TECHNICAL EVALUATION REPORT

STORMTREE® STORMWATER BIO-FILTRATION PERFORMANCE VERIFICATION PROJECT

Prepared for
StormTree, Inc.

Prepared by
Herrera Environmental Consultants, Inc.

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StormTree® Stormwater Bio-Filtration Performance Verification Project

Prepared for
StormTree, Inc.
24 Corliss Street, Suite 9092
Providence, Rhode Island 02940

Prepared by
Herrera Environmental Consultants, Inc.
2200 Sixth Avenue, Suite 1100
Seattle, Washington 98121
Telephone: 206-441-9080

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EXECUTIVE SUMMARY

The StormTree® Stormwater Bio-Filtration System (StormTree®) is a water quality treatment device consisting of a four-sided open container to house engineered filter media and vegetation with an underdrain. The container is constructed using precast concrete and comes in a variety of configurations that allow the system to be used for treatment applications across a broad range of urban settings.

Installation of the monitored StormTree® system in Seattle, Washington.

From March 24, 2020, through May 27, 2021, Herrera Environmental Consultants, Inc. (Herrera) conducted hydrologic and water quality monitoring of a StormTree® system for StormTree, Inc. at the Ship Canal Test Facility (SCTF) in Seattle, Washington. Herrera conducted the monitoring to obtain performance data to support the issuance of a General Use Level Designation (GULD) for the StormTree® by the Washington State Department of Ecology (Ecology). Monitoring was performed in accordance with procedures described in the *Guidance for Evaluating Emerging Stormwater Treatment Technologies; Technology Assessment Protocol – Ecology (TAPE)* (Ecology 2018).

This technical evaluation report (TER) was prepared by Herrera to demonstrate that the StormTree® meets minimum treatment goals identified in the TAPE to obtain a GULD for basic (total suspended solids), enhanced (dissolved copper and zinc), and phosphorus treatment.

This report was prepared after 30 storm events were successfully sampled to characterize the stormwater treatment performance of a StormTree® system installed at the SCTF. The sampling yielded 29 paired influent and effluent composite samples and three paired grab samples.

Sampling Procedures

Primary and secondary flow measurement devices were installed to continuously measure influent, effluent, and bypass flow volumes for the test StormTree® system. Automated sampling equipment was installed to collect volume-weighted composite samples of the system's influent and effluent during 29 separate storm events over the monitoring period.

The collected volume-weighted composite samples were analyzed for the following water quality parameters:

- Total suspended solids (TSS)
- Particle size distribution
- Total and dissolved copper
- Total and dissolved zinc
- Total phosphorus (TP)
- Orthophosphorus
- Hardness

In addition, grab samples for fecal coliform were collected, and pH was measured in the field during three storm events. Additional parameters were also analyzed, and the associated results are included in the appendices to this report. However, the main body of this report focuses on the results for TSS, copper, zinc, orthophosphorus, and total phosphorus which are required monitoring parameters pursuant to the TAPE guidelines for assessing basic, enhanced and phosphorus treatment. The water quality data were subsequently analyzed in the following ways:

- Computation of pollutant removal efficiencies
- Statistical comparisons of influent and effluent concentrations
- Regression analysis to examine the influence of influent flow rate on system performance

The results were then compared to the TAPE goals for basic, enhanced, and phosphorus treatment.

Hydraulic Performance

The StormTree® system was sized to capture and treat 91 percent of the average annual runoff volume pursuant to minimum requirements for runoff treatment in western Washington. For a 6′ by 4′ StormTree® system the design flow rate for achieving that goal is 36.9 gpm. Due to the open wall construction of the StormTree system, the surface of the treatment media becomes saturated outside of the inner dimensions of the concrete structure to the approximate extent of the outer edge of the concrete structure (5 inches). So, a typical 6 foot by 4 foot unit with four open walls has an effective media surface area of 32.1 square feet (ft^2) instead of 24 ft^2. The tested unit had only three open walls as it was originally cast for another project where infiltration was not desired on the roadway prism side of the unit. Consequently, the effective media area for the test unit was 29.6 ft^2.

The project Quality Assurance Project Plan (QAPP) (Herrera 2020) indicated that the system would have a design flow rate of 1.1 gallons per minute/ square foot (gpm/ft^2). However, once deployed in the field it became apparent that the system could easily treat hydraulic loading rates up to 1.25 gpm/ft^2. With an effective media area of 29.6 ft^2 and a hydraulic loading rate of 1.25 gpm/ft^2, the resultant design flow rate for the test unit was 36.9 gpm. During the monitoring period 458,598 gallons of stormwater entered the StormTree® system; of this, 10,100 gallons were bypassed, resulting in an annual treatment of 97 percent of the influent flow. However, it should be noted that the valve upstream of the test system was frequently closed when storm events were not being targeted, so the system did not see a full water years' worth of flows. By comparing treated effluent volume to treated volumes for a typical water year and properly sized system in a theoretical 100 percent impervious basin, the test system treated 40.8 percent of a water year by the end of the study.

The system went online on March 24, 2020, the first sampled event with bypass occurred on April 22, 2020 or about 1 month later. The system bypassed towards the end of this event at 10 gpm or 62 percent below the design flow. To address this apparent clogging, the mulch was replaced May 11, 2020, after this point the system did not bypass again until December after 25.5 percent of a water year had passed through the filter. The mulch was replaced again on December 20, 2020 and subsequently the treated flow rate never fell below the design flow rate over an additional 28.3 percent of a water year.

These data indicate that mulch replacement spaced 3 months apart is an adequate maintenance interval to keep flows at the design flow rate at the SCTF where sediment loads are relatively high given the land use (highway) in the associated drainage basin. It is anticipated that the maintenance frequency would be considerably less in a more typical land use application (e.g., commercial parking lot or street).

Water Quality Performance

Basic Treatment

The basic treatment goal in the TAPE guidelines is ≥80 percent removal of TSS for influent concentrations ranging from 100 to 200 milligrams per liter (mg/L). For concentrations less than 100 mg/L, treatment technologies must achieve an effluent concentration of ≤20 mg/L.

All 29 composite sampled storm events were sampled for TSS. Influent samples from three events had concentrations below 20 mg/L and one event had a concentration above 100 mg/L. Consequently, sample results from the remaining 24 events were compared to the treatment goal for effluent concentrations. The upper 95th percentile confidence limit (UCL95) of the mean effluent concentration was 3.5 mg/L, below the goal for effluent concentration identified above. A regression analysis of sampled influent flow rate versus effluent TSS concentration indicated that the tested StormTree® achieved ≤20 mg/L TSS in the effluent for flows up to and including the design flow rate of 36.9 gpm (120 inches per hour (in/hr), 1.25 gpm/ft^2 of media).

Enhanced Treatment

Copper

The enhanced treatment goal in the TAPE guidelines is ≥30 percent removal of dissolved copper for influent concentrations ranging from 0.005 to 0.02 mg/L.

Out of the 29 composite sampled events, 17 were sampled for dissolved copper. The influent sample for one event (September 18, 2020) had a concentration above 0.02 mg/L and one event was excluded due to low sample coverage, so these data were excluded from the analysis resulting in an n-value of 15. The lower 95th percentile confidence limit (UCL95) of the mean dissolved copper removal for samples collected during these 15 events was 31.4 percent, exceeding the percent removal goal identified above. A regression analysis of sampled influent flow rate versus dissolved copper removal indicated that the system can achieve ≥30 percent removal up to and including the design flow rate of 36.9 gpm (120 in/hr, 1.25 gpm/ft^2 of media).

Zinc

The enhanced treatment goal in the TAPE guidelines is ≥60 percent removal of dissolved zinc for influent concentrations ranging from 0.02 to 0.30 mg/L.

Out of the 29 composite events sampled, 17 were sampled for dissolved zinc. Influent samples for three events had concentrations below 0.02 mg/L; sample results from all were included in subsequent calculations to be conservative. The LCL95 of the mean dissolved zinc removal for samples collected during these events was 66.7 percent, exceeding the percent removal goal identified above. A regression analysis of sampled influent flow rate versus dissolved zinc removal indicated that the system can achieve ≥60 percent removal up to and including the design flow rate of 36.9 gpm (120 in/hr, 1.25 gpm/ft^2 of media).

Phosphorus Treatment

The phosphorus treatment goal in the TAPE guidelines is ≥50 percent removal of TP for influent concentrations ranging from 0.1 to 0.5 mg/L.

Out of the 29 composite events sampled, 27 were sampled for phosphorus. Influent samples from 10 events had concentrations below 0.1 mg/L. Consequently, only the samples from the remaining 17 events were compared to the treatment goal for percent removal. The LCL95 of the mean TP removal for samples collected during these events was 61.6 percent, exceeding the percent removal goal identified above. A regression analysis of sampled influent flow rate versus TP removal indicated that the system can achieve ≥50 percent removal up to and including the design flow rate of 36.9 gpm (120 in/hr, 1.25 gpm/ft^2 of media).

Recommendation

Based on the performance results presented above, it is recommended that the StormTree® system be granted a GULD for basic, enhanced, and phosphorus treatment when sized based on a surface loading rate of 1.25 gpm/ft^2 of media.

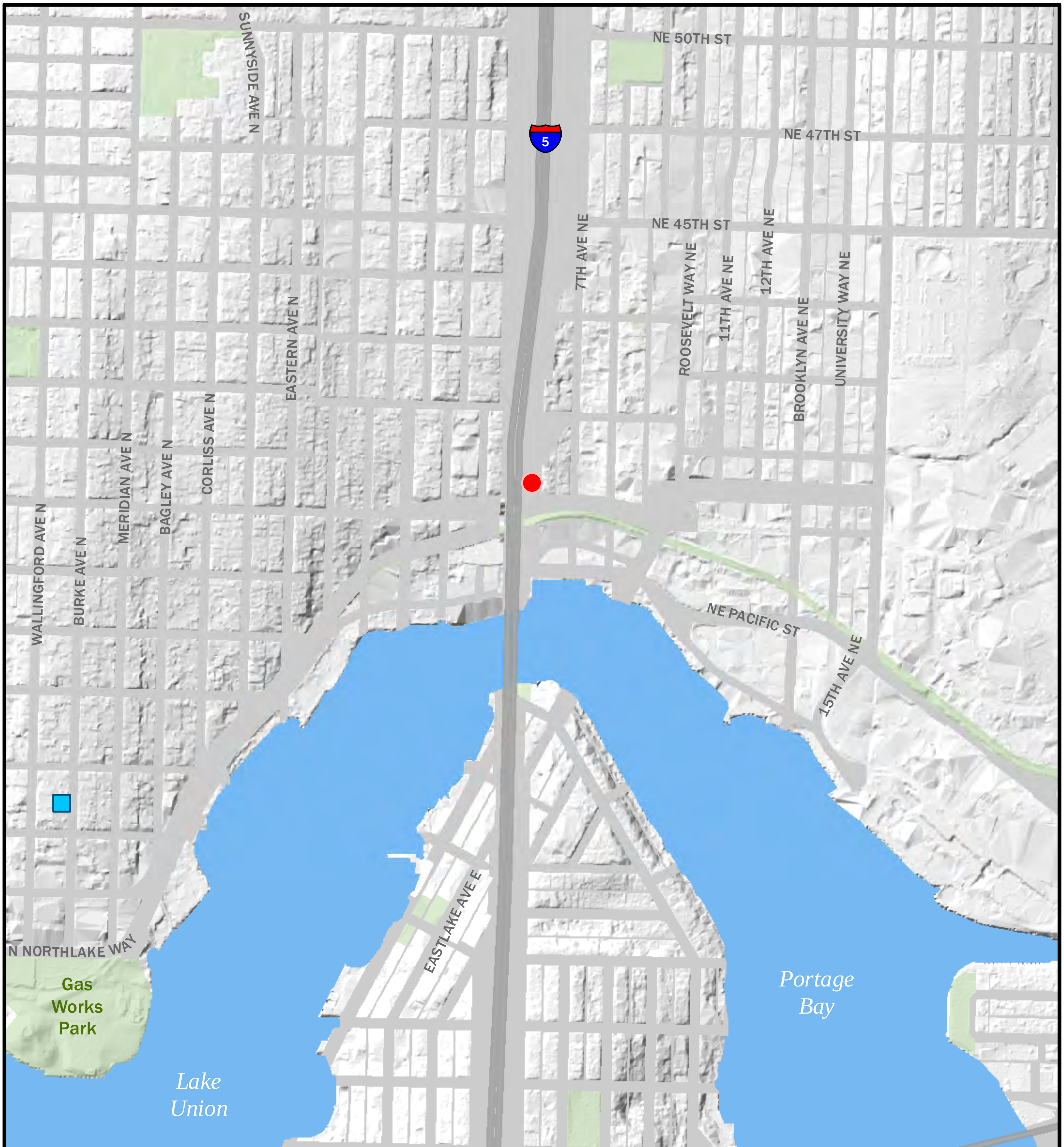
INTRODUCTION

The StormTree® system is a structural stormwater treatment system developed by StormTree, Inc. that combines living plants and an engineered media to remove common pollutants through biofiltration. The container is constructed using precast concrete and comes in a variety of configurations that allow the system to be used for treatment applications across a broad range of urban settings.

