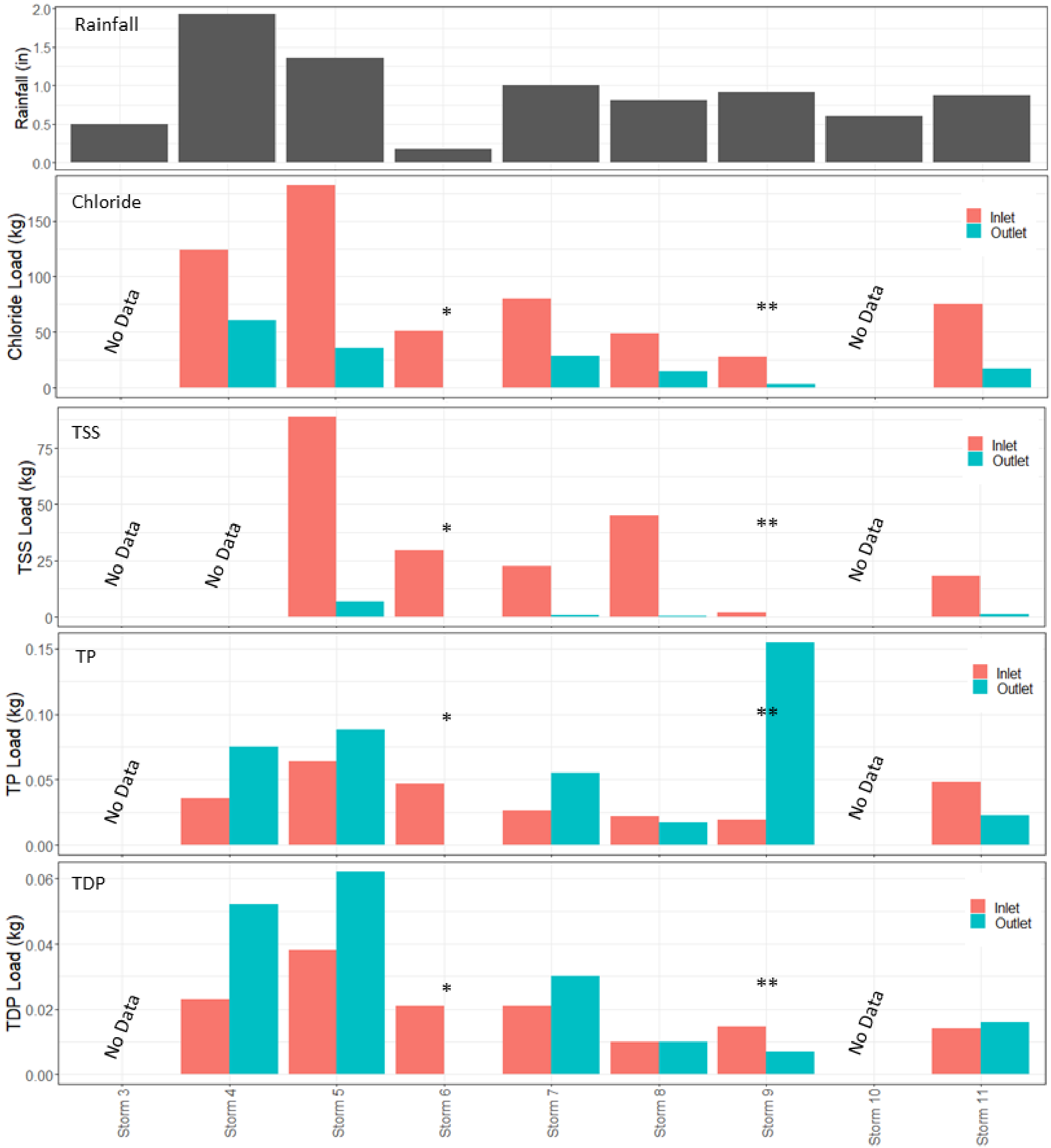
Figure 33. Fairview Drive inlet and outlet Cl-, TSS, TP, and TDP loads in Year 1 (2020).

Year 2 Results

Chloride loading at the inlets and outlet of the Fairview Drive wetland were collected from seven storm events in Year 2. Just as in Year 1, the total chloride inlet loading, as displayed in Figure 34 below, is the sum of the inlet loadings from the Fairview Inlet, the FV Drive Inlet, and the Route 15 Inlet. Chloride loading into the system was greatest during the two largest storm events (Storms 4 and 5). However, the positive correlation between chloride loading inflow and rainfall intensity was relatively weak (Spearman's $\rho = 0.6$). The average load reduction in Year 2 for chloride was 73.79% (Figure 34). This was a 29% improvement in reduction efficiency from Year 1.

TSS loading at the inlets and outlet of the Fairview Drive gravel wetland were collected from six storm events in Year 2. While the largest storm in Year 2 did lead to the largest inflow in TSS, there was no discernible relationship between rainfall intensity and TSS entering the system, similar to chloride. TSS outflow however, did show a strong positive correlation with chloride (Spearman's $\rho = 0.94$) and TDP (Spearman's $\rho = 0.94$) leaving the system. The loading plots, as shown in Figure 34, do show notable reductions in TSS in every storm event, with an average load reduction in Year 1 of 96.04% (Figure 37). This was a 4.28% improvement from Year 1.

TP and TDP loadings were collected from seven storm events. TP and TDP loads entering the system showed minimal correlation with rainfall intensity (Spearman's $\rho = 0.26$ and Spearman's $\rho = 0.55$, respectively). Interestingly however, the outflow of these constituents from the system did show strong relationships with rainfall (TP Spearman's $\rho = 0.83$ and TDP Spearman's $\rho = 0.83$). This aligns with the observed trend of more TP and TDP leaving the system then entering in Year 2. The greatest amount of TP export occurred in Storm 9. The average load increase in Year 2 of TP and TDP were 13.79% and 24.00% respectively (Figure 37). This was a 71.04% and 79.27% decline from Year 1.



* Inlet load was the sum of Route 15 Inlet & FV Drive Inlet only. No flow at Fairview Inlet. No flow at outlet.

** Inlet load was the sum of Fairview Inlet & FV Drive Inlet only. No data available from Route 15 Inlet.

Figure 34. Fairview Drive inlet and outlet Cl-, TSS, TP, and TDP loads in Year 2 (2021).

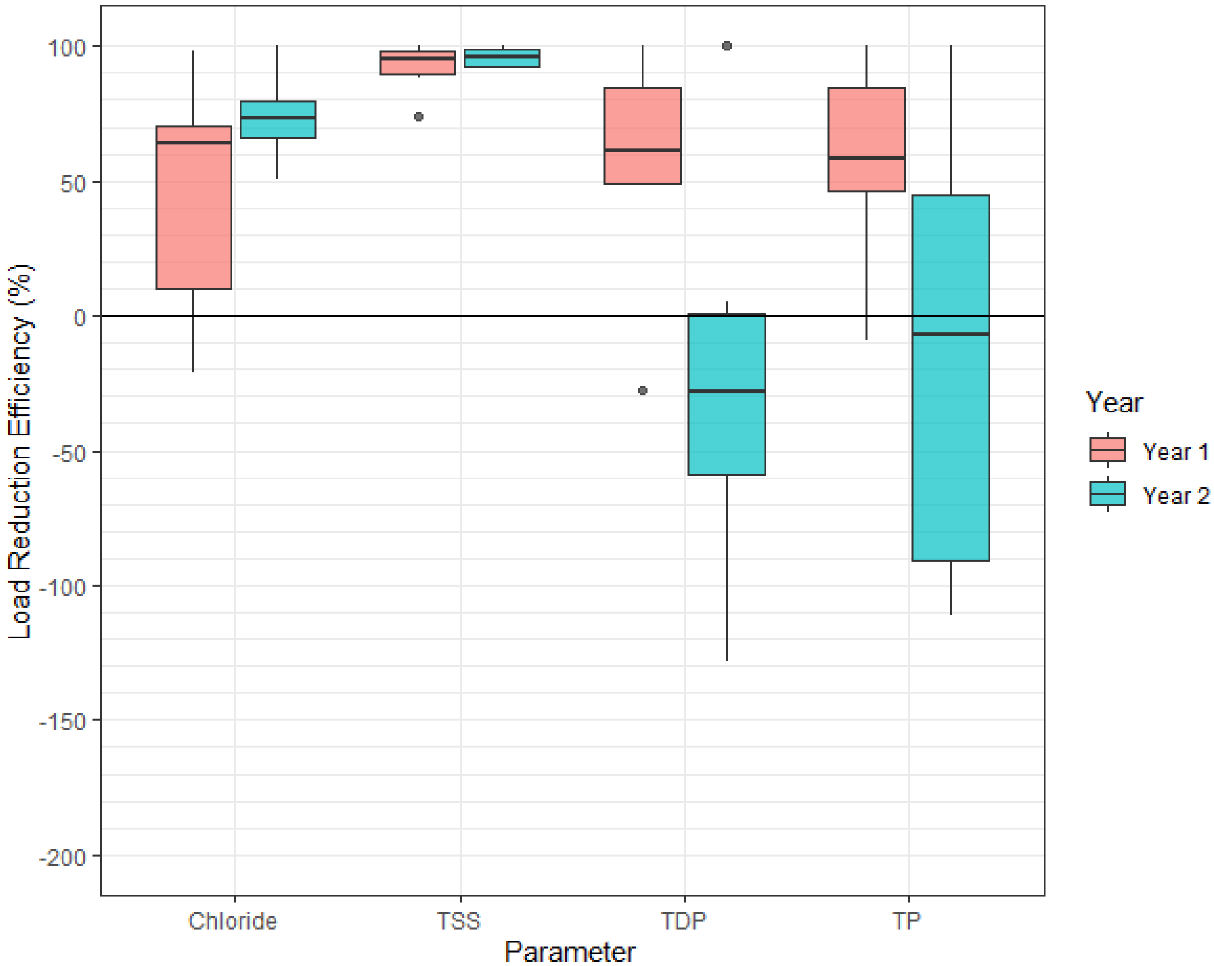


Figure 35. Load reduction efficiency of Cl-, TSS, TDP, and TP in Years 1 & 2 at the Fairview Drive wetland.