The Washington State Department of Ecology (Ecology) has established specific use level designations for emerging stormwater treatment technologies, in accordance with guidelines that are identified by Ecology (2018) in the Technology Assessment Protocol – Ecology (TAPE). There are three use level designations: pilot, conditional, and general. Pilot and conditional use level designations allow limited application of emerging stormwater treatment technologies in Washington to facilitate field testing. If the testing shows that the treatment technology meets minimum treatment goals identified in the TAPE guidelines, Ecology may issue a General Use Level Designation (GULD) for the treatment technology, permitting its widespread use in Washington. The TAPE guidelines require preparation of a technical evaluation report (TER) for any stormwater treatment system under consideration for a GULD. The TER must demonstrate a treatment technology will achieve Ecology's performance goals for target pollutants, as shown by field testing performed in accordance with the TAPE guidelines.

In August of 2017, StormTree received a Pilot Use Level Designation (PULD) for basic treatment from Ecology for the StormTree® system. To demonstrate the StormTree® system meets the treatment requirements for a GULD for basic, enhanced, and phosphorus treatment, monitoring was conducted to document the water quality treatment effectiveness of a StormTree® system installed at the Washington State Department of Transportation's (WSDOT's) Ship Canal Test Facility (SCTF) that is located beneath the Interstate 5 Ship Canal Bridge, in Seattle, Washington (Figure 1). The monitoring involved the collection of water quality and flow data from the StormTree® system over a 14-month period extending from March 24, 2020, through May 27, 2021. During that period, 30 storm events were sampled yielding 29 paired influent and effluent composite samples and 3 paired grab samples, with one of the grab sample pairs collected during an event where no composite samples were collected.

Herrera Environmental Consultants, Inc. (Herrera) prepared this TER to support the issuance of a GULD for the StormTree® system. This TER is organized to present a description of the StormTree® system, sampling procedures used during the monitoring, detailed summaries of the compiled data, and major conclusions from the monitoring.



Legend

- Project area
- Project rain gauge

Figure 1.
Site Vicinity Map, WSDOT Ship Canal Facility, Seattle, Washington.

N

0 500 1,000 2,000 Feet

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TECHNOLOGY DESCRIPTION

The StormTree® system provides water quality treatment of captured flows through physical, chemical, and biological processes. This section describes the system's physical components, site installation requirements, treatment processes, and system sizing method.

Physical Description

The StormTree® is a proprietary system (US Patent No. 8333885, 10563392, and other patents pending) that is designed as a biofiltration practice that combines living plants and engineered media within a structural system. The integration of plants and engineered media with stormwater runoff collection is a proven treatment practice for nonpoint source pollution attenuation and remediation. The StormTree® is unique in being the only "open designed" structural biofiltration practice. Unlike most closed box biofiltration systems and "tree box filters," the StormTree® is open bottomed and primarily open sided to provide for direct subsurface infiltration of treated stormwater (where desirable) and significant unobstructed lateral plant root migration. This open design model also allows for the "communication" of the engineered media within the interior of the StormTree® with the surrounding native soils, providing additional irrigation of system subsurface biomass through conveyance and capillary action. This functionality is unique to the StormTree®.

The StormTree® is designed and available in multiple configurations (Figure 2) and dimensions to service varying treatment requirements and operational functionalities throughout the United States. Systems with interior pretreatment sumps or attached (monolithic) catch basins provide enhanced performance by the segregation of quantities of sands and sediment, particularly found in areas with heavy snow loading. The system can also be lined to inhibit infiltration where it is not feasible or desirable. Appendix A provides a description of the alternate configurations that are available for the system. The test system for this performance monitoring project did not have an internal pretreatment sump and was lined, thus providing a conservative estimate of performance. Individual standard StormTree® units are sized to treat between approximately 0.25 acre and 2 acres, depending upon percent impervious surface.

Structure

The StormTree® is designed as a structural four-sided open container, or framed structure. The structure is typically of precast concrete construction; however, it is also designed to be fabricated from metal or plastic. Depending upon roadway or pedestrian traffic loading requirements, the StormTree® precast concrete frame (and integrated catch basin if applicable) is designed for HS-20 loading; H-20, or lesser loading requirements may be designed as appropriate. Standard sizes range from between 5-feet by 5-feet (OD) to 8-feet by 18-feet (OD) footprint; customization allows for additional configurations and dimensions. Within street or sidewalk applications, the front curb inlet side of the structure integrates with existing or newly formed curbing.

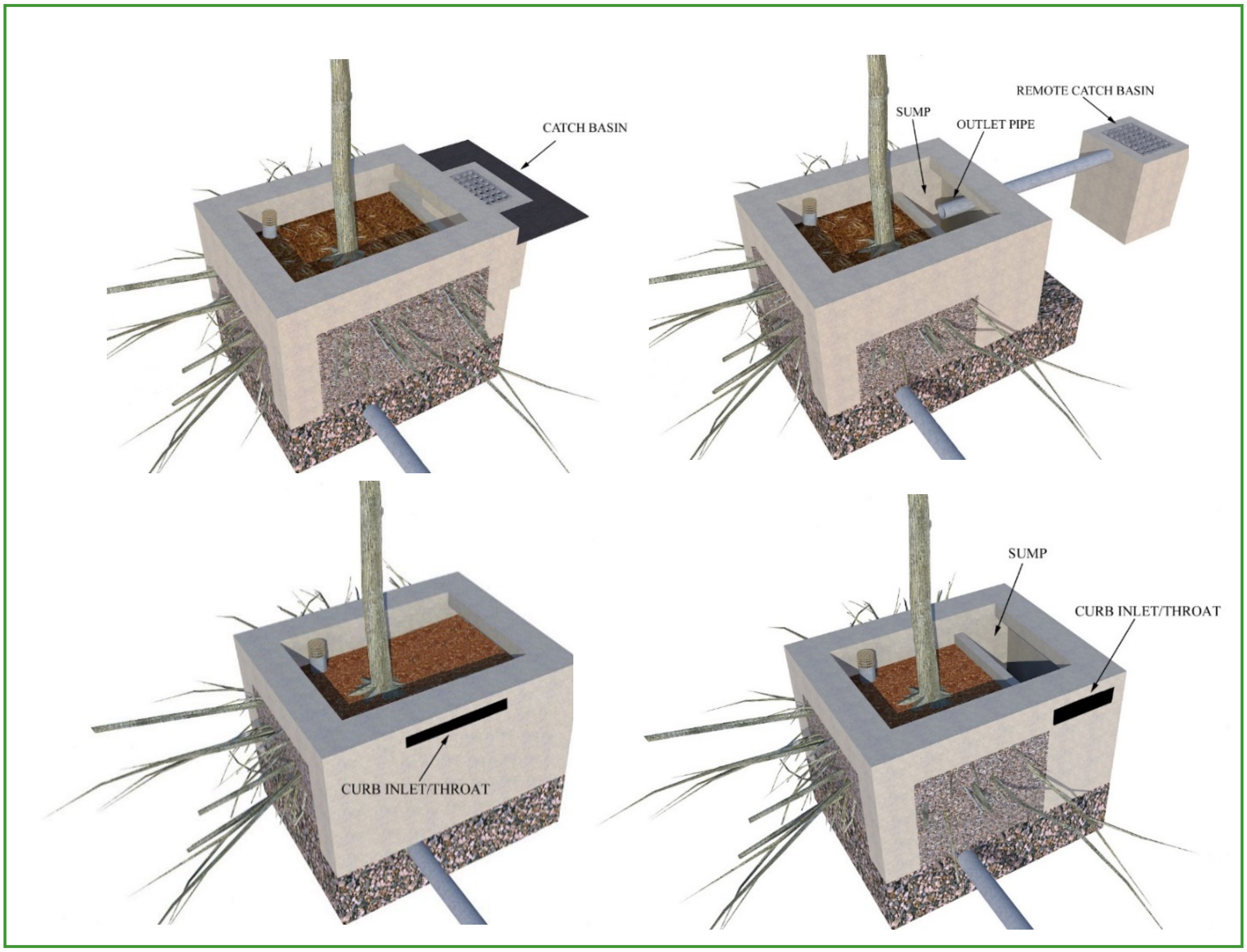

Figure 2. StormTree® System Designs.

It is important to note that for the purposes of this performance monitoring project, and to accurately determine treatment efficiencies for the engineered media, a secondary containment structure was built to enclose the primary frame. This secondary containment was filled with the same engineered media as was used in the inner concrete structure and was designed to allow water to freely flow through the primary container in order to simulate field conditions. The secondary containment structure provided approximately 4 inches of lateral space (filled with engineered media) outside of the primary container. This design provided conservative flow and treatment estimates because typical installations have 24 (or greater) lateral inches of media between the structure and the surrounding native soil.

The following subsections provide more detailed information on the StormTree® system's physical components, treatment processes, sizing methods, expected treatment capabilities, expected design life, and maintenance procedures.

Physical Components

This section provides a description of each physical component of the StormTree® system including vault, inlet, prefilter and media beds, underdrains, and bypass.

Inlet

Stormwater runoff receptor configurations may be curb (gutter) inlet, catch basin inlet, piped (inflow) inlet, or grated inlet:

- Curb inlet – stormwater entry through a dimensional opening or throat on the front (curb side) of the structure
- Catch basin inlet – stormwater entry through a dimensional frame/grate attached catch basin which extends within the paved surface, opposite of curb face
- Piped inlet – stormwater entry through an external dimensional pipe with invert at varying elevation
- Grated inlet – stormwater entry through top surface grate

For this performance monitoring project, a test system with a curb inlet configuration will be evaluated. Appendix A presents how the hydraulics of each alternate configurations are equivalent in terms of flow distribution across the media and bypass dynamics. The objective of this performance monitoring project is to assess the efficacy of the curb inlet model with no pretreatment sump.

Surface Storage

The StormTree® system is typically designed with a ponding depth of between 6 and 8 inches. This difference in height is based on whether a pretreatment sump or attached catch basin is included, the latter having an effective ponding depth of approximately 6 inches.

Mulch Layer

A 3-inch layer of hardwood mulch overlying the engineered media serves as a prefilter by providing sediment capture and segregation, thereby reducing material buildup and surface occlusion of the engineered media. An additional benefit of a mulch layer is to provide moisture retention and surface cooling to benefit plant survival and growth. Hardwood mulch is generally used since decomposition and breakdown occurs at a slower rate than softwood mulch.

Engineered Filter Media

A 24-inch layer of an engineered filter media underlies the mulch layer. The media is collectively composed of a coarse sand, small diameter stone, non-composted organic material, and proprietary additives. The top 18 inches of the treatment media is composed of a primary treatment media which is underlain by 6 inches of secondary media designed to target dissolved pollutants. The PULD for the StormTree® system was based on column tests which assessed a 30-inch engineered media layer (24-inch primary media and 6-inch secondary). A column test conducted after the issuance of the PULD confirmed basic, enhanced, and phosphorus performance for the shallower 24-inch media configuration. This configuration was used for this performance monitoring project. Refer to the *Performance Claims* section below for more details on the additional column testing.

Vegetation

The StormTree® system includes specified vegetation that includes a single tree to occupy the system. Vegetation is selected based on aesthetics, local climatic conditions, traffic safety (e.g., may limit the height or breadth of the vegetation), and maintenance considerations (e.g., may restrict deciduous vegetation). No vegetation will be used in the test system for this performance monitoring project. This decision was made based on previous experience at the SCTF which has shown a tree may not survive due to low light and rain conditions that prevail at its location beneath a bridge.

Underdrain Layer and Pipe

A minimum 6-inch-thick layer of washed aggregate envelopes an underdrain pipe that resides beneath the engineered filter media layer. The underdrain layer will be separated from the engineered filter media with a coarse woven fiberglass mesh to prevent media migration into the underdrain layer. Below this layer and the underdrain is a washed stone material to provide structural support and improved infiltration. A greater thickness of stone may be utilized in the StormTree® system to provide additional support for the structure, and for additional infiltration capacity and detention.

A minimum 4-inch-diameter slotted PVC pipe is used in most system designs to provide evacuation and conveyance of treated stormwater; larger diameter pipe is used in systems treating larger catchments. A 4-inch-diameter slotted PVC pipe was installed in the test system used for this performance monitoring project.

Bypass

The StormTree® typically includes a bypass pipe to provide overflow functionality. The vertical (standup) bypass pipe is typically interconnected with the effluent end of the underdrain pipe. The interconnection is provided via a “wye” pipe fitting. The placement of the wye at the outflow end of the underdrain pipe prevents possible backwashing of untreated bypass water into the underdrain, thereby preventing possible cross contamination of the treated water in the underdrain pipe and surrounding stone layer. The minimum diameter of the bypass pipe is 6 inches. Larger StormTree® systems may utilize a bypass pipe diameter of 8 inches or greater to service larger catchments. This multi-diameter bypass feature is unique to the StormTree®. In addition, the StormTree® can be configured with an external bypass. Once water fills the treatment chamber it creates a hydraulic dam which does not allow additional head to build in the system, this forces water across the inlet throat and down the curbline. The test system used for this performance monitoring project was configured with an external bypass.

Treatment Processes

The StormTree® uses the following treatment processes to remove pollutants from stormwater.

Segregation

Segregation takes place in StormTree® systems that are configured with an interior pretreatment sump or attached catch basin.

Settling

Floatables and gross pollutants are removed through settling as the water level within the StormTree® recedes and materials are suspended on the mulch layer surface.

Screening

The hardwood mulch acts as a prefilter and screening mechanism restricting quantities of sands and sediment from occluding the surface and entering the engineered filter media layer. The varying shapes and dimensions of mulch particles form an open lattice which allows for only limited restriction in water movement.

Filtration

As flow passes through the mulch layer and then infiltrates through the engineered media layer, finer particulate material is removed by filtration through the multi-gradation particles. Some of these particles may be held in suspension or broken down further and/or made bioavailable.

Adsorption

Based on chemical reactions involving positive and negative particle attraction/repulsion within the organic and non-organic matrix, adsorption and sequestration may take place rendering pollutants immobile and/or potentially bioavailable (Hua et al 2012).

Volatilization

When captured in the filter media, volatile organic compounds such as gasoline may ultimately volatize.

Biological Processes

Biological breakdown within media filter systems is predicated on several factors including the quantity and proportion of organic to inorganic material within the system, and environmental factors (e.g., pollutant, soil moisture, pH, available oxygen, temperature, carbon content, and other factors). The presence and balance of these elements determines the degree and rate of biological processes. Although most of this activity occurs at the microbiological level within the media, aboveground plant material may also play a role in pollutant reduction based on micro/macro nutrient bioavailability and uptake.

Nutrient Assimilation

Biologically available forms of nitrogen, phosphorus, and carbon are actively taken into the cells of vegetation and bacteria and used for metabolic processes (i.e., energy production and growth) (Karpiscak et al 2001). Nitrogen and phosphorus are actively taken up as nutrients that are vital for a number of cell functions, growth, and energy production. These processes remove metabolites from the media during and between storm events making the media available to capture more nutrients from subsequent storms in a sustainable manner.

Nitrification/Denitrification

Bacteria may transform and cycle various forms of nitrogen, converting nitrogen inputs into organic matter or free nitrogen in gaseous form (Blecken et al 2007). These processes may reduce the total effluent nitrogen, but may also contribute nitrogen to the discharge, depending on the rate of concurrent organic decomposition.

Biodegradation

Organisms can break down a wide array of organic compounds into less toxic forms or completely break them down into carbon dioxide and water (Haritash and Kaushik 2009, Means and Hinchee 1994).

System Sizing

Table 1 provides sizing guidance for the StormTree® that were developed using MGSFlood (version 4.40) based on a design infiltration rate of 120 inches per hour (in/hr) and a goal of treating 91 percent of the average annual runoff volume in western Washington. For sizing in eastern Washington, Hydrocad, StormSHED, or another approved single-event model should be used to size the system for the 6-month design storm.

The PULD for the StormTree® identifies an approved design infiltration rate of 33 inches per hour (in/hr). This limit was established based on column test results that showed performance meeting TAPE criteria for basic, enhanced, and phosphorus treatment at an infiltration rate of 55 in/hr. Subsequent column testing showed equivalent performance at an infiltration rate of 83 in/hr (Attachment C of Appendix B). Based on the field results presented herein, the StormTree® system can meet treatment goals at flow rates up to 120 in/hr. Consequently, Table 1 provides sizing for a system with a design flow rate of 120 in/hr (36.9 gpm or 1.25 gpm/ft^2).

Table 1. StormTree® Sizing Table for Western Washington.[a]

Available Sizes (feet)	Effective Media Surface Area (square feet)[b]	Water Quality Design Flow Rate Target (gpm)	Maximum Contributing Drainage Area (acres)[c]	Annual Volume (million gallons)
4 x 6	**29.6**	**36.9**	**0.9**	**1.0**
4 x 8	38.6	48.3	1.2	1.3
4 x 10	47.6	59.5	1.4	1.6
4 x 15	69.6	87.0	2.1	2.4
4 x 21	97	121.3	2.9	3.3
6 x 6	42	52.5	1.3	1.4
8 x 8	72	90.0	2.2	2.5

Bold values are the sizing for the test configuration.

[a] Sizing table intended for planning level use. The design engineer must use WWHM2012 or approved equivalent and the site location mapping to calculate the appropriate facility size for each installation in western Washington.

[b] This area includes the media surface within the frame as well as the media under the openings in the frame.

[c] Sizing table based on WWHM2012 parking/flat basin (100 percent impervious) and SeaTac rain gage with precipitation factor of 1.0.

Site Installation Requirements

The following subsections describe the site installation requirements for the StormTree® system including necessary soil characteristics, hydraulic grade requirements, depth to groundwater limitations, utility requirements, and other limitations.

Necessary Soil Characteristics

Although surrounding soil characteristics including permeability are important in evaluating the potential for direct infiltration in the design of the StormTree®, for the purposes of this performance monitoring project, a closed system was evaluated. A minimum 6-inch layer of stone is typically placed beneath the structure which is suitable for most structural loading and compaction requirements. The test system utilizes a 4-inch stone layer because the secondary containment provides structural support.

If the StormTree® receives a GULD, systems installed in Washington State must adhere to site suitability requirements for infiltration (per local and state regulations) prior to construction. If infiltration is not feasible, the StormTree® system can be configured with an impermeable membrane liner.

Hydraulic Grade Requirements

When used in a surface treatment application, the design of the StormTree® is based on the elevational difference between the curb inlet or catch basin invert (entry invert), and the underdrain pipe invert. The difference in elevation between entry invert and outlet invert is approximately 3.4 feet. Inflow and surface grate systems may have slightly less or greater difference in elevation.

Depth to Groundwater Limitations

In its typical design, the StormTree® system is open bottomed, and primarily open sided, therefore, seasonal high groundwater elevation is an important factor in consideration of application. Pursuant to the *Stormwater Management Manual for Western Washington* (Ecology 2019), a groundwater mounding analysis should be conducted to determine the effect of local hydrologic conditions on BMP performance if seasonally high groundwater is within 15 feet of the base of the system and the drainage area is greater than an acre. If this analysis indicates that infiltration will be infeasible, then the system can be installed with an impermeable liner and underdrain.

For the purposes of this performance monitoring project, a secondary containment vessel was used; therefore, groundwater elevation is not a factor. Water that builds up in the secondary containment vessel beneath the underdrain gravity drained before each sampled storm event.

Utility Requirements

The StormTree® system is a free draining passive system and therefore does not require an internal or external power source.

Maintenance Requirements

The StormTree® system has prescribed maintenance requirements that are identified in an Operation and Maintenance Plan (O&M Plan) that is provided with all system installations (Appendix C). This O&M Plan recommends maintenance be performed on a biannual basis, ideally in fall and spring. General maintenance practices are as follows:

- Evaluate plant material: prune and remove dead or dying limbs and foliage as necessary.
- Remove any debris or trash from the concrete surface and/or grating.

- Remove surface grating surrounding the `tree and media bed; remove any visible debris and trash on mulch surface.
- Remove surface mulch layer.
- Rake the surface engineered media layer with a stiff tine steel (garden) rake to ensure a loose and unobstructed surface media layer and reduce surface occlusion.
- If present, remove cast iron grate from catch basin. Evacuate accumulated debris, sands and sediment via clam shell or Vactor equipment. If hand tools are to be utilized, shovel out as necessary. Replace grate and ensure stable positioning.
- If overflow/bypass port and piping exist, remove any debris or obstruction surrounding the atrium grate or exposed inlet.
- Complete any required maintenance logs or paperwork.
- Properly dispose of collected mulch, debris, and trash.

After several years of operation, the system may experience excessive sand and sediment loading depending upon the extent and frequency of (regional) winter sanding operations and system maintenance. This condition may require more thorough cleaning, and possible renovation that may include the removal of the top 4 to 6 inches of surface material (media/mulch), and subsequent replenishing.

Performance Claims

The StormTree® currently has a PULD from Ecology through the TAPE program. Results from laboratory testing of the system conducted by the University of Washington at Tacoma with a 30-inch treatment media depth indicated the StormTree® system can remove 94 percent of influent total suspended solids, 54 percent of dissolved copper, 72 percent of dissolved zinc, and 94 percent of total phosphorus at an infiltration rate of 55 in/hr (Attachment B of Appendix B); however, Ecology established a design infiltration rate of 33 in/hr in the PULD for the system.

After the PULD was granted, further laboratory testing was conducted by the University of Washington at Tacoma (Attachment C of Appendix B). This testing was conducted using a new media configuration for the StormTree®. Specifically, the column used in the testing was constructed with six fewer inches of primary treatment media. Results from this testing showed this shallower media configuration for the StormTree® met TAPE performance goals for basic (99 percent removal of TSS), enhanced (61 and 94 percent removal of dissolved copper and zinc respectively), and phosphorus (90 percent total phosphorus removal) at an infiltration rate of 83 in/hr. These results suggest improved performance could be achieved at a higher flow rate and a shallower media depth relative to the results that were used to obtain the PULD.

Therefore, this field performance monitoring used a test system with a 24-inch media depth and a design flow rate of 120 in/hr.

Reliability

The StormTree® system is a robust water quality system designed to withstand a variety of conditions in the field (see Figure 3). The system is easy to maintain (no confined space entry required or heavy lifting) and is designed to last for 25 years if regularly maintained.

Other Benefits and Challenges

The StormTree® system is a uniquely designed open bottom bio-filtration system. The open design provides the opportunity for stormwater infiltration into the surrounding area, resulting in additional treatment capabilities. The open structure also allowed for tree roots to reach the surrounding native soil, further promoting infiltration and contributing to tree vigor and longevity.