Vegetation Performance

Kennedy Drive

An evaluation of total dry weight biomass per unit area found that plant growth was greater in August of 2021 than in October of 2020 (Figure 39). During both sampling periods, vegetation biomass appeared to be the most abundant at the inlet and the sparsest at the midpoint upon visual inspection (Figure 39). This was substantiated by the total dry weight biomass per unit area which was consistently greatest at the inlet and lowest at the midpoint. To evaluate spatial and temporal variability in the vegetation performance, the coefficient of variation (CV) was calculated. It is a metric that has been used before to assess variability in soil conditions (Loescher et al., 2014). The CV in biomass between the sampling locations was similar in October 2020 (CV=26.15) and in August 2021 (CV=23.73).

The total dry weight biomass per unit area did not equate to chloride content however, as the outlet cross-section showed to have consistently the greatest chloride content with the inlet and midpoint displaying less (Figure 39). At the inlet and midpoint chloride content was greater in the samples collected in October 2020 than during August 2021. Variability in chloride content between the two sampling periods was discernibly different as October 2020 showed minimal variability (CV = 12.85) and August 2021 showed slightly more variability (CV = 48.53). This is in contrast to the variability in biomass between the sampling locations which was similar.

Figure 36. Kennedy Drive wetland vegetation over time. Year 1 photos are on the top, and Year 2, 2021, on the bottom.

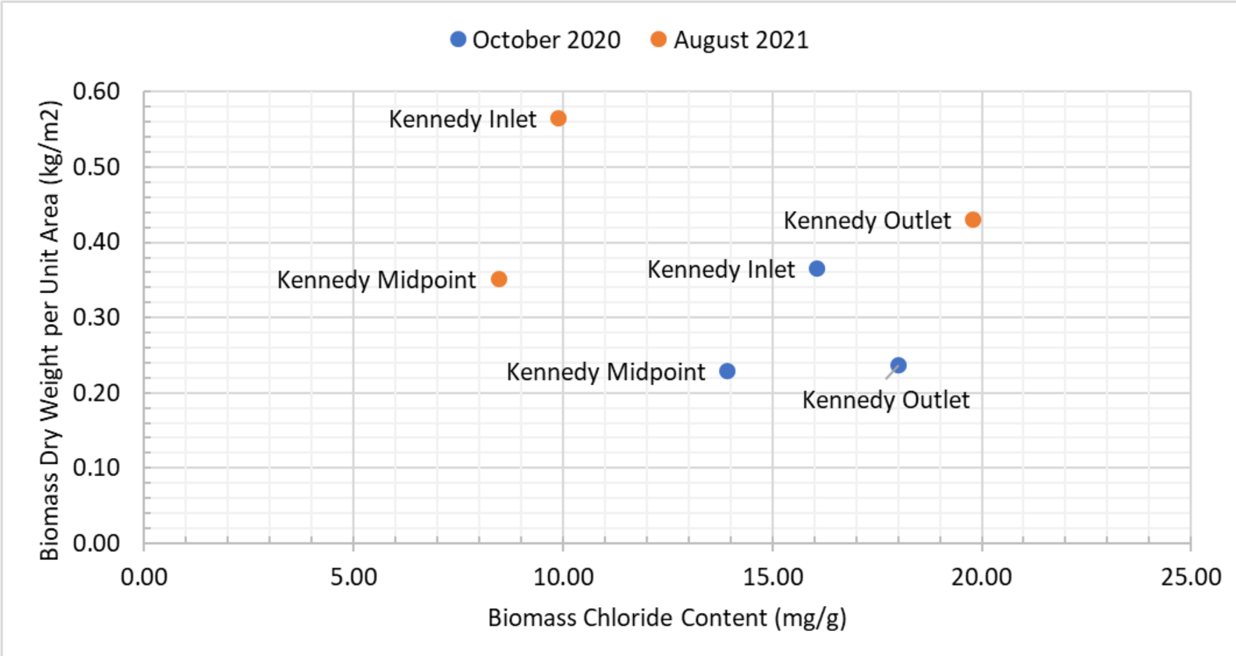


Figure 37. The chloride content of plant biomass in comparison to its dry weight per unit area in Kennedy Drive cross-sections.

Fairview Drive

An evaluation of total dry weight biomass per unit area found that plant growth was greater in August of 2021 than in October of 2020 (Figure 41). This is consistent with the results of Kennedy Drive as well. In October 2020, variance between cross sections was minimal (CV=31.77) with the Fairview Inlet and Outlet showing to have similar amounts of biomass and the Fairview Midpoint about half as much. In August 2021, variance in biomass between cross-sections was only slightly greater (CV=36.74) with slightly more vegetation found at the inlet in comparison to the midpoint and outlet (Figure 41).

Results of the analysis of the chloride content within the vegetation biomass of the Fairview wetland revealed there was notably more chloride content in plant biomass collected during the October 2020 season than in August 2021. There was minimal discernable variance in chloride content between the cross-section sampling locations during October 2020 (CV = 21.05) and August 2021 (CV = 14.88). Across both sampling seasons there is a clearly defined inverse relationship between plant biomass chloride content and plant biomass dry weight per unit area. This relationship is consistent with findings that suggest that chloride can have an adverse effect on plant growth (Shambaugh, 2008).

April 3rd, 2020

August 4th, 2020

October 25th, 2020

July 2021

August 2021

October 2021

Figure 38. Fairview Drive vegetation growth over time in 2020, Year 1 of sampling, and Year 2, below.

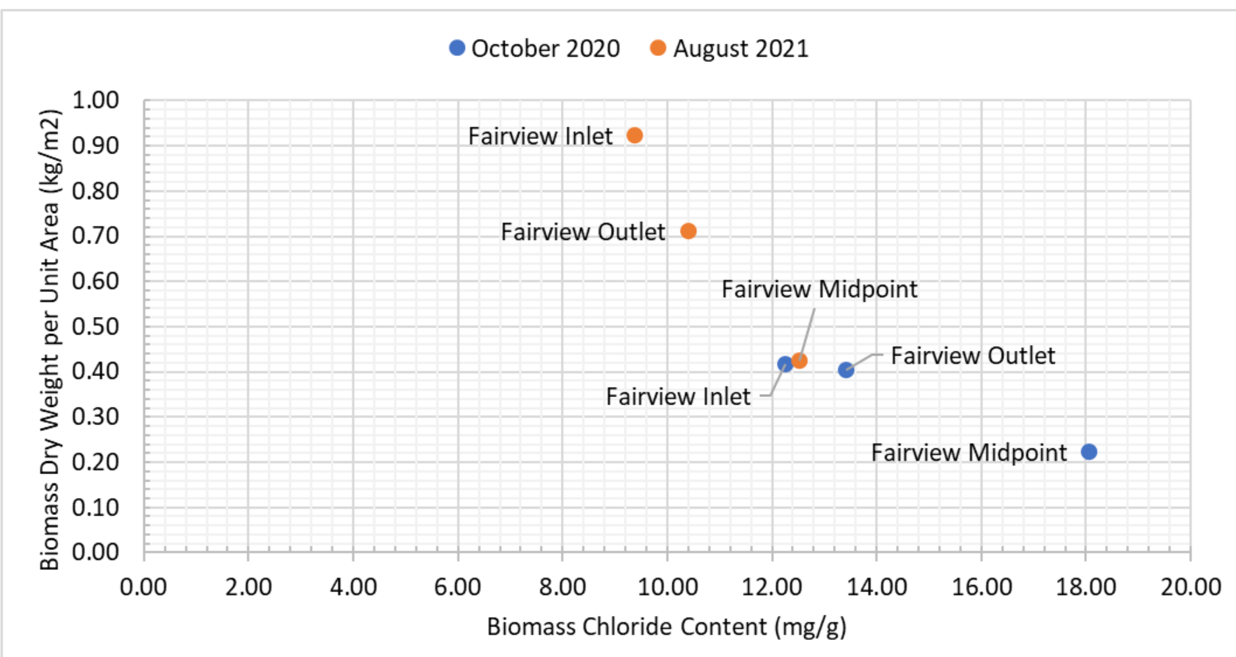


Figure 39. The chloride content of plant biomass in comparison to its dry weight per unit area in Fairview cross-sections.

Vegetation Performance Compared to Published Literature

Using high-salt accumulating plants to treat chloride is a form of phytoremediation known as phytodesalinization. This is a process that has been studied under a number of varying conditions and with different species, however there is limited information on the comparative potential of different species under the same conditions, specifically in the context of constructed wetlands (Lymbery et al., 2006; Morteau et al., 2009; Nilratnisakorn et al., 2009; Rozema et al., 2014; Rozema et al., 2016; Shelef et al., 2012). See Appendix E for the wetland seed mix listing for the Kennedy Drive and Fairview Drive wetland systems. A summary of vegetation performance studies, methods, and materials can be found in the following table.

Table 10. Literature Review of Vegetation Performance.