Due to the open nature of the StormTree® system, which creates valuable groundwater infiltration opportunities, potential obstacles do exist depending on installation location. Steep slopes or high groundwater tables would pose hydraulic complications to the open bottom system. In these challenging installation locations, it is possible to modify the StormTree® system with an impermeable membrane to inhibit infiltration and route all treated water to the underdrain.

Sampling Procedures

This section describes the sampling procedures that were used to evaluate the performance of the StormTree® system. It begins with a general overview of the monitoring design and the specific goals Ecology has established for basic, enhanced, and phosphorus treatment. Separate sections then describe in more detail the site location, test system, monitoring schedule, and specific procedures used to obtain the hydrologic and water quality data, respectively. Analytical methods, quality assurance and control measures, data management procedures, and data analysis procedures are also described.

Monitoring Design

To facilitate performance monitoring pursuant to the TAPE guidelines, a 4-foot by 6-foot (internal dimensions) StormTree® was installed for testing purposes at the Ship Canal Testing Facility in Seattle, Washington (Figure 1).

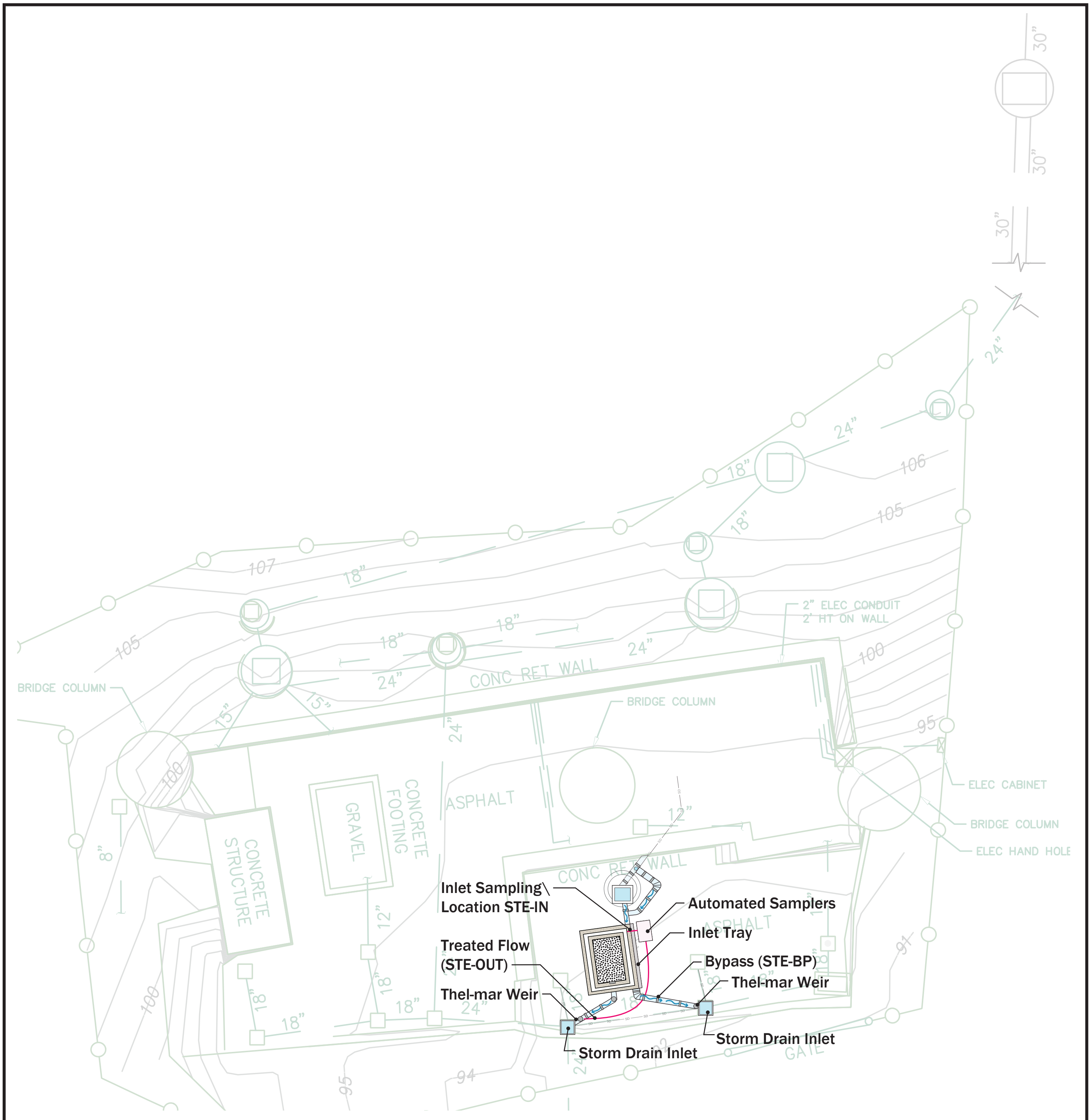

Figure 3.
Site Map of the StormTree® Bio-Filtration System Performance Evaluation Site (STE) at the the Ship Canal Test Facility.

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Automated equipment was installed in conjunction with the StormTree® system to facilitate continuous monitoring of influent, effluent, and bypass flow volumes over a 14-month period extending from March 24, 2020, through May 27, 2021. In association with the hydrologic monitoring, automated samplers were employed to collect volume-weighted composite samples of the influent and effluent during discrete storm events for subsequent water quality analyses.

Using the monitoring data from the StormTree® system, Herrera characterized removal efficiencies and effluent concentrations for targeted monitoring parameters and subsequently compared them to goals identified in the TAPE guidelines to support the issuance of a GULD for the StormTree®. The Ecology treatment goals are described below for the three types of treatment that are under consideration for inclusion in the GULD:

1. **Total Suspended Solids (Basic) Treatment:** 80 percent removal of TSS for influent concentrations that are greater than 100 mg/L but less than 200 mg/L. For influent concentrations greater than 200 mg/L, a higher treatment goal may be appropriate. For influent TSS concentrations less than 100 mg/L, the facilities are intended to achieve an effluent goal of <20 mg/L.

2. **Dissolved Copper and Zinc (Enhanced) Treatment:** 30 percent removal of dissolved copper for influent concentrations ranging from 0.005 to 0.02 mg/L. 60 percent removal for dissolved zinc for influent concentrations ranging from 0.02 to 0.30 mg/L.

3. **Phosphorus Treatment:** 50 percent removal of TP for influent concentrations ranging from 0.1 to 0.5 mg/L.

Site Location and System Sizing

A test system (4-foot by 6 -foot ID unit) for the StormTree® was installed at the SCTF, located in Seattle, Washington, in the Interstate 5 right-of-way beneath the north side of the Lake Union Ship Canal Bridge (Figure 1). The drainage area contributing to the site is approximately 31.6 acres, with 22.7 acres of pavement and 8.9 acres of roadside landscaping. The WSDOT stormwater collection system is separate from the City of Seattle collection system; and it includes runoff from the Interstate 5 northbound, southbound, express lanes, and the on- and off-ramps. All runoff in the drainage basin passes through catch basins prior to entering the stormwater collection system and being consolidated in a 30-inch pipe. The drainage basin contains 15 Type 1 and 53 Type 2 catch basins.

WSDOT constructed the SCTF to allow the simultaneous testing of up to four stormwater treatment technologies. This is accomplished by diverting stormwater flow from the 30-inch pipe to the site using a “draw-bridge” half-pipe structure and a series of flow splitters. First, flow from the draw bridge enters an adjustable flow splitter that diverts water toward test bays 1 and 2 on one side, and toward test bays 3 and 4 on the other side (Figure 3). On each side, the divided water then enters a second flow splitter that further divides the flow such that each of the four test bays can be used independently. Flow to each test bay can be further controlled through the use of a 6-inch gate valve located at the inflow to each test bay (Appendix D). This valve will be periodically adjusted to ensure the test system is not overwhelmed with stormwater.

Ecology approved the use of this site for field testing under the TAPE guidelines and entered into an agreement with WSDOT on February 25, 2016, to allow testing at the facility. StormTree subsequently entered into a property use agreement with Ecology (Appendix E) on April 11, 2019 for the duration of the monitoring.

Due to historical issues with filter clogging at the SCTF, a type 2 catch basin was installed upstream of the StormTree® to act as a debris sink/mixing tank (Figure 4). As shown in Appendix D, the structure has a 4-foot diameter and a 4.5-foot sump. The intake for influent sampling was located downstream of this structure so the test system will not be credited with any removal which occurred in the sump.

Figure 4. Panoramic photo of the front of the StormTree® System as installed at the Ship Canal Test Facility.

MONITORING SCHEDULE

Hydrologic monitoring was conducted at the StormTree® system over a 14-month period from March 24, 2020, through May 27, 2021. During that time, 29 paired influent and effluent composite samples and three grab samples were collected for characterizing the stormwater treatment performance of the StormTree® system.

TEST SYSTEM DESCRIPTION

The StormTree® system consists of a 4-foot by 6-foot interior dimension open-walled vault with a 6-inch layer of washed aggregate, covered by a 24-inch layer of engineered media covered by 3 inches of shredded wood mulch. The open-walled unit was placed in a 6-foot by 8-foot secondary solid-walled container (Figure 5). Stormwater enters the system via a curb inlet tray (Figure 4) and exits the vault through a 4-inch underdrain and then to the treated outlet flow monitoring station (Figure 5).

Figure 6 shows a plan view schematic of the StormTree® system (also see Appendix D). As water enters the StormTree® unit, it is distributed across the mulch and infiltrates into the engineered filter media. The open walls become solid walls as the surface of the media, which allows for head to build on the media within the 4-foot by 6-foot interior dimension of the open-walled vault. The test unit has three open walls, and it was observed that water would quickly seep through the openings for about the width of the 5-inch concrete walls. Consequently, the surface media in the openings was engaged during all storm events, resulting in an effective surface area which was slightly larger than the 24 ft^2 interior area of the unit. Calculating the additional area inside the three wall openings, the total effective surface area was 29.6 ft^2.

Once water fills the treatment chamber it creates a hydraulic dam which does not allow additional head to build in the system, this forces water across the inlet throat and down the curbline. For the test system, an external bypass was installed at the end of the inlet tray, mimicking a curbline.

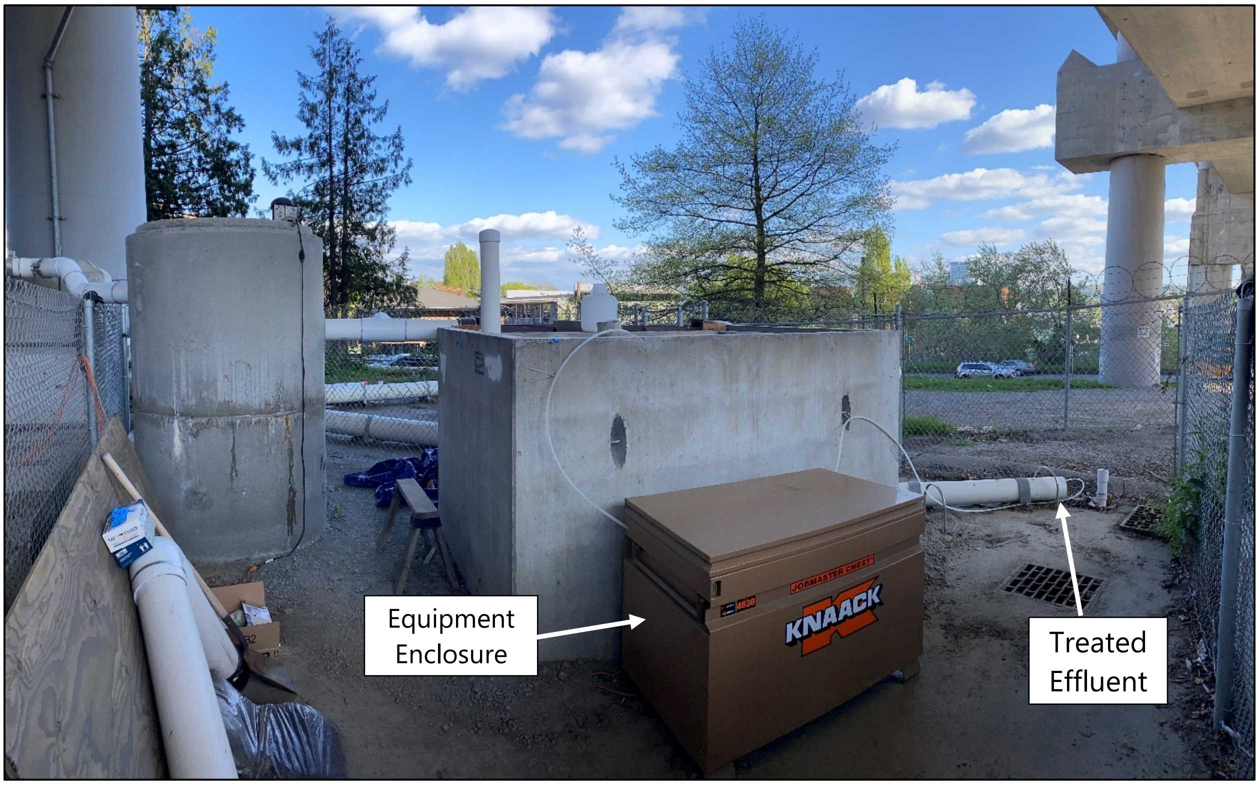
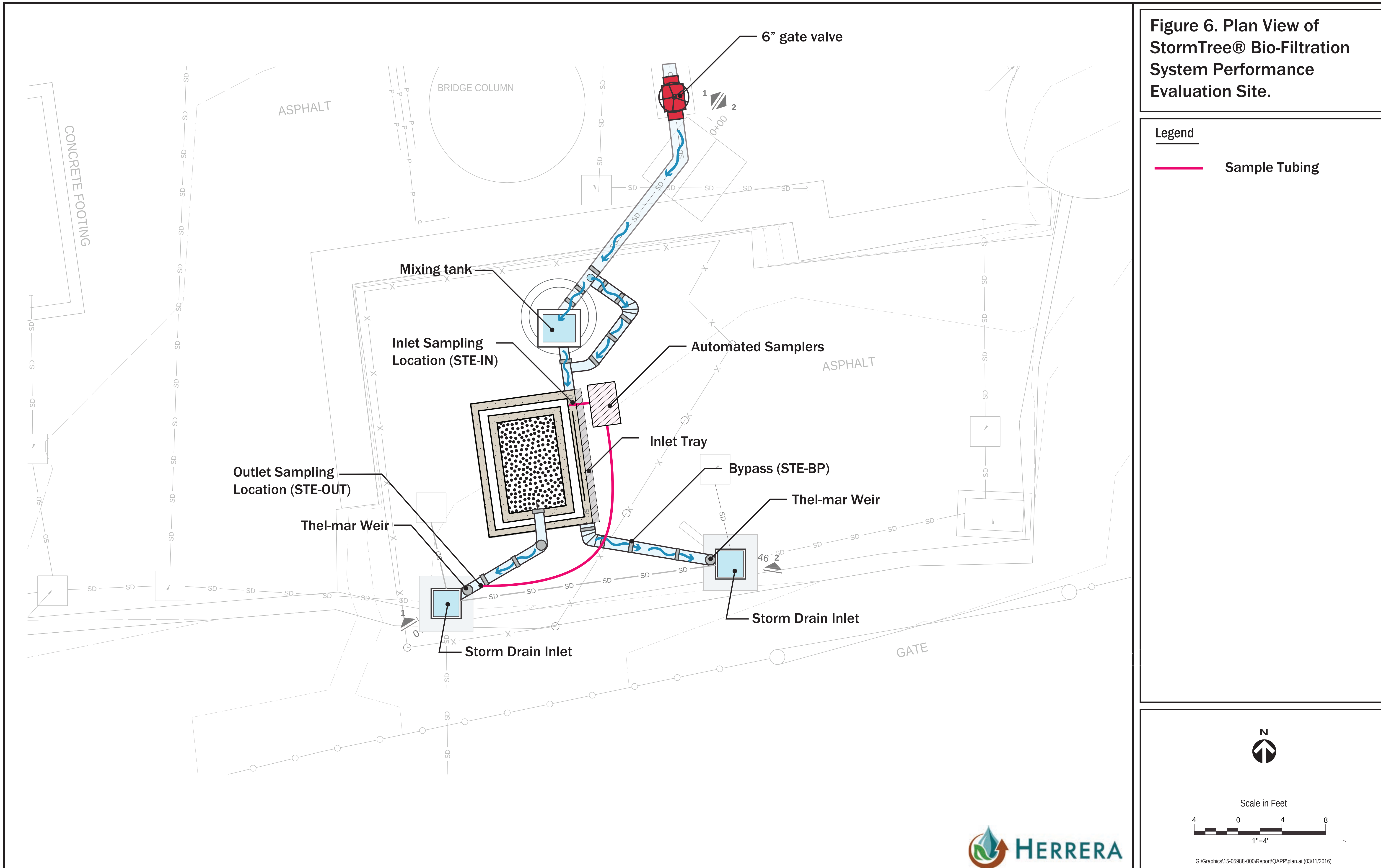


Figure 5. Photo of the back of the StormTree® System as installed at the Ship Canal Test Facility.

Figure 6. Plan View of StormTree® Bio-Filtration System Performance Evaluation Site.



Test System Maintenance Schedule

Typical maintenance of the StormTree® consists of raking or replacing the mulch and raking the top few inches of engineered media. Maintenance is required when sediment and/or oil build up on top of the mulch layer, so the maintenance schedule is driven by pollutant loading from the site.

Maintenance was conducted at the site on an as-needed basis. The system went online on March 24, 2020. In May it became apparent that the system needed maintenance. The mulch was replaced on May 11, 2020. On December 20, 2020 and approximately 7 months after the first replacement, the mulch was replaced again. The effect of these maintenance activities on hydraulic performance of the system are discussed in the *Results* section.

Hydrologic Monitoring Procedures

Generalized schematics of the equipment that was installed in association with the StormTree® system are provided in Figures 6 and 7. The equipment installation was completed in February 2020, and monitoring began in March of 2020. Continuous hydrologic monitoring was performed in conjunction with the StormTree® system at four separate monitoring stations: STE-OUT, STE-IN, STE-BP (Figures 6 and 7), and Wall-RG. STE-BP is a bypass flow monitoring station; STE-OUT is a treated effluent flow monitoring station located at the outlet; combined flows from STE-BP and STE-OUT were used to estimate the flow rate at STE-IN, the influent monitoring station. Wall-RG is a precipitation monitoring station. The four hydrologic monitoring stations are described in separate subsections below, followed by a summary of the maintenance procedures performed on the associated monitoring equipment. The monitoring procedures are described in greater detail in the quality assurance project plan (QAPP) prepared for the study (Appendix B).

Power to the monitoring equipment was supplied using onsite AC power. A Campbell Scientific CR300 datalogger, battery, and digital cell modem for the monitoring were housed in a Knaack Model 4824 enclosure. Conduit was installed to convey pressure transducer cabling and automated sampler suction lines (see description below) from the base of the enclosure to each station.

Bypass Flow Monitoring (STE-BP)

Bypass flows were monitored at the terminus of an 8-inch bypass pipe where it discharges into the nearest downstream catch basin (see Figures 6 and 7). An 8-inch Thel-Mar weir was installed at the end of the bypass pipe, and a hole was drilled through the face of the weir for connecting a section of reinforced 1/2-inch internal diameter polyethylene tubing. The other end of the tubing was connected to a stilling well that was constructed from 3-inch-diameter PVC pipe. A Campbell Scientific CS450-L submersible pressure transducer (0 to 2.5 psi) was installed in the stilling well to measure water levels behind the Thel-Mar weir. The pressure transducer was interfaced with the datalogger described above. When bypass occurred, the datalogger converted water level readings (behind the bypass weir) to estimates of discharge based on standard hydraulic equations (Walkowiak 2006).

Effluent Flow Monitoring Station (STE-OUT)

To facilitate continuous monitoring of treated effluent flow rates, a monitoring station, designated STE-OUT, was established at the end of the 8-inch outlet pipe (Figures 6 and 7). A 8-inch Thel-Mar weir was installed at the end of the outlet pipe, and a hole was drilled through the face of the weir for connecting a section of reinforced 1/2-inch internal diameter polyethylene tubing. The other end of the tubing was connected to a stilling well that was constructed from 3-inch-diameter PVC pipe. A Campbell Scientific CS450-L submersible pressure transducer (0 to 2.5 psi) was installed in the stilling well to measure water levels behind the Thel-Mar weir. The STE-OUT pressure transducer was interfaced with the datalogger described above. The datalogger converted water level readings in the stilling well (which were equivalent to water levels behind the Thel-Mar weir) to estimates of discharge based on standard hydraulic equations (Walkowiak 2006).

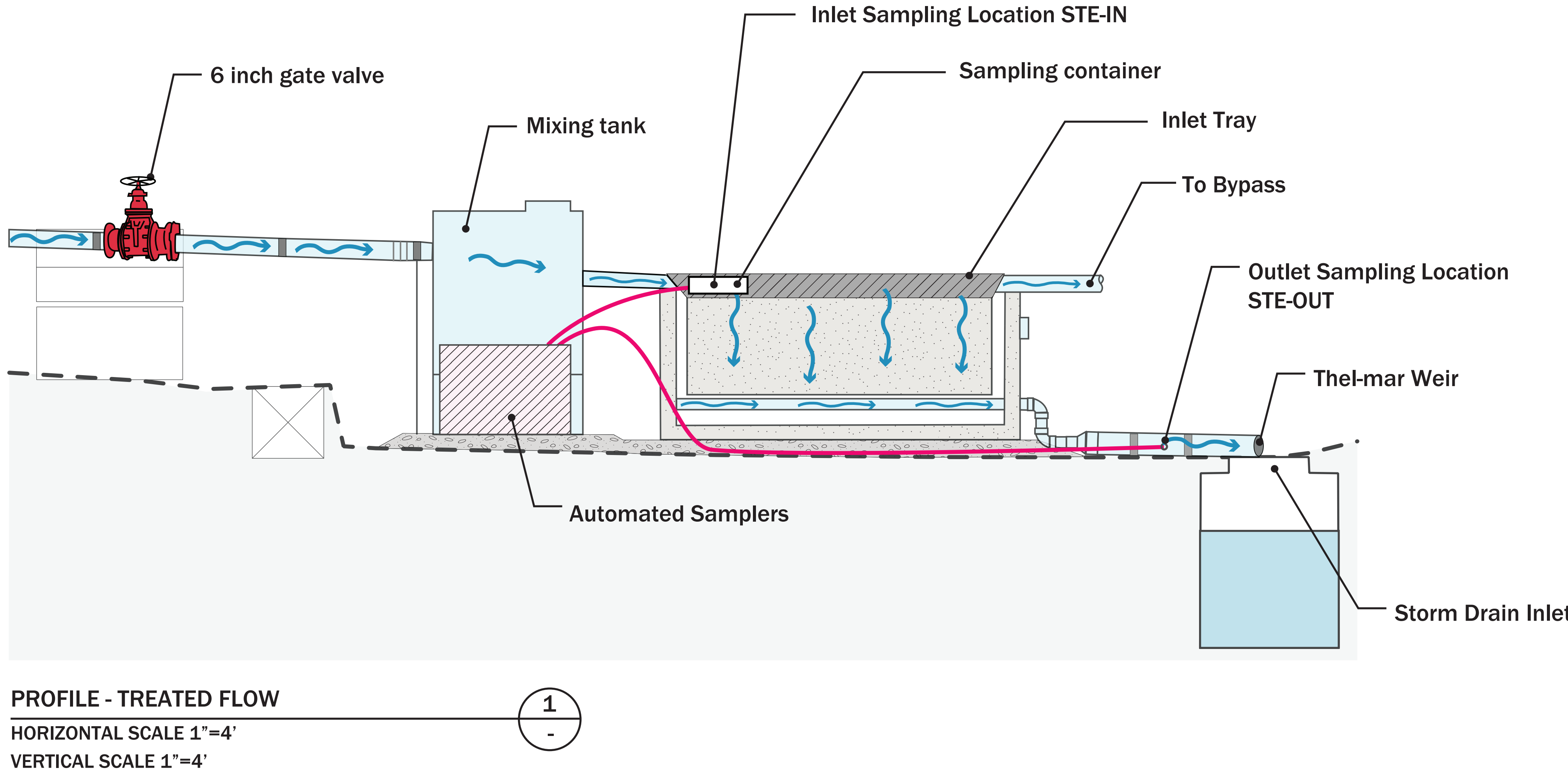
Influent Flow Monitoring Station (STE-IN)

Inflow to the StormTree® system was estimated by adding the flow rates measured at STE-BP and STE-OUT, respectively. Due to the short residence time within the filter of the StormTree® system, this approach was deemed accurate enough for inlet autosampler pacing.