Citation	Summary of Methods	Summary of Results
Lymbery et al., 2006	*"Replicate plots of a pilot-scale, subsurface-flow wetland treatment system incorporating the estuarine sedge Juncus kraussii were constructed to test the relative efficacy of sodium chloride (NaCl) removal over a 38 day period."*	*"Overall nutrient levels, plant growth decreased with increasing salinity of the inflow water."* Percentage of NaCl removed from the different treatments ranged from 43.8% to 53.0%.
Morteu et al., 2009	*"Typha latifolia, Atriplex patula, and Spergularia canadensis were selected and assessed for their ability to survive and grow in salted water by accumulating salt in their tissues."* Chloride accumulation experiments were conducted over a 2 month period.	*"Accumulation of chloride has been found significant for all species. Typha latifolia showed the best accumulation of chloride 63 mg Cl/g of dry mass."*
Shelef et al., 2012	*"We performed three experiments to evaluate the capability of B. indica for salt phytoremediation as follows: a hydroponic system with mixed salt solutions, a recirculated vertical flow constructed wetland (RVFCW) with domestic wastewater, and a vertical flow constructed wetland (VFCW) for treating goat farm effluents."*	*"B. Indica plants developed successfully in all three systems and reduced the effluent salinity by 20–60% in comparison with unplanted systems or systems planted with other wetland plants."*
Rozema et al., 2014	*"Two microcosm experiments were conducted to evaluate eight plant species including Atriplex prostrata L. (triangle orache), Distichlis spicata (L.) Greene (salt grass), Juncus torreyi Coville. (Torrey's rush), Phragmites australis (Cav.) Trin. Ex Steud. (common reed), Spartina alterniflora Loisel. (smooth cordgrass), Schoenoplectus tabernaemontani (C.C. Gmel.) Palla (softstem bulrush), Typha angustifolia L. (narrow leaf cattail), and Typha latifolia L. (broad leaf cattail) for their Na+ and Cl– accumulation potential."*	*"An initial (indoor) experiment determined that J. torreyi, S. tabernaemontani, T. angustifolia, and T. latifolia were the best candidates for phytodesalinization. J. torreyi, S. tabernaemontani, T. angustifolia, and T. latifolia accumulated 25.7, 18.2, 31.6, and 27.2 g·m−2 of Cl–, respectively."*
Rozema et al., 2016	*"To determine the ideal frequency of CW plant harvesting, an 18-week, outdoor microcosm experiment was conducted in which three wetland*	*"The average Na+ and Cl− removal efficiencies of the all treatments were low, between 1–5 % for Na+ and 7–15 %*

	plant species, Juncus torreyi Coville. (Torrey's rush), Schoenoplectus tabernaemontani (C.C. Gmel.) Palla (softstem bulrush), and Typha latifolia L. (broad leaf cattail), were subjected to one, two or three harvesting treatments."	*for Cl−, suggesting that phytodesalinization may not be the best option for Na+ and Cl− treatment."*

Lab Studies

Plants vary in their tolerance of chloride (Shambaugh, 2008), as evidenced by the results of the lab bioassay component of this project. Broadfruit bur-reed (BFB) biomass after 8 weeks did not significantly differ across chloride treatments (ANOVA, p = 0.112) (Figure 40). Shallow sedge (SS) biomass, however, declined with increased chloride, with biomass for the 100% treatment significantly lower than the 0% treatment (Dunn-Bonferroni, p = 0.022) (Figure 40).

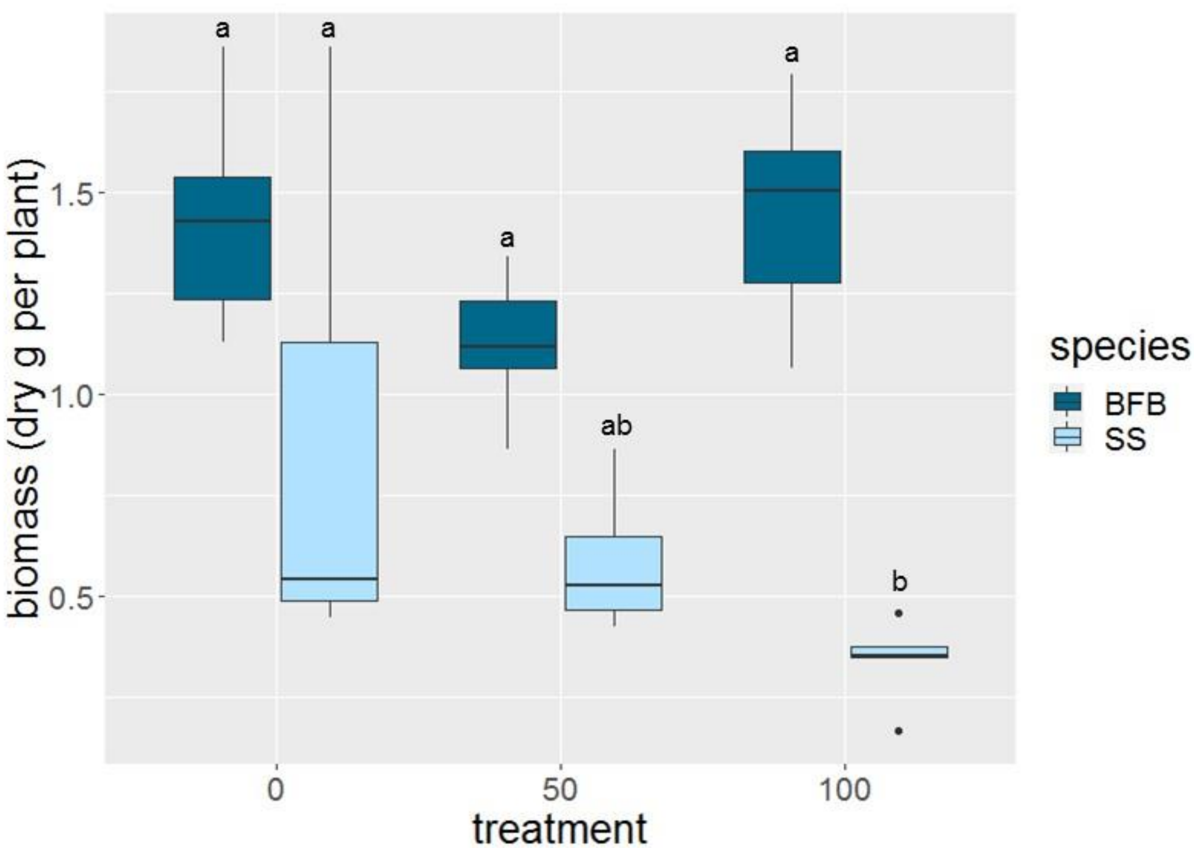


Figure 40. Bioassay aboveground biomass results after 8 weeks for broadfruit bur-reed (*Sparganium eurycarpum*, BFB) and shallow sedge (*Carex lurida*, SS) irrigated with water having chloride concentrations equivalent to 0% (0 mg Cl/L), 50% (325 mg Cl/L), or 100% (650 mg Cl/L) of that observed for urban stormwater in Vermont. Different letters across boxplots for each species (n = 5 per species-treatment combination) indicate significant differences (Dunn-Bonferroni, p < 0.05).

Chloride contents in plant tissue (Figure 41A) and soil (Figure 41C) at the conclusion of the 8-week bioassay indicated clear effects of the chloride treatment, with increasing chloride in plant tissues and soils as the chloride concentration in the irrigation water increased. These results illustrate plant assimilation of chloride, as well as retention of chloride in the soil matrix under conditions of prolonged inundation where some irrigation water could be lost via evaporation, concentrating any chloride added over the course of the experiment. Soil electrical conductivity largely followed the same trends as soil chloride (Figure 41D), while chlorophyll-a appeared unaffected by treatment for BFB, but was greater at greater chloride loading conditions with lower biomass for SS (Figure 41E). Increased chlorophyll *a* has been observed as a salinity stress response for some plant species (Acosta-Motos et al., 2017; Agathokleous et al., 2020), which may help explain the observations in this study for shallow sedge.

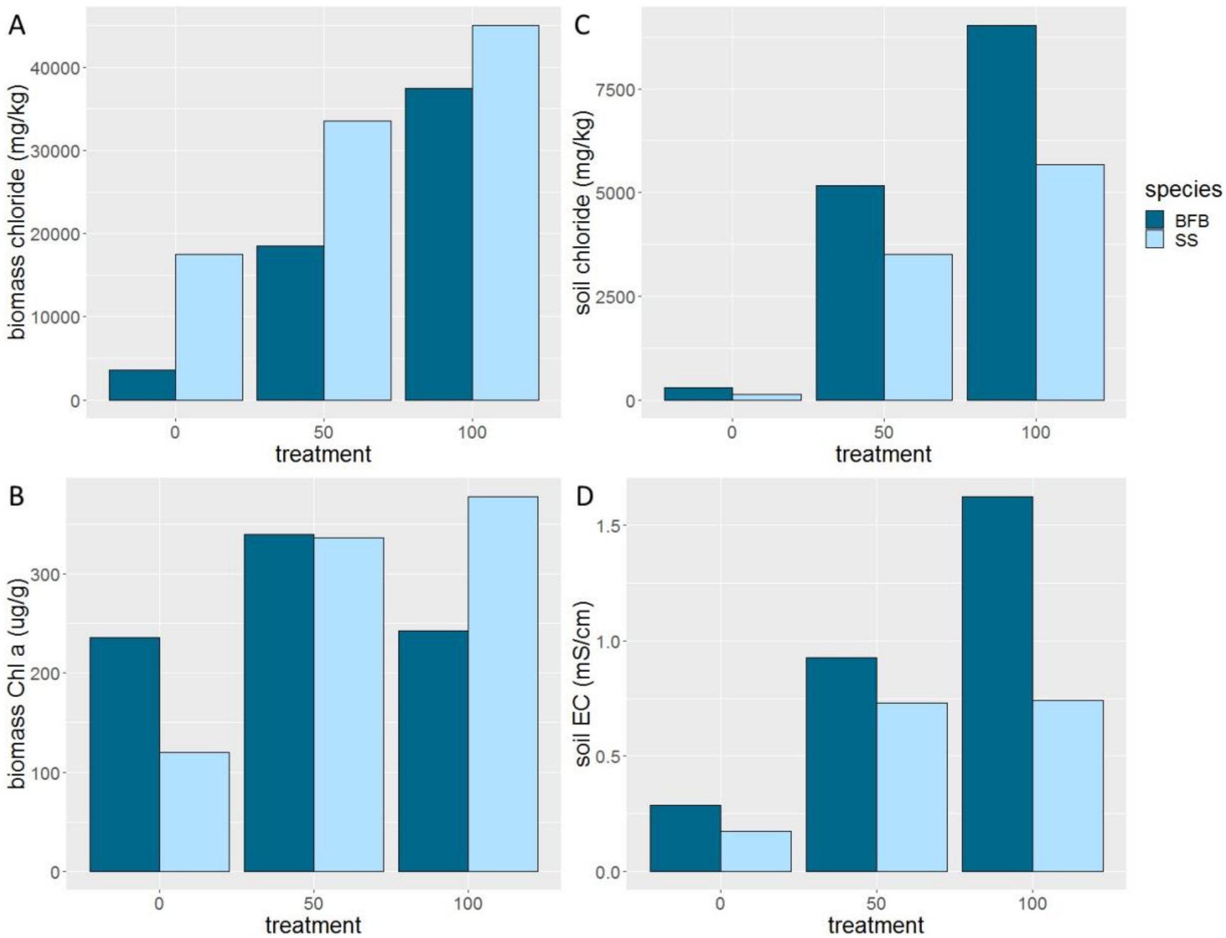


Figure 41. Bioassay aboveground biomass and soil characteristics after 8 weeks for broadfruit bur-reed (*Sparganium eurycarpum*, BFB) and shallow sedge (*Carex lurida*, SS) irrigated with water having chloride concentrations equivalent to 0% (0 mg Cl/L), 50% (325 mg Cl/L), or 100% (650 mg Cl/L) of those observed in Vermont. Data are means of duplicate samples. Chl a = chlorophyll *a*. EC = electrical conductivity.

Wetland Soil Muck and Gravel Media

Lab Studies

Table 11 displays the values of water extractable P (WEP), Modified Morgan P (MM-P), Mehlich-3 P (M3-P), Mehlich-3 P Saturation Ratio (M3-PSR), and K_{sat}. WEP, MM-P, M3-P, and M3-PSR were all substantially greater for engineered muck #1 (em1), engineered muck #1 after ~1 year in the field (em1_f), and engineered muck #2 (em2) compared to engineered muck 3 (em3) and the two native soils (ns1 and ns2). The WEP, MM-P, M3-PSR results suggest that labile P content dropped in em1 after 1 year in the field (em1_f). Engineered muck #3 had similar WEP and K_{sat} values compared to the native soils. Engineered muck #1 (em1 and em1_f) was the only muck material tested with a K_{sat} value < 1 ft day^{-1}, and all materials tested had K_{sat} values at least one order of magnitude greater than the target specification of 0.01 ft day^{-1}. The K_{sat} for engineered muck #2 was especially high, measuring close to that of coarse sand.

Table 11. Phosphorus metrics and saturated hydraulic conductivity for the muck materials tested in this study.

Sample	WEP	Modified Morgan	Mehlich-3		Ksat
	(mg P kg^{-1})	(mg P kg^{-1})	(mg P kg^{-1})	PSR	(ft day^{-1})
em1	41 ± 3	307	339	1.34	0.49 ± 0.29
em1_f	22 ± 0	192	316	0.75	0.32 ± 0.11
em2	27 ± 5	572	676	1.00	65.1 ± 26.2
em3	3 ± 2	30	161	0.10	6.72 ± 5.78
ns1	1 ± 1	2	10	0.01	5.57 ± 4.95
ns2	2 ± 0	3	56	0.04	2.40 ± 2.58

In the muck column experiments, six muck treatments and two controls (i.e., blank) in total were run in triplicate and monitored across 6 daily simulated storm events using synthetic stormwater (0.2 mg PO_4-P/L, 0.5 mg NO_3-N L^{-1}, 0.5 mg NH_4-N L^{-1}, and 650 mg Cl^-/L) as influent. Muck columns were run in two experiments: Experiment 1 included a control and three engineered mucks (em1, em2, and em3). Experiment 2 included a control, one engineered muck following ~1 year of residence in a field system (em1_f), and two native soil materials (ns1 and ns2). In muck Experiment 1, the linear model log10(SRP) ~ muck × storm (R^2 = 0.81, p < 0.001) indicated that engineered mucks #1 and #2 had significantly greater effluent SRP concentration than the control (p < 0.001 and p = 0.015, respectively) (Figure 42A). The interaction between em1 and storm number was also significant (p < 0.001), as illustrated by the decreasing trend in SRP effluent across storms for em1 in Figure 42A. In muck Experiment 2, effluent SRP concentration was affected by muck material (Kruskal-Wallis rank sum test, p = 0.001) (Figure 42B). SRP concentrations in effluent from the engineered muck collected from the field system (em1_f) were significantly greater than those for both native soils (Dunn-Bonferroni, $p \leq 0.01$ in both cases), but none of the three materials in Experiment 2 differed from the control (Dunn-Bonferroni, p > 0.05 in all cases).

Like SRP, effluent TP concentrations from the muck columns in muck Experiment 1 could be predicted well by a linear model with the form log10(TP) ~ muck × storm (R^2 = 0.83, p < 0.001). The model indicated that all three engineered mucks (em1, em2, and em3) released effluents with significantly greater TP concentrations compared to the control (p < 0.001, p = 0.006, and p = 0.005, respectively) (Figure 42C). The interaction between em1 and storm number was also significant, as TP in effluents from em1 declined in storms 3 and 6 compared to storm 1 (Figure 42C). The greatest SRP concentration observed for em1 was < 1 mg P/L, whereas TP concentration during the initial storm event was on average ~5.5 mg P/L. This indicates substantial potential for P loss from the em1 material via transport of fine particles. For muck Experiment 2, muck treatment significantly affected effluent TP concentration (ANOVA, $p < 0.001$). The engineered muck collected from the field system (em1_f) had significantly greater effluent TP concentrations than the control and both native soils (Tukey post-hoc contrasts, $p < 0.001$ in all cases) (Figure 42D). Native soils did not differ from the control in terms of effluent TP concentrations (Tukey post-hoc contrasts, $p > 0.05$ in all cases).

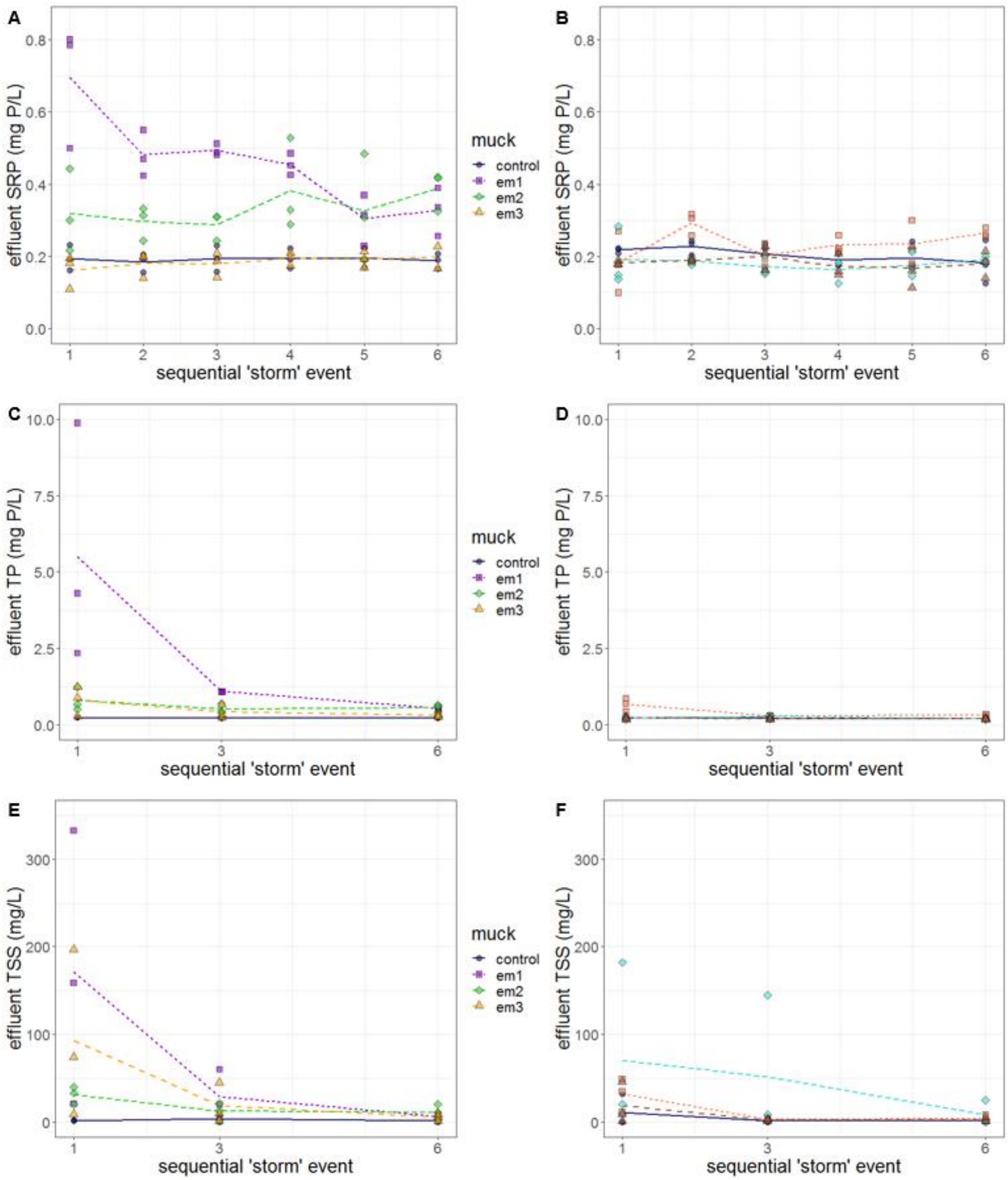


Figure 42. Results from wetland muck column experiments for SRP (A-B), TP (C-D), and TSS (E-F), with all measured effluent concentrations shown as points by treatment and storm event (n=3 replicates per treatment-storm

combination, except in two cases for SRP where n=2). Lines connect mean values for each muck across storm events. SRP was measured for all 6 sequential simulated storms, while TP and TSS were measured for storms 1, 3, and 6. The "control" results are for empty columns subjected to the same experimental conditions (e.g., residence time, stormwater volume) as the treatments including muck materials. Abbreviations: em = engineered muck, ns = native soil, em1_f = engineered muck #1 collected from one of the systems monitored in the field study after ~1 year of exposure to field conditions.