Precipitation Monitoring Station (Wall-RG)

In addition to the three flow monitoring stations (STE-IN, SET-OUT and STE-BP), a third hydrologic station, designated Wall-RG, was installed approximately 4,000 feet southwest of the monitoring location in a residential yard to facilitate continuous monitoring of precipitation depths. Precipitation monitoring at the actual test site is not feasible because it is located beneath a bridge. Precipitation depths were monitored by a Texas Electronics TR525USW rain gauge. The rain gauge was installed on a 10-foot steel pole and interfaced with another Campbell Scientific CR1000 datalogger. The datalogger was equipped with a Campbell Cell210 digital cell phone link to allow communication with the STE-OUT and STE-BP datalogger via remote access. If the Texas Electronics rain gauge failed, Seattle Public Utilities rain gauge (RG-03), at the University of Washington Hydraulic Lab approximately 3,700 feet southeast of the site, was used.

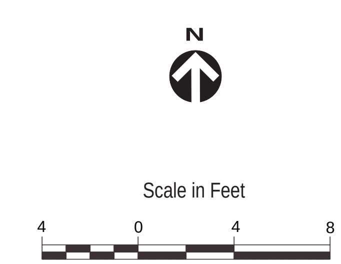
Figure 7. Section Diagram of StormTree® Bio-Filtration System Performance Evaluation Site.



Legend

Direction of Flow

Sample Tubing



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Monitoring Equipment Maintenance and Calibration

The rain gauge and flow monitoring equipment were maintained and calibrated on a routine basis during pre- and post-storm checks. Instrument maintenance and calibration activities were documented on standardized field forms. Rain gauge and level calibration data can be found in the hydrologic data quality assurance memorandum in Appendix F.

Water Quality Monitoring Procedures

To evaluate the stormwater treatment performance of the StormTree® system, water quality sampling was conducted at the influent (STE-IN) and effluent (STE-OUT) stations (Figures 6 and 7) over a 14-month period from March 24, 2020, through May 27, 2021. During this period, 30 storm events were sampled, yielding 29 paired influent and effluent composite samples, three paired grab samples. A general description of the monitoring procedures used is provided herein. A more detailed description can be obtained from the QAPP prepared for this study (Appendix B).

To facilitate water quality sampling for this study, Isco 6712 portable automated samplers were installed in association with the STE-IN and STE-OUT stations. The intake strainer for the automated sampler at the STE-IN station was placed inside a small container positioned beneath the false curb inlet where it could collect water before spilling onto the mulch surface layer. This container was emptied after each event. The intake strainer for the automated sampler at the STE-OUT station was installed just inside the Thel-Mar weir of the outlet pipe (Figures 6 and 7). In both cases, the sampler intakes were positioned to ensure the homogeneity and representativeness of the collected samples. Specifically, sampler intakes were installed to make sure adequate depth was available for sampling and to avoid capture of litter, debris, and other gross solids that might be present. The sampler suction lines consisted of Teflon tubing with a 3/8-inch inner diameter.

The following conditions served as guidelines in defining the acceptability of specific storm events for sampling:

- **Target storm depth:** A minimum of 0.15 inch of precipitation over a 24-hour period
- **Antecedent conditions:** A period of at least 6 hours preceding the event with less than 0.04 inch of precipitation
- **End of storm:** A continuous period of at least 6 hours after the event with less than 0.04 inch of precipitation

Antecedent conditions and storm predictions were monitored via the Internet, and a determination was made as to whether to target an approaching storm. Once a storm was targeted, field staff visited each station to verify that the equipment was operational, to start the sampling program, and to place a clean 20-liter polyethylene carboy and crushed ice in the sampling equipment. The speed and intensity of incoming storm events were tracked using Internet-accessible Doppler radar images. Actual rainfall totals during sampled storm events were quantified based on data from the Wall-RG rain gauge. The datalogger was programmed to enable the sampling routine in response to a predefined increase in water level (stage) at STE-OUT during the storm event sampling. The automated samplers were programmed to collect 220-milliliter sample aliquots at preset flow increments. Based on the expected size of the storm, the flow increment was adjusted to ensure that the following criteria for acceptable composite samples were met at each station:

- A minimum of **10 aliquots** are collected for each event.
- Sampling is targeted to capture **at least 75 percent** of the hydrograph.
- Due to sample holding time considerations, the maximum duration of automated sample collection is **36 hours**.

After each targeted storm event, field personnel returned to each station, made visual and operational checks of the sampling equipment, and determined the total number of aliquots composited. Pursuant to the sampling goals identified above, the minimum number of aliquots that constituted an acceptable sample was 10. If the sample was determined to be acceptable, the carboy was immediately capped, removed from the automated sampler, and kept below 6 degrees Celsius (°C) using ice during transport to the laboratory. All samples were delivered to the laboratory with appropriate chain-of-custody documentation. At the laboratory, collected volume-weighted composite samples were analyzed for the following parameters:

- Total suspended solids (TSS)
- Particle size distribution
- Total phosphorus (TP)
- Orthophosphorus
- Total and dissolved copper
- Total and dissolved zinc
- Hardness

Four of the composite samples were also analyzed for:

- Total Kjeldahl Nitrogen
- Nitrate + Nitrite

In addition to automated sampling, grab samples were collected during three storm events and analyzed them for:

- pH
- Fecal Coliform
- E. coli

At the initiation of a storm event, field personnel would mobilize to collect grab samples in pre-labeled bottles. Inlet sample bottles were filled as water poured into the StormTree® from the false curb (Figures 6 and 7). At the outlet the sample was collected as the water spilled over the STE-OUT weir.

All sample bottles were immediately placed on ice and kept below 6°C until delivery to the laboratory. During the grab sample field visits, field personnel also checked the field equipment and performed any necessary maintenance (without interfering with the functioning of the automated sampling programs). Appendix G provides the Chemistry Data Quality Assurance Memorandum, which assesses the chemistry results in relation to the goals identified in the QAPP.

Analytical Methods

Analytical methods for this study are summarized in Table 2. Analytical Resource, Inc. in Tukwila, Washington was the primary lab used in this study. Analyses for particle size distribution were performed by MTC, Inc., in Tukwila, Washington. Fecal Coliform and E. coli analysis was performed by AmTest Laboratories, Inc. in Kirkland, Washington.

Analytical Resource, Inc. is certified by Ecology, and participates in audits and inter-laboratory studies by Ecology and the US Environmental Protection Agency (US EPA). Such performance and system audits have verified the adequacy of the laboratory's standard operating procedures, which include preventive maintenance and data reduction procedures.

Quality Assurance and Control Measures

Field and laboratory quality control procedures used for the StormTree® system evaluation are described in the following sections.

Field Quality Assurance/Quality Control

This section summarizes the quality assurance/quality control (QA/QC) procedures that were implemented by field personnel to evaluate sample contamination and sampling precision.

Field Blanks

Field blanks were collected at the influent and effluent monitoring locations (STE-IN and STE-OUT) prior to monitoring on February 27, 2020, after monitoring had commenced on April 13, 2020, and after completion of the collection of project samples on March 31, 2021. The field blanks were collected by pumping reagent-grade water through the intake tubing into a pre-cleaned sample container. The volume of reagent grade water pumped through the sampler for the field blank was similar to the volume of water collected during a typical storm event. The results of the field blanks are presented in the Chemistry Data Quality Assurance Review Memorandum in Appendix G.

To help prevent cross contamination from the tubing during routine sampling, the automated sampler tubing was rinsed with stormwater before the collection of each aliquot using an automated double-rinse cycle. In addition, deionized water was back-flushed through the sample tubing before each monitored event.

Field Duplicate Samples

Field duplicates were collected for approximately 10 percent of the samples. To assure high enough concentrations for the duplicate analysis to be meaningful, only the influent station samples were duplicated. To collect the field duplicates, the collected sample in the 20-liter carboy was split using a 22-liter churn splitter. The resultant data from the duplicate samples were used to assess variation in the results that is attributable to analytical variability combined with variability induced by field collection and transportation. The results of the field duplicates are presented in the data Chemistry Quality Assurance Review Memorandum in Appendix G.

Hydrologic Measurements

The accuracy and precision of the automated flow and precipitation measurement equipment were tested prior to monitoring and periodically throughout the project. The results from these checks can be found in the Hydrologic Data Quality Assurance Memorandum in Appendix F.

Laboratory Quality Control

Accuracy of the laboratory analyses was verified with blank analyses, duplicate analyses, laboratory control spikes, and matrix spikes in accordance with the analytical methods employed. Analytical Resources Inc. were responsible for conducting internal QA/QC measures in accordance with their own quality assurance plans.

Water quality results were first reviewed at the laboratories for errors or omissions, and to verify compliance with acceptance criteria. The laboratories also validated the results by examining the completeness of the data package to determine whether method procedures and laboratory QA procedures were followed. The review, verification, and validation by the laboratories were documented in case narratives that accompanied the analytical results.

Table 2. Water Quality Analysis Methods and Detection Limits.										
Parameter	**Analytical Method**	**Method Number[a]**	**Field Sample Container**	**Pre-Filtration Holding Time**	**Total Holding Time[b]**	**Field Preservation**	**Laboratory Preservation**	**Actual Reporting Limit/Resolution**	**Target Reporting Limit/Resolution**	**Units**
Total suspended solids	Gravimetric[c]	SM 2540D	20-liter HDPE bottle	7 days	7 days	Maintain ≤6°C	Maintain ≤6°C	1.0	1.0	mg/L
Particle size distribution	Sieve and hydrometer	ASTM D422		7 days	7 days		Maintain ≤6°C	NA	NA	microns
Total phosphorus	Automated ascorbic acid	SM 4500P-F		NA	28 days		Maintain ≤6°C, H_2SO_4 to pH <2	0.008	0.001	mg/L
Orthophosphorus	Automated ascorbic acid	SM 4500P E		24 hours[d]	48 hours		Maintain ≤6°C	0.004	0.001	mg P/L
Hardness as $CaCO_3$	Titration	SM 2340B		28 days	28 days		Maintain ≤6°C, HNO_3 to pH <2	0.05	1.0	mg/L
Copper, dissolved	ICP-MS	EPA 200.8		24 hours[d]	6 months		Maintain ≤6°C, HNO_3 to pH <2 after filtration[e]	0.0005	0.0001	mg/L
Copper, total				NA			Maintain ≤6°C, HNO_3 to pH <2	0.0005	0.0001	
Zinc, dissolved	ICP-MS	EPA 200.8		24 hours[d]	6 months		Maintain ≤6°C, HNO_3 to pH <2 after filtration[e]	0.004	0.001	mg/L
Zinc, total				NA			Maintain ≤6°C, HNO_3 to pH <2	0.004	0.005	
pH	Field meter (potentiometric)	NA	NA	NA	NA		NA	0.01	0.01	standard units
Fecal Coliform	Membrane filtration	SM 9222 D	4 oz	8 hours	8 hours		$Na_2S_2O_3$ Tablet, Cool <10 ºC	1 CFU/100ml	1 CFU/100 ml	CFU 100/ml
E. coli bacteria	Most probably number	SM 92223B	4 oz	8 hours	8 hours		$Na_2S_2O_3$ Tablet, Cool <10 ºC	1 MPN/100ml	1 MPN/100ml	MPN/100ml
Total Kjeldahl nitrogen	Colorimetric	SM 4500-Norg D mod	500 mL HDPE	NA	28 days		Maintain ≤6°C, pH <2	0.5	0.5	Mg/L
Nitrate+ nitrite nitrogen	Colorimetric	SM 4500-NO_3I	500 mL HDPE	28 days	28 days		Maintain ≤6°C, pH <2 with 2 mL 9N H_sSO_4	0.01	0.01	mg/L

[a] SM method numbers are from APHA et al. (1998); EPA method numbers are from US EPA (1983, 1984); ASTM method numbers are from ASTM (2003). The 18th edition of Standard Methods for the Examination of Water and Wastewater (APHA et al. 1992) is the current legally adopted version in the Code of Federal Regulations.