Like SRP and TP, effluent TSS concentrations from the muck columns in muck Experiment 1 could be predicted well by a linear model with the form log10(TSS+1) ~ muck × storm ($R^2 = 0.62$, $p < 0.001$). The model indicated that all 3 engineered mucks (em1, em2, and em3) released effluents with significantly greater TSS concentrations compared to the control ($p < 0.001$, $p = 0.014$, and $p = 0.002$, respectively) (Figure 42E). This confirms transport of fine particles from the mucks and through the geotextile used in the muck columns. The interaction between em1 and storm number was again significant, as TSS in effluents from em1 declined in storms 3 and 6 compared to storm 1 (Figure 42E). In muck Experiment 2, muck treatment did not significantly affect effluent TSS concentrations (ANOVA, $p = 0.065$) (Figure 42F).

Collectively, the muck column testing results (Figure 43) indicate that: (1) Two out of the three engineered mucks tested here will likely be a source of SRP post-installation in the field (em1 and em2). (2) SRP loss from engineered mucks will likely decline over time, as evidenced by the SRP results for em1 (reduced SRP in effluent across successive storms) and em1_f (not different from control), which originated from the same source. (3) SRP leaching was not observed for native soils collected from two SGW field sites (ns1 and ns2). (4) Fine solids with attached P are likely to be lost from all three engineered mucks tested here, adding to the overall P loss from the material on top of SRP leaching, although this loss of fine particles could fade over time, as evidenced by the TSS results for em1_f (not different from control).

Based on the results of the laboratory muck column tests and muck characterization, we developed a recommendation for the P testing requirement to be used for the upper media layer of bioretention systems and gravel wetland soil layers, which was shared with the state of Vermont (see Appendix F). The selection of the upper limit of 0.10 for PSR calculated using Mehlich-3 extractable P, Fe, and Al is supported by multiple lines of evidence:

1. Several soil studies have reported thresholds near 0.10 for Mehlich-3 PSR calculated as specified in Appendix F, above which release of soluble reactive P is more likely to occur (e.g., Nair, 2014 and citations within, Dari et al. 2018).
2. For gravel wetland soils assessed in column leaching tests conducted in this study, those with Mehlich-3 PSR ≤ 0.10 did not leach any soluble reactive phosphorus (Figure 43).
3. Assessment by the Roy Lab of riparian soils in Vermont has found a PSR threshold of ~0.23 for P release based on oxalate-extractable P, Fe, and Al (Wiegman, 2022). Kleinman and Sharpley (2002) found that PSR calculated using Mehlich-3 P, Fe, and Al is ~70% of that determined with the oxalate extraction. Therefore, the VT riparian soil threshold for PSR based on Mehlich-3 extractions can be approximated as 0.23 x 0.7 = 0.16, again suggesting that a PSR limit of 0.10 will be sufficient to reduce P leaching risk.

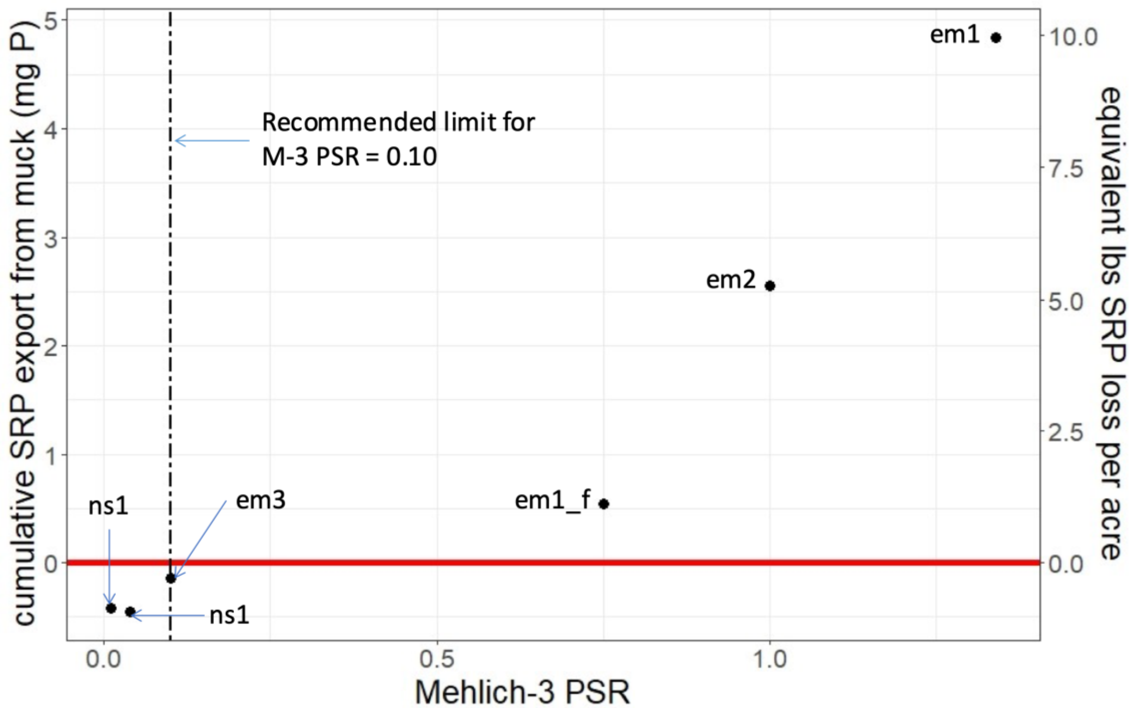


Figure 43. Mean cumulative SRP export (mg P) from muck materials during the lab column testing, including all 6 simulated storm events, versus Mehlich-3 P saturation ratio. Values on the y axes above zero indicate net loss, while values on the y axes below zero indicate net retention. The second y-axis on the right-hand side shows the equivalent areal loss of SRP in lbs P per acre, estimated using the surface area of muck tested in the columns and assuming an 8" depth of the muck layer (same depth used in lab column experiment).

One caveat for the recommended PSR limit described above is that it is possible that a muck material testing at or below PSR = 0.10 could still be a source of other non-SRP forms of P. For example, in our lab study, engineered muck #3 (em3) was a net sink for SRP, but a net source of total P, indicating that other P forms such as particulate inorganic P, particulate organic P, or dissolved organic P were lost from the em3 muck material. Such non-SRP P export will likely be most pronounced immediately following installation as fine particles are transported out of the muck layer.

For the gravel column experiment, the best linear model for effluent SRP concentration included both gravel type and day as predictors (log10(SRP) ~ gravel + day, $R^2 = 0.40$, $p < 0.001$). This model indicated that SRP effluent for all three gravels was significantly less than for the control ($p < 0.001$, p = 0.004, and $p < 0.001$ for granite, quartzite, and limestone dummy variables, respectively) (Figure 44A). Day was also a significant predictor ($p < 0.001$), with results showing a declining trend in SRP concentration for all columns, including the control with no gravel, over the course of the 6-day experiment (Figure 44A). Similar changes were observed in daily influent samples to the gravel columns, suggesting that some SRP was adsorbing to particles present in the feed solution made from muck column effluent over time. For all gravel column experiments in the lab, chloride concentration remained stable near the influent levels (≈ initial synthetic stormwater concentration of 650 mg/L), regardless of gravel material (Figure 45).

For Limestone (g3) column TP effluents were significantly less than the control (Tukey post-hoc contrasts, $p = 0.039$), but no other differences between columns were detected (Figure 44B). TSS concentrations in gravel column effluents were variable and not significantly different from the control (ANOVA, $p = 0.386$) (Figure 44C).

Mean TP effluent concentrations for granite (g1), quartzite (g2), and limestone (g3) columns were 0.30, 0.34, and 0.25 mg P/L (Figure 44B), equal to 150%, 170%, and 125% of the P concentration for the synthetic stormwater solution initially fed to the muck columns (0.20 mg P/L). This illustrates the potential for SGW substrates to cumulatively serve as net P sources, despite evidence of some P retention by all gravels (according to SRP results) and especially limestone (according to SRP and TP results). Average gravel column TSS effluents ranged from 4-15 mg TSS/L (Figure 44C). Considering that the initial synthetic stormwater fed to mucks contained 0 mg TSS/L, these results demonstrate the potential for some export of fine particles from SGWs using these substrates.

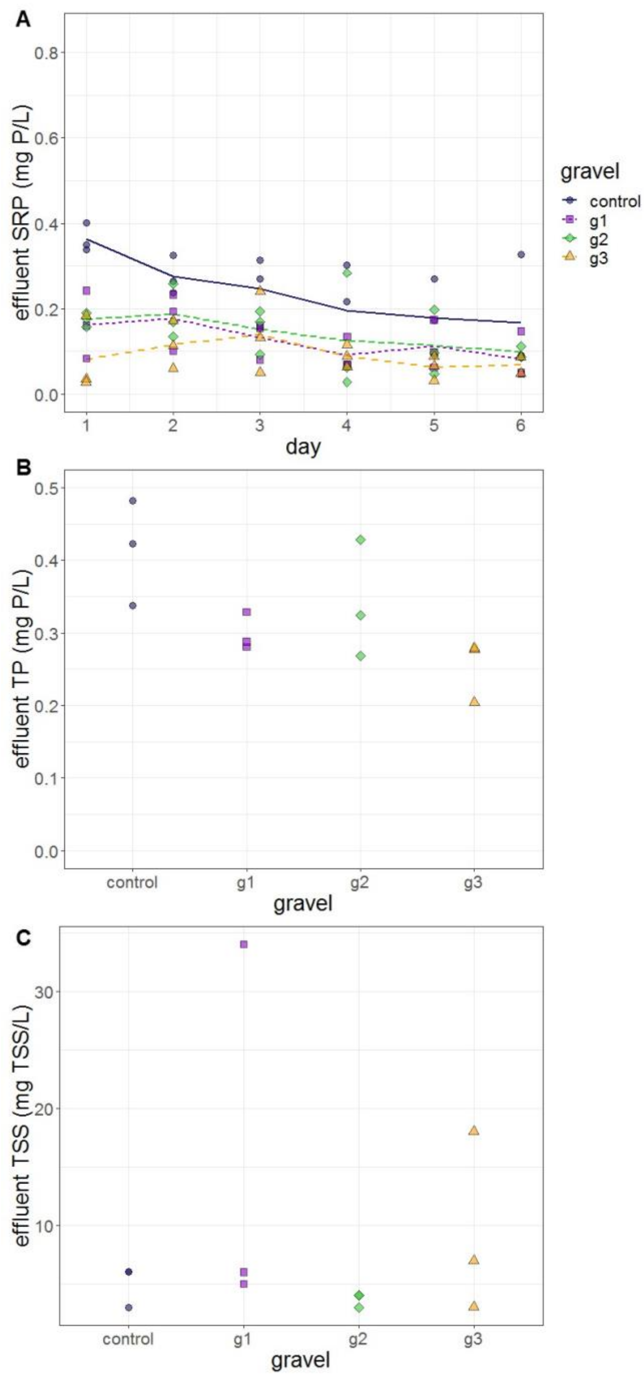


Figure 44. Results from gravel column experiments for SRP (A), TP (B), and TSS (C), with all measured effluent concentrations shown as points by treatment and (in panel A only) day (n=3 replicates in all but 2 cases where n=2). SRP was measured for all 6 days of each experiment, while TP and TSS were measured for representative composite samples made using 6 daily samples for each replicate. The "control" results are for empty columns subjected to the same experimental conditions (e.g., residence time, stormwater volume) as the treatments including gravel materials. Abbreviations: g1 = granite, g2 = quartzite, and g3 = limestone.

For all lab column experiments, chloride concentrations in effluents (from mucks and gravels) and influents (to gravels) remained stable near the initial synthetic stormwater concentration of 650 mg/L, regardless of muck or gravel material (Figure 45). These results indicate that muck and gravel substrates will have minimal direct effects on chloride concentrations as stormwater moves through SGW systems. Indirect effects, however, are possible in the field. For example, water absorbed by the surface muck layer can evaporate over time, enabling (at least temporary) build up of chloride in the muck soil matrix. Additionally, muck materials can facilitate plant growth, leading to assimilation of chloride into biomass (Figure 44A), providing another mechanism of chloride retention and build up.

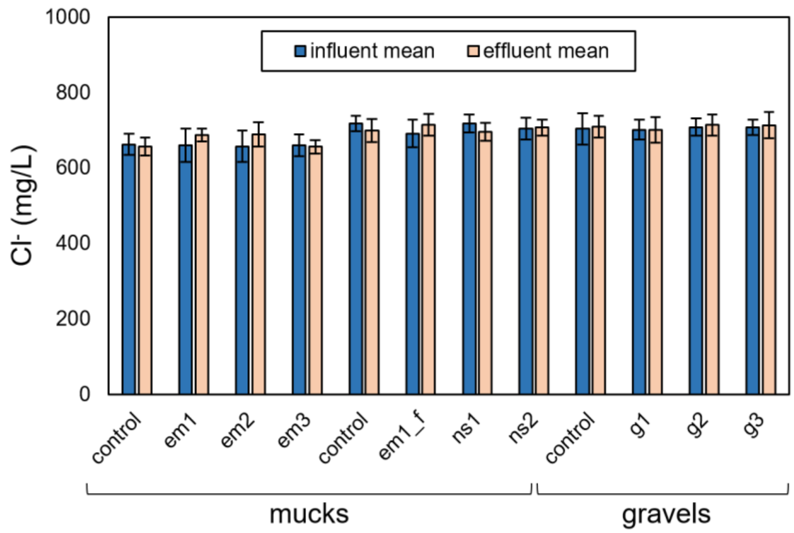
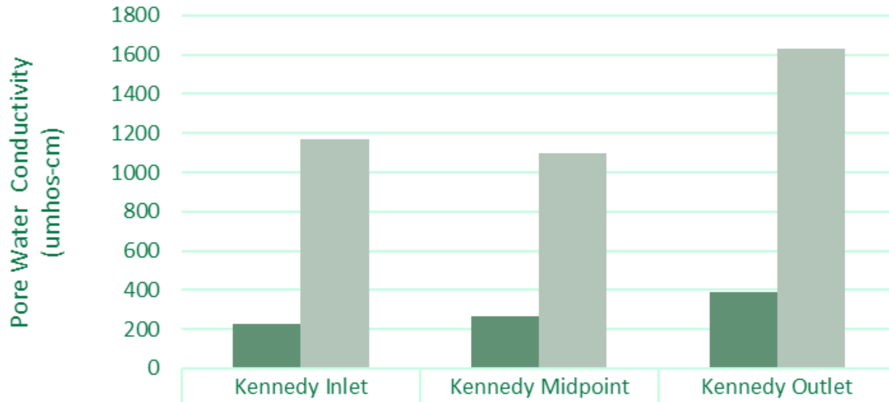


Figure 45. Mean (+/- 1 standard deviation) chloride concentrations for influent and effluent samples for each material tested in the muck and gravel column experiments (n=6 in all cases).

Kennedy Drive - Chloride & Conductivity

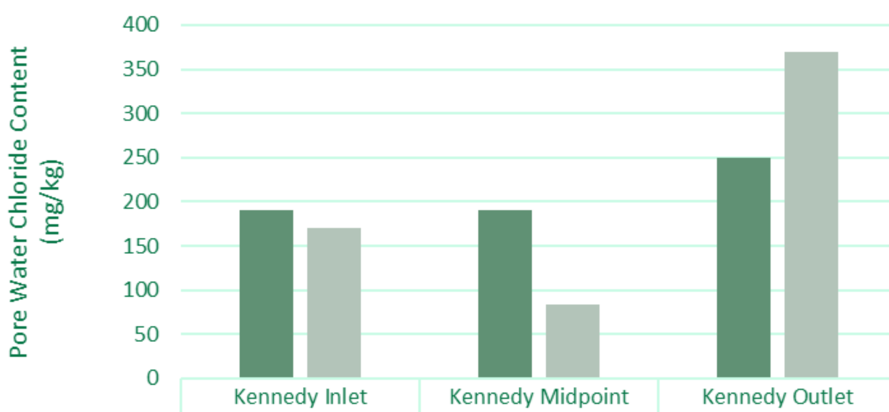
The electrical conductivity (EC) of the soil muck at Kennedy Drive was low when assessed in October 2020, ranging from 227 umhos/cm at the inlet to 391 umhos/com at the outlet (Figure 46). In August of 2021, the EC of muck was notably higher, most so at the outlet (EC = 1630 umhos/cm).



	Kennedy Inlet	Kennedy Midpoint	Kennedy Outlet
October 2020	227	263	391
August 2021	1170	1100	1630

Figure 46. Conductivity of muck at Kennedy Drive, measured in umhos/cm.

Where conductivity differed significantly between the October 2020 and August 2021 sampling periods, chloride did not (Figure 47). In October 2020, muck chloride content was the same at the inlet and midpoint with slightly more at the outlet and minimal variability across the three cross sections (CV = 16.50). In August 2021, the Kennedy midpoint had the lowest chloride content, with the inlet appearing to have slightly more and the most at the outlet. Variability between cross sections was notably greater during this sampling period (CV = 70.55).



	Kennedy Inlet	Kennedy Midpoint	Kennedy Outlet
October 2020	190	190	250
August 2021	170	84	370

Figure 47. Chloride content of muck at Kennedy Drive, measured in mg/kg.

Fairview Drive - Chloride & Conductivity

The electrical conductivity (EC) of muck at Fairview Drive was low when assessed in October 2020, ranging from 257 umhos/cm at the inlet to 338 umhos/com at the outlet (Figure 47). In August of 2021, the EC of muck was notably higher, most so at the outlet (EC = 2420 umhos/cm). This is similar to the results at the Fairview Drive gravel wetland.

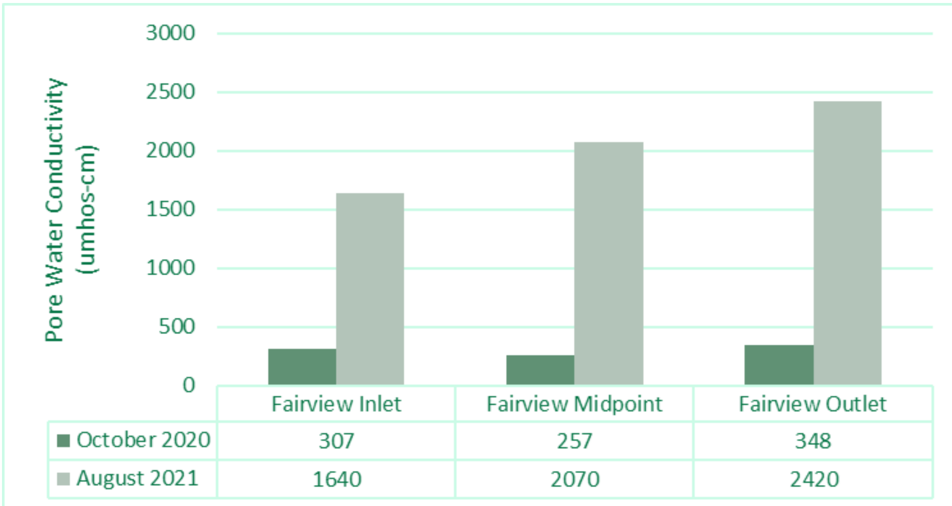


Figure 48. Conductivity of muck at Fairview Drive, measured in umhos/cm.