[b] Holding time specified in US EPA guidance (US EPA 1983, 1984, or referenced in APHA et al. (1992) for equivalent method.

[c] A G4 glass fiber filter will be used for the total suspended solids filtration.

[d] US EPA requires filtering for dissolved metals within 15 minutes of the collection of the last aliquot. This goal is exceedingly difficult to meet when conducting volume-weighted sampling. A more practical proxy goal of 24 hours has been adopted for this study, both goals will be reported with the data.

[e] A 0.45-micron fiber nylon filter will be used for dissolved metals (copper and zinc) filtration.

[f] Reporting limit will be dependent upon dilution used in the laboratory.

[g] Washington State Department of Ecology methods (Ecology 2007) includes silica gel extract cleanup step.

°C = degrees Celsius

$CaCO_3$ = calcium carbonate

GC/FID = gas chromatography/flame ionization detection

HDPE = high-density polyethylene

ICP-MS = inductively coupled plasma/mass spectrometry

mg/L = milligrams per liter

mg P/L = milligram phosphorus per liter

MPN = most probably number

NA = not applicable

Herrera also reviewed and validated sampling data within 7 days of receiving the results from the laboratory to ensure that all data were consistent, correct, and complete, and that all required QC information was provided. Specific QC elements for the data were also examined to determine if the method quality objectives (MQOs) for the project were met. Herrera summarized results from the data validation reviews QA worksheets prepared for each sample batch. Values associated with minor QC problems were considered estimates and were assigned *J* qualifiers. Values associated with major QC problems were rejected and were qualified with an *R*. Estimated values were used for evaluation purposes, but rejected values were not used. The results from this chemistry data quality assessment are presented in Appendix G.

Data Management Procedures

Flow and precipitation data were uploaded remotely on a 5-minute interval using cellular telemetry and were transferred to a database (LoggerNet and Aquarius software) for all subsequent data management tasks.

Analytical Resources Inc. reported the analytical results within 30 days of receipt of the samples. Due to complications stemming from the COVID-19 pandemic, receipt of the PSD data from the laboratory was delayed; those data were received 3-6 months after samples were submitted for analysis. The laboratories provided sample and QC data in standardized reports suitable for evaluating project data. The reports included all QC results associated with the data, a case narrative summarizing any problems encountered in the analyses, corrective actions taken, any changes to the referenced method, and an explanation of data qualifiers. Laboratory data were subsequently entered into a database for all subsequent data management and archiving tasks.

Data Management Quality Control

An independent review was performed to ensure that the data were entered into the database without error. Specifically, a random 10 percent of the sample values in the database were crosschecked to confirm they were consistent with the laboratory reports. If an error was found, another random 10 percent were checked. Checks were made until no errors were found. The data entry error check record is reported in Appendix H.

Data Analysis Procedures

Analysis procedures used for the hydrologic and water quality data are summarized below.

Hydrologic Data Analysis Procedures

The compiled hydrologic data were analyzed to obtain the following information for each sampled and unsampled storm during the monitoring study:

- Precipitation depth
- Average precipitation intensity
- Peak precipitation intensity
- Antecedent dry period
- Precipitation duration
- Bypass flow duration
- Effluent flow duration
- Bypass peak discharge rate
- Effluent peak discharge rate
- Bypass discharge volume
- Effluent discharge volume

A subset of the information was examined in conjunction with sample collection data to determine if individual storm events met the TAPE guidelines for valid storm events. Bypass frequency data was also used to assess when system maintenance was required.

Water Quality Data Analysis Procedures

Data analyses were performed to evaluate the water quality treatment performance of the StormTree® system. Three specific procedures were used in the analyses:

- Statistical comparison of influent and effluent concentrations
- Calculation of pollutant removal efficiency
- Calculation of pollutant removal efficiency as a function of flow

Each procedure is described in more detail in the following subsections.

Statistical Comparisons of Influent and Effluent Concentrations

Pollutant concentrations were compared for paired influent and effluent across all storm events using a 1-tailed Wilcoxon signed-rank test (Helsel and Hirsch 2002). Using a paired test, differences in the influent and effluent concentrations could be more efficiently assessed because the noise (or variance) associated with monitoring over a range of storm sizes can be factored out of the statistical analyses. A 1-tailed test was used to evaluate the specific hypothesis that effluent pollutant concentrations were significantly lower than those in the influent. In all cases, the statistical significance was evaluated at an alpha level (α) of 0.05.

Calculation of the Pollutant Removal Efficiency using Bootstrap Analysis

The removal (in percent) in pollutant concentration during each individual storm (ΔC) was calculated as:

$$\Delta C = 100 \times \frac{\left(C_{in} - C_{eff}\right)}{C_{in}}$$

Where: C_{in} = Influent pollutant concentration
C_{eff} = Effluent pollutant concentration

After the percent removal for each qualifying event was calculated, the mean percent removal values and 95 percent confidence interval about the mean were estimated using a bootstrapping approach (Davison and Hinkley 1997). Bootstrapping offers a distribution-free method for estimates of confidence intervals of a measure of central tendency. The generality of bootstrapped confidence intervals means they are well suited to non-normally distributed data or datasets not numerous enough for a powerful test of normality. Results from the bootstrap analysis were used to determine if the mean percent removal was significantly different from percent removal thresholds presented in the TAPE guidelines (e.g., 80 percent TSS removal).

Pollutant Removal as a Function of Flow Rate

For volume-proportional composite sampling, the 90th percentile of the influent flow rate was calculated for each storm event. Specifically, the instantaneous influent flow rate, in gallons per minute, measured at the point that each aliquot was collected during the sampling period was tabulated and the 90th percentile flow rate value computed from the entire range of sampled times. This process will be completed for each volume-proportional composite sample. A linear regression model was developed using the 90th percentile influent flow rates as the independent variable and pollutant removal performance data from the composite samples as the dependent variable. These regressions were performed for TSS, dissolved copper, dissolved zinc, and total phosphorus removal. The regressions were used to determine whether treatment performance varies as a function of flow and at what flow rate performance falls below the goals identified through the TAPE program for each treatment category. The suitability of the regression equation should be evaluated using the diagnostics described in Helsel and Hirsch (2002).

DATA SUMMARIES AND ANALYSIS

This section summarizes data collected during the monitoring period. The presentation of these data is organized under separate subsections for the hydrologic and water quality monitoring results, respectively. A memorandum discussing the quality of the hydrologic data is presented in Appendix F, while Appendix G presents results from the validation review that was performed on the chemistry data.

HYDROLOGIC DATA

To provide some context for interpreting the data, this section begins with a comparison of rainfall totals measured during the monitoring period relative to historical data. The actual hydrologic monitoring results are then presented in a subsequent section.

Historical Rainfall Data Comparison

To provide context for interpreting the hydrologic performance of the StormTree® system, an analysis was performed on rainfall data collected at the National Weather Service (NWS) rain gauge at Sand Point, Seattle to determine if rainfall totals from the monitoring period (March, 2020, through May, 2021) were anomalous. The NWS rain gauge is located at Sand Point, approximately 4.25 miles northeast of the Wall-RG rain gauge. The analysis specifically involved a comparison of rainfall totals measured at the Sand Point rain gauge over the monitoring period to average totals for the same gauge from the 1986 - 2016 (the available historical data from the gauge). These data are summarized in Table 3 along with data from the rain gauge associated with the StormTree® monitoring site (Wall-RG) and rain data from the back up rain gauge (City of Seattle RG-03).

Results from this analysis showed the average March through May total rainfall at the Sand Point rain gauge from 1986 through 2016 was 44.27 inches. In comparison, the rainfall total at the same rain gauge over the monitoring period was 49.17 inches. This indicates rainfall over the monitoring period was 11 percent wetter than is typical. Wall-RG, RG-03, and the Sand Point gauge had a coefficient of variation of 3.2 percent during the monitoring period. Taken together, these data indicate that the rainfall measured at Wall-RG was representative of regional rainfall as measured by two other gauges during the study period and that the monitoring period was wetter than average.

Table 3. Monthly and Annual Precipitation Totals (in inches) for 2020-21 at the StormTree® Test Site Compared to Historical Totals at Sand Point.

Month	StormTree® Rainfall Data (Wall-RG)	RG-03 Rainfall Data[a]	Sand Point NWS Station Rainfall Data[b]	Historical Sand Point NWS Station Rainfall Data (1986 – 2016)[b]
March 2020	3.06	3.39	3.38	3.74
April 2020	1.58	1.64	1.73	2.81
May 2020	3.43	3.26	4.21	2.23
June 2020	2.04	1.94	3.06	1.61
July 2020	0.14	0.14	0.16	0.77
August 2020	0.43	0.36	0.58	0.97
September 2020	3.34	2.90	4.16	1.39
October 2020	3.07	3.10	2.98	3.18
November 2020	5.55	5.45	5.38	5.59
December 2020	6.12	6.02	5.96	5.33
January 2021	9.01	8.47	7.61	4.99
February 2021	4.36	4.10	4.41	2.88
March 2021	3.28	3.16	3.22	3.74
April 2021	0.91	0.93	0.96	2.81
May 2021	1.13	1.22	1.37	2.23
Total	**47.45**	**46.08**	**49.17**	**44.27**

[a] Source: City of Seattle Rain Gauge – RG-03. Located at the University of Washington Hydraulic Lab approximately 3,700 feet southeast of the project site.

[b] Source: NWS Office at Sand Point Seattle (<http://w2.weather.gov/climate/index.php?wfo=sew>). Located 4.25 miles northeast of the project site.

Hydraulic Performance Assessment

To assess the hydraulic performance of the StormTree® test system, the compiled hydrologic data were first assessed for quality using the Aquarius Continuous Data Management System (Aquarius). Based on this assessment, Herrera determined that all the method quality objectives for hydrologic data identified in the project QAPP were met (Appendix B). The data were then exported into a custom data management system for further analyses, which included the development of a water budget for the StormTree® system to determine influent volume, effluent volume, and bypass frequency and volume. Using that water budget, additional analyses were performed to determine whether treatment goals for the StormTree® system were met based on the volumes treated and bypassed.

The StormTree® system was sized to capture and treat 91 percent of the average annual runoff volume pursuant to minimum requirements for runoff treatment in western Washington. The design flow rate for achieving that goal is 36.9 gpm. Using this design flow rate and assuming a 100 percent impervious basin and Seattle precipitation, the modeled (MGSFlood 4.40) average annual treated volume is 865,000 gallons. The treated volume measured during the study was compared with this annual volume to determine the percent water year treated by the StormTree® test system.

Table 4 presents the hydraulic monitoring results for the StormTree® system for the 29 sampled events from March 24, 2020, to May 27, 2021 (also see Appendix I). As shown in Table 4, the mulch layer in the StormTree® system needed to be replaced two times during the 14 months of monitoring (40.8 percent of a water year) due to instances of excessive sediment and oil buildup on the surface of the mulch layer (see Figure 8) that resulted in clogging. This equates to a mulch change approximately every 2.4 months (20 percent of a water year), which is more frequent than the recommended 6 to 12 months. The StormTree® system treated 40.8 percent of the annual runoff for a properly sized 6-foot by 4-foot unit; thus, the system was not able to meet the 91 percent minimum requirement goal identified above for western Washington.