Similarly to conductivity, chloride content in muck was greater in the samples collected in August 2021 in comparison to those collected in October 2020 (Figure 49). In October 2020, muck chloride content was roughly the same at the inlet and midpoint with slightly more at the outlet and moderate variability across the three cross sections (CV = 60.63). In August 2021, the Fairview midpoint had the lowest chloride content, with the inlet appearing to have slightly more and the most at the outlet. Variability between cross sections was less during this sampling period (CV = 24.25).

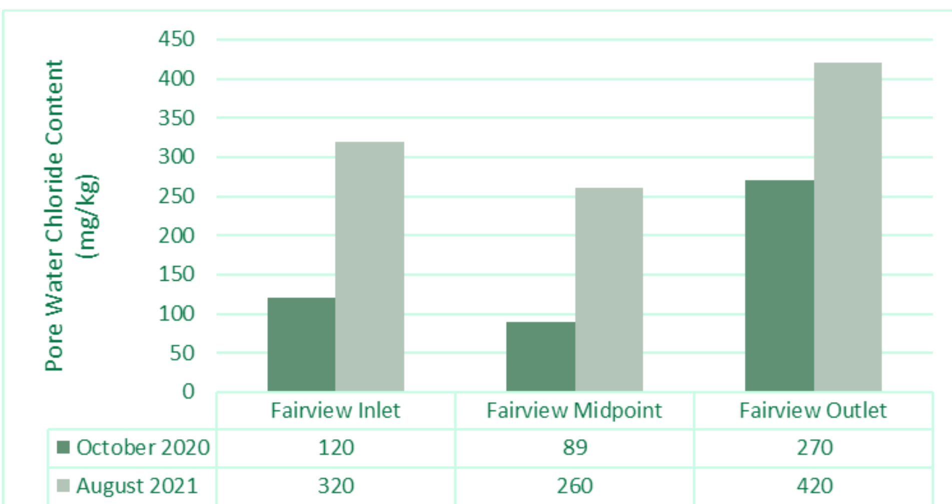


Figure 49. Chloride content of muck at Fairview Drive, measured in umhos/cm.

Challenges Encountered

The experimental field design required innovative solutions in order to function effectively in both of the newly constructed wetland systems. A combination of new and used monitoring equipment was acquired to configure automated flow sampling in the two wetland systems. With most of the used equipment being in poor condition due to damage or age, automated sampling was often disrupted with malfunctions during a storm event. The most salient malfunctions observed in the field was both external battery shutdown while powering the ISCO autosamplers, corroded area-velocity and conductivity sensors, and clogged suction lines.

Additional factors that disrupted data collection were variable temperatures during the summer and fall months as well as sediment accumulation at monitoring locations that displaced equipment. Field staff removed as much sediment as possible and secured equipment prior to each storm to prevent displacement.

Figure 50. The Fairview Drive culvert had significant sediment accumulation during peak stormflow. This was often significant enough to displace the Thel-mar weir and disrupt water level readings.

External battery sources for the ISCO autosamplers were charged for at least twelve hours before every attempted storm sampling. However, if these malfunctions occurred, real time flow rate and conductivity measurements acquired in the field were disrupted, thus producing incomplete or inaccurate datasets and water quality samples that could not be used for analysis. This was a consistent issue particularly at the Fairview Drive wetland as this system required significantly more equipment than the Kennedy Drive system in order to monitor three inlet locations and one outlet simultaneously. As a result of the significant number of incomplete datasets collected during the first monitoring period, particularly at the Fairview Drive wetland, new products were purchased prior to the second monitoring period to replace the damaged or aged equipment.

Field staff continued to ensure that equipment was properly cleaned, calibrated, and secured before each attempted storm. Culverts were cleaned regularly to remove debris and sediment as seen below in Figure 51. The newly acquired internal batteries, sensors, and suction lines for the ISCOs improved the data collection process and were effective in providing accurate datasets to support findings made about each wetland's performance.

Figure 51. Beehive trash rack at the inlet of Kennedy Drive, hidden under debris from the incoming swale, running along Kennedy Drive.

Challenges with vegetation growth and plant tissue sampling were particularly salient at the Kennedy Drive wetland. Due to the acute level of chloride loads entering the system and saturating the soil muck layer, the seed mixes applied in 2020 struggled to establish within the two treatment cells during the first monitoring year. Subsequently, the volume of plant tissue sampled was incredibly sparse at the inlet, midpoint, and outlet in Year 1. However, vegetation growth improved significantly in Year 2. Additional plant species that were not in the original wetland seed mix began establishing in the 2021 growing season. This allowed for a higher volume of plant tissue samples at the inlet, midpoint, and outlet volumes in 2021.

Figure 52. In 2020, the vegetation was sparse in both treatment cells of the Kennedy Drive wetland. A technician is laying a transect down along the midpoint of the wetland.

In spite of these difficulties, water quality sampling was attempted for 28 storm events at each wetland over the two-year monitoring period. See Table 11 below for a breakdown of the number of storms attempted and completed at each wetland in 2020 and 2021.

Table 11. Table displays the number of storms attempted compared to the number of complete datasets for the attempted storms at the Fairview Drive and Kennedy Drive wetlands.

	Fairview Drive		Kennedy Drive	
	2020	2021	2020	2021
Storms Attempted	16	12	16	12
Storms Completed	6	6	12	8

Conclusions

SGW Hydraulics and Phosphorus Capture

- **Field Investigation:** With the Kennedy Drive and Fairview Drive wetlands both being located in flow-impaired watersheds, these systems were required to attenuate flow from the Channel Protection Storm (1-yr, 24-hr rainfall depth) which produces a total rainfall of 2.1 inches (VSMM, 2017). Flow monitoring of the two wetland systems in the first two years of their construction provided empirical evidence that these systems were most effective at attenuating the peak flow from storms within two of the four monitored storm size categories (0.0-0.3 inches and 0.3-1.0 inches). The storm size that the Kennedy Drive system attenuated flow best in was the 0.3-1.0-inch storm with an average volume reduction efficiency of 25.7%. The Fairview Drive wetland was extremely effective at reducing flows in the 0.0-0.3-inch storm with an average reduction efficiency of 99.3%. The Kennedy Drive wetland provided moderate volume reductions for the 1.0-2.0-inch storm and the 2.0-inch storm. The Fairview Drive wetland provided higher volume reductions for the 1.0-2.0-inch storm and the 2.0-inch storm than the Kennedy Drive system. However, the combined field results exhibited a sufficient performance in both systems' flow attenuation for storms flows up to the Channel Protection volume.

  The Kennedy Drive system's performance in TP and TDP loading reduction was poor over the two-year monitoring period. TP loads increased at the outlet by an average 188% in 2020 and 108% in 2021. The reduction efficiency of the TP loads improved between Year 1 and Year 2. For the Fairview Drive system, TP loads decreased at the outlet in both Year 1 and Year 2. TP loads decreased by 57% in 2020 and by 14% in 2021. The reduction efficiency of TP and TDP loads decreased between Year 1 and Year 2 for Fairview Drive. With a significant net loss of SRP from the wetland muck material in each system leaching into their treatment cells, it is expected that removal of TP and TDP will continue to be poor, particularly at the Kennedy Drive system, until there are enough storm events to flush out the more readily available P forms in the wetland muck material. Extended monitoring of TP and TDP loading within this system will determine how long this "flushing" period will last until the wetland begins retaining enough phosphorus to observe the desired P load reductions.

- **Lab-scale Investigation:** Results from the lab testing help elucidate mechanisms likely at play in the field and indicate that wetland muck material and gravel media have important implications for flow attenuation and phosphorus capture. Only the muck material used at the field sites (em1) had a saturated hydraulic conductivity (K_{sat}) value < 1 ft day^{-1}, and all materials tested had K_{sat} values at least one order of magnitude greater than the target specification of 0.01 ft day^{-1}. Therefore, infiltration of stormwater vertically through the muck layer is likely to occur, creating the potential for some short-circuiting to occur, reducing contact time with the gravel media. All three of the engineered mucks showed substantial potential to be phosphorus sources in the lab study, especially the material used at the field sites (em1). This includes both dissolved P (SRP) and particulate P associated with fine particles. These lab findings suggest that the presence of the engineered muck layer is likely a key factor leading to observations of net export of P from the SGW systems studied in the field. All three gravels tested in the lab, and especially limestone, showed some potential to retain P, but this is unlikely to completely counteract the loss of P from the muck layer. Native soils tested in the lab did not release P and therefore could be superior from a P perspective, as well as from a cost perspective. However, both native soils had relatively high hydraulic conductivity, so will likely still fail to meet hydraulic objectives. We have provided a recommendation for testing of engineered mucks and native soils to reduce the likelihood of materials installed in SGWs serving as P sources.

Effects of Road Salt on SGW Systems

- **Field Investigation:** Wetland vegetation provided variable chloride uptake levels across the inlet, midpoint, and outlet in both systems. Chloride loads inundated the Kennedy Drive system significantly more than the Fairview Drive system. Due to the highly impervious and commercialized land use within the Kennedy Drive wetland's drainage area, salt applications are a common practice in the winter months as a road deicing mechanism. With deicing salt being a direct source of chloride, the consistent application of salt on these surfaces led to varying influxes of chloride into the wetland system downstream. These consistent chloride loads have the potential to create adverse impacts on plant growth in both the immediate and long term, particularly at the Kennedy Drive system. This was confirmed by visual inspection and reduced plant tissue sample volumes in 2020 when vegetation struggled to establish during the first year after system construction. However, even with limited growth in the first year, wetland vegetation provided a role in the chloride storage mechanism of the system's treatment cells.
- **Lab-scale Investigation:** The lab bioassay study indicated that chloride concentrations observed in Vermont stormwater can likely have negative impacts on some, but not all, species included in common wetland seed mixes, based on the different results for the two species studied. Furthermore, uptake of chloride into aboveground biomass was directly observed in the lab bioassay, confirming vegetative uptake as a potential chloride storage mechanism in the field. Lab testing of wetland mucks and gravels indicated that these materials are likely to have little direct effect on chloride concentrations as stormwater moves through SGWs. However, dynamics occurring in the field but not prominent in the lab column tests (evaporation, uptake of water by plants) likely help explain observations of changes in chloride observed in the field.

Research efforts are aligned with the LCSG focus areas of:

- **Resilient Communities and Economies, Goals 1 & 2**

Opportunities to improve the quality of surface waters should be prioritized in tandem with changes made among Vermont landscapes. With ubiquitous development and redevelopment within our towns and cities, coupled with anticipated increases in rainfall in Vermont due to global climate change, green stormwater infrastructure offers promising solutions to treat increasing volumes of stormwater runoff before it reaches surface waters. Findings from this study have exhibited that constructed gravel wetlands are effective at mitigating storm flows in both high-traffic, commercialized areas and residential neighborhoods. As both these land use types are distributed in pockets within the Lake Champlain Basin and around Vermont, we expect that findings from this study will support the implementation of new and retrofitted SGWs in these communities.

- **Environmental Literacy & Workforce Development, Goals 3 & 4**

Outreach efforts from this study have informed and will continue to inform various groups including the academic community, environmental consultants, and state and local regulatory agencies on the benefits and potential pitfalls of subsurface gravel wetland design. Thus far, interim study findings have been presented to the American Ecological Engineering Society, Vermont stormwater professionals, and both undergraduate and graduate students at the University of Vermont. Recommendations for optimized SGW design have also been made as part of the upcoming efforts to update the 2017 VSMM. Although this combined field and lab study was performed on a local scale and within the Lake Champlain Basin, the recommended SGW design specifications can be adapted for similarly designed systems within the New England region or regions with similar geologic and topographic features.

This field and lab work was completed with students from the Rubenstein Perennial Internship Program, the Richard Barrett Scholarship, and a master student under the mentorship of Drs. Eric Roy and Donna Rizzo. Student reports from the two Barrett Scholarship program participants can be viewed upon request. The lab portion of this project was integrated into Dr. Roy's course NR 289 Advanced Ecological Design at UVM (17 students). This included introduction to permitting requirements for gravel wetlands, review of relevant literature, and active hands-on engagement in the research process for testing wetland muck materials using column studies in the Aiken Center Eco-Design Makerspace. Undergraduate students engaged in experimental design, column testing procedures, water sampling, data analysis, and acquiring skills and knowledge that will help prepare them for future careers focused on green infrastructure. A copy of the final student infographic for the project is included in Appendix G.

- **Healthy Coastal Ecosystems, Goal 6**

This study provided the performance data to support the efficacy of select SGW treatment mechanisms. Performance data demonstrated the ability of SGWs to reduce peak storm flows to flow-impaired waterbodies, provide chloride storage, and reduce sediment loads that would usually cause short- and long-term erosion and destabilization on the landscape. As the data and recommended design specifications (referenced below) generated from this study will be used to update the 2017 VSMM in the coming months, our goal to refine and optimize SGW design will provide a foundation to implement systems that help meet the treatment goals of surface waters within the Lake Champlain Basin.

Recommendations

1. In the coming months, the State plans to update specifications for the gravel wetland muck material in the Vermont Stormwater Management Manual (VSMM). Refer to Appendix H for our recommendations of an optimized set of wetland soil specifications. This document is the most recent version and additional monitoring may allow for updates in the future.
2. Future analysis of the practicality of testing, material sourcing, cost implication of this new specification should be investigated further by tracking and analyzing new permit applications and project implementation.
3. Utilizing native soils to develop gravel wetland mix is a very promising strategy to limit introduction of nutrients, save cost, and reduce unnecessary carbon emissions by trucking. The procedure for investigators to determine the feasibility of using onsite materials need to be further refined including the possibility of amending onsite soils. One caveat is that onsite soils may not have the desired low hydraulic conductivity.
4. The two subject wetlands in the study should be monitored for an additional period of time to better understand how nutrient and chloride dynamics may change over time. In addition, our study results suggest that export of P may be occurring over a long duration after storm events that were beyond the capability of the monitoring equipment. Future monitoring programs should be designed to capture flow and pollutant export for a period of time greater than 24-hours following the peak release of the storm.
5. The Kennedy wetland exhibited very high chloride inputs that were correlated to storm flow outside of the winter salting season. While high chloride during non-winter periods is common in groundwater, it was unexpected that high chloride was found in storm flow. This indicates a source of chloride in the watershed, potentially trapped in stone voids or other locations. This finding should be further investigated to determine if this type of pattern exists in other locations, and how management practices such as street sweeping or cleaning can remove chloride sources before they are mobilized by storm flows.
6. The need for sourcing additional wetland vegetation seeding should be evaluated in gravel wetland design. While planting vegetation is favorable for providing additional pollutant uptake from influent and aesthetic benefits, the nutrient requirements within the wetland soil to support plant growth may contribute to greater export of these nutrients rather than uptake. An unplanted wetland system will likely establish plant species that already exist within its drainage area. Further consideration of unplanted wetland design should be explored to reduce the nutrient input to the system in the form of engineered wetland mucks.
7. Operation and Maintenance responsibilities may vary based on the location of the wetland system. Wetlands located in high-traffic, commercial areas subject to an influx of sediment and trash will typically require more maintenance than wetlands located in a residential neighborhood. Additional volumes of water, not originally accounted for in the wetland design may shorten the longevity and effectiveness of the system. With the addition of continuous base flows, the available pore space for uptake of sediment and nutrients fills at a faster rate than what the system is designed for during storm flows. The introduction of additional flows may bring sediment influx that requires additional removal.

Outreach

Table 12. Table of outreach opportunities.

Outputs	Outcomes	Target Audience	Mechanism	Timeframe	Intended impact	Implementation Schedule
Presentation to WUV annual meeting	Watershed groups are familiar with the study results and able to communicate with their municipal partners on best practices of SGW	Watershed Groups/ Nonprofits	Presentation (Non-academic)	2022	*Immediate*: Municipal managers observe, and report impacts to vegetation in SGW from salt. *Midterm*: Snow and salt storage and application is limited in SGW drainage area. *Long-term:* Areas of reduced salt usage are expanded – protecting water quality.	*Spring 2022*
Presentation at GI Roundtable meeting	Stormwater professionals and regulators are familiar with the results and informed enough to make changes to existing regs and/or suggest new and related research avenues	Stormwater professionals State stormwater regulators	Presentation (Non-academic)	2021/2022	*Immediate & Midterm*: Design professionals change their practices to include the most effective materials, vendors, and approaches for water quality.	*February 17th, 2022*
Fact sheet or other summary document	The actionable results of the research are shared with resource managers. Those learning about O&M of GSI will be provided with additional skills in identifying potential salt impacts as well as medias to avoid.	Municipal workers Watershed groups	Fact sheet/ other summary document (Non-academic)	2022/2023	*Immediate & Midterm*: Operation and Maintenance protocols include elements of lessons learned from this research – improving data collection for state tracking.	*Spring 2022*

Outputs	Outcomes	Target Audience	Mechanism	Timeframe	Intended impact	Implementation Schedule
Academic Conference Presentation/ Poster	Academic researchers are aware of the results of the study and the implications for water quality and GSI performance	Academic Researchers	Presentation/ Poster (Academic)	2022/2023	*Midterm & Long-term*: Researchers are aware of salt impacts to GSI practices and factors that influence SGW performance, and as a result the research community responds with greater focus on this issue.	*American Ecological Engineering Society Academic Conference 2021, see poster in Appendix I*
Professional Conference Presentation/ Poster	Watershed professionals are aware of the results of the study and the implications for water quality and GSI performance	Design/ Management Professionals	Presentation/ Poster (Non-academic)	2022/2023	*Midterm & Long-term*: Stormwater professionals prioritize media selection in filtration practices – improving water quality outcomes.	*Year 1 Presentation, presented January 8, 2021* *Lunch and Learn, November 18, 2020* *LCBP Presentation in Fall 2022*
Scientific Paper Publication	Researchers learn from and reference this work to expand our understanding of SGW, design, and salt impacts on GSI	Academic Researchers and Professionals	Scientific Paper (Academic)	2022/2023	*Midterm & Long-term*: LCSG-funded research is identified regionally as leading the field at a critical time on both GSI understanding and chloride movement and storage in the environment.	*Manuscript submission planned for 2022*

Outputs	Outcomes	Target Audience	Mechanism	Timeframe	Intended impact	Implementation Schedule
On campus green stormwater infrastructure research	Visitors, students, staff, and faculty at UVM learn about SGW and active research efforts on the topic in Aiken Center	Students, Visitors	Students conducted hands-on research and developed a digital infographic (alternative to physical signage due to COVID-related challenges)	2020/2021	*Immediate, Midterm & Long-term*: More than 20 students developed practical skills for future work in green stormwater infrastructure and water quality science in Vermont and beyond. More students are drawn to the UVM ecological design program as a result.	*Student Gravel Wetland Project, NR 289 Advanced Ecological Design, January-May 2021 (Spring Semester), Appendix G*

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