Three different systems were also being tested at the SCTF during the same time period (a downward flow sand filter, an upward flow sand filter, and a cartridge filter) and exhibited similar clogging issues. Subsequently, Ecology has recognized that stormwater at the SCTF may be atypical for manufactured treatment device applications because of the intermittent occurrence of excessive sediment and oil loading. We suggest conducting follow up hydraulic testing at another location with more typical runoff conditions in order to prove the recommended 6-to-14-month maintenance interval. Given the StormTree is a "treebox" style filter which using the same mulch spec as three previously approved treebox filters, we anticipate the maintenance requirements to be similar.

Table 4. Hydraulic Performance of the Sampled Events at the StormTree® System.

Date	Average Sampled Treated Flow (gpm)	Peak Inflow (gpm)	Peak Outflow (treated) (gpm)	Peak Bypass Flow (gpm)	Peak Treated Flow During Bypass (gpm)	Cumulative Percent of a Water Year Treated
3/24/20	4.7	27	27	–	–	2.7%
3/28/20	1.0	11	11	–	–	2.9%
3/30/20	3.2	12	12	–	–	3.2%
4/22/20	6.6	40	40	2.5	40	4.6%
5/2/20	1.7	20	20	6.5	20	5.4%
Maintenance 5/11/20 – Mulch replaced						
5/16/20	2.1	24	24	–	–	5.8%
Upstream CB bypassed 5/19/20						
5/20/20	7.1	30	30	–	–	6.8%
5/30/20	4.5	19	19	–	–	9.6%
6/8/20	4.9	33	33	–	–	10.2%
6/15/20	1.4	17	17	–	–	13.5%
Upstream CB bypass removed 7/2/20						
9/18/20	1.3	19	19	–	–	15.9%
9/23/20	2.6	27	27	–	–	16.4%
9/25/20	6.3	22	22	–	–	17.2%
10/9/20	4.0	20	20	–	–	17.5%
10/13/20	3.4	13	13	–	–	18.1%
11/3/20	5.6	31	31	–	–	18.8%
11/24/20	3.6	10	10	–	–	20.6%
12/8/20	3.5	20	20	–	–	21.3%
12/14/20	0.52	5.5	5.5	–	–	22.0%
12/16/20	2.8	9.5	9.5	–	–	22.4%
Maintenance 12/20/20 – Mulch replaced						
12/21/20	3.9	18	18	–	–	25.0%
12/29/20	5.8	34	34	–	–	25.5%
1/11/21	12	29	29	–	–	28.0%
1/24/21	3.4	11	11	–	–	30.4%
1/31/21	5.5	25	25	–	–	31.7%
3/4/21	4.0	13	13	–	–	38.9%
3/20/21	6.4	21	21	–	–	39.6%
3/22/21	3.0	32	32	–	–	39.8%
5/27/21	7.9	14	14	–	–	40.8%
Mean	**4.2**	**21**	**21**	**4.5**	**30**	**–**

Figure 8. Photo of Sediment Loading at the StormTree® Bio-Filtration System Performance Evaluation Site.

WATER QUALITY DATA

This section summarizes water quality data collected at the StormTree® system over the monitoring period extending from March 24, 2020, through May 27, 2021. It begins with a comparison of the collected data to criteria identified in the TAPE guidelines for determining sample acceptability. Water quality data are then compared to treatment goals identified in the TAPE guidelines. A complete database of all the analyzed parameters is provided in Appendix I. Field forms completed by staff during each sampling visit are presented in Appendix J. Individual storm reports showing sample collection times in relation to influent and effluent hydrographs are presented in Appendix K for all sampled storm events. Finally, laboratory reports for each sampled event are presented in Appendix L.

Comparison of Data to TAPE Criteria

The TAPE guidelines identify criteria for determining data acceptability based on the characteristics of sampled storm events and the collected samples. Data collected through this monitoring effort are evaluated relative to those criteria below.

Storm Event Guidelines

During the March 24, 2020, through May 27, 2021, monitoring period, 29 storm events were sampled to characterize the water quality treatment performance of the StormTree® system. Precipitation data from these sampled storm events were compared to the following criteria from the TAPE guidelines for determining their acceptability:

- **Minimum precipitation depth**: 0.15 inch
- **Minimum antecedent dry period**: 6 hours with less than 0.04 inch of rain
- **Minimum storm duration**: 1 hour
- **Minimum average storm intensity**: 0.03 inch per hour for at least half the sampled storms

Summary data related to these criteria are presented in Table 5. As shown, the criterion for minimum precipitation depth (0.15 inch) was met during all storm events except the June 15, 2020 event. Because the flows which enter the test system are not only a function of the rainfall amount, but also a function of the upstream valve setting, the peak flow associated with the June 15, 2020 event was 16.6 gpm, almost 50 percent of the design flow rate. In a typical field application a storm of such a low rainfall total would have produced a much lower flow rate. For comparison, the much larger October 13, 2020 event was characterized by a rainfall total of 0.53 inches, but due to the valve setting resulted in a peak influent discharge of only 12.8 gpm. So, although the June 15, 2020 was not qualifying per the rain total criteria it produced a qualifying hydrograph, thus we argue that it should be kept in the dataset.

The minimum, median, and maximum precipitation depths across all sampled storm events were 0.09, 0.44, and 2.5 inches, respectively. The criterion for minimum antecedent dry period (6 hours) was met for all except one storm on January 31, 2021. The antecedent dry period for this storm was close to the criteria, at 4.9 hours. Storm duration criterion (1 hour) were met for all storm events. Antecedent dry periods during the sampled storm events ranged from 4.9 to 341 hours, with a median value of 27.5 hours. Storm durations ranged from 2.9 to 37 hours, with a median value of 11.5 hours (Table 5).

The criterion for minimum average storm intensity is to sample across a range of intensities. Table 5 indicates that this objective was achieved.

Table 5. Comparison of Precipitation Data from Sampled Storm Events at the StormTree® System to Storm Event Guidelines in the TAPE.

Storm Start Date and Time	Storm Precipitation Depth (inches)	Storm Antecedent Dry Period (hours)	Storm Precipitation Duration (hours)	Average Storm Intensity (inches/hour)
3/24/20	0.41	10	13	0.03
3/28/20	0.47	28	11	0.04
3/30/20	0.34	21	3.8	0.09
4/22/20	0.81	92	23	0.04
5/2/20	0.24	55	12	0.02
5/16/20	0.63	48	16	0.04
5/20/20	0.61	88	17	0.04
5/30/20	1.2	69	26	0.05
6/8/20	0.20	37	12	0.02
6/12/20	0.25	24	11	0.02
6/15/20	**0.090**	22	7.3	0.01
9/18/20	0.29	64	2.9	0.10
9/23/20	0.94	63	16	0.06
9/25/20	0.63	16	12	0.05
10/9/20	0.94	341	10	0.10
10/13/20	0.53	15	6.8	0.08
11/3/20	0.78	248	7.8	0.10
11/24/20	0.24	21	5.8	0.03
12/8/20	0.45	6.8	17	0.03
12/14/20	0.18	7.8	11	0.02
12/16/20	0.43	27	8.5	0.05
12/21/20	2.5	27	23	0.11
12/29/20	0.81	54	33	0.02
1/11/21	2.1	25	31	0.07
1/24/21	0.26	70	15	0.02
1/31/21	1.2	**4.9**	37	0.03
3/4/21	0.40	107	6.8	0.06
3/20/21	0.22	6.3	4.9	0.04
3/22/21	0.20	6.2	5.8	0.03
5/27/21	0.20	71.2	8.8	0.02
Minimum	**0.090**	**4.9**	**2.9**	**0.01**
Median	**0.44**	**27.5**	**11.5**	**0.04**
Maximum	**2.5**	**341**	**37**	**0.11**
Criteria	**≥0.15**	**≥6**	**≥1**	**Range[a]**

[a] Majority of events exceeded the rainfall intensity criterion of 0.03 inch per hour.

Values in **bold** do not meet storm event guidelines recommended in the TAPE (Ecology 2011).

Sample Collection Guidelines

As described in the *Water Quality Monitoring Procedures* section, automated samplers were programmed with the goal of meeting the following criteria, identified in the TAPE guidelines, for acceptable composite samples:

- A minimum of 10 aliquots is collected for each event.
- Sampling is targeted to capture at least 75 percent of the hydrograph.
- Due to sample holding time considerations, the maximum duration of automated sample collection at all stations is 36 hours.

The criterion for minimum number of sample aliquots (10) in composite samples was met for all of the sampled events (see Table 6). Table 6 also indicates that the criterion for minimum hydrograph capture (75 percent) was met for all sampled events, except for the June 15, 2020 event. During the June 15, 2020 event the storm coverage was 68 percent at the inlet and 66 percent at the outlet. Due to this, the water quality results for this event were excluded from further analysis. The composite sample collection duration did not exceed 36 hours for any of the 29 composite-sampled events.

Table 6. Comparison of Sampling Data from Storm Events at the StormTree® System to TAPE Guidelines for Sample Events.						
Storm Start Date and Time	**Sample Aliquots (number)**		**Storm Coverage (percent)**		**Sampling Duration (hours)**	
	STE-IN	**STE-OUT**	**STE-IN**	**STE-OUT**	**STE-IN**	**STE-OUT**
3/24/20	74	67	97	96	15	15
3/28/20	27	12	95	86	5.9	5.7
3/30/20	42	20	98	92	4.0	3.8
4/22/20	69	66	96	96	8.0	8.0
5/2/20	38	35	92	93	12	12
5/16/20	36	40	86	94	11	14
5/20/20	58	70	76	97	8.5	20
5/30/20	26	37	93	92	23	22
6/8/20	42	42	88	88	13	13
6/12/20 [a]	-	-	-	-	-	-
6/15/20	31	30	**68**	**66**	2.9	2.9
9/18/20	49	48	97	96	5.9	5.8
9/23/20	29	28	94	93	20	19
9/25/20	44	43	97	94	8.6	7.7
10/9/20	38	37	97	94	13	12
10/13/20	15	14	95	91	4.2	4.1
11/3/20	38	37	98	96	8.8	8.3
11/24/20	24	23	94	88	10	8.8
12/8/20	69	68	99	98	18	18
12/14/20	14	13	92	85	4.0	3.8
12/16/20	47	45	98	95	11	10
12/21/20	33	31	98	95	26	26
12/29/20	79	78	84	84	21	21
1/11/21	81	80	99	98	26	22
1/24/21	47	46	84	83	14	13
1/31/21	100	100	97	97	27	27
3/4/21	50	49	99	95	10	8.8
3/20/21	78	74	99	99	5.8	5.8
3/22/21	35	34	97	94	4.8	4.6
5/27/21	24	23	95	90	5.1	5.0
Minimum	14	12	**68**	**66**	2.9	2.9
Median	42	40	97	94	10	10
Maximum	100	100	99	99	27	27
Criteria	**≥10**		**≥75**		**≤36**	

Values in **bold** do not meet storm event guidelines recommended in the TAPE (Ecology 2011).

NA = not applicable

[a] Grab sample only, no composite samples collected for this event.

Water Quality Treatment Performance Evaluation

This section evaluates water quality data based on treatment goals identified in the TAPE guidelines. Particle size distribution data are presented first to assess the representativeness of influent stormwater; results from monitoring performed to evaluate the performance of the StormTree® system relative to the goals for basic and phosphorus treatment are then presented.

Particle Size Distribution

The TAPE guidelines indicate that stormwater in the Pacific Northwest typically contains mostly silt-sized particles; therefore, results for particle size distribution should be provided to indicate whether the stormwater runoff analyzed conforms to this assumption and is thus representative of regional conditions. The average D_{50} of the influent water was 83 microns with ~40 percent of the PSD silt and finer (Figure 9). The sand-silt boundary is a particle size of 62 microns. It is assumed that a 21 micron difference in the D_{50} will not bias the TSS removal and maintenance results presented herein.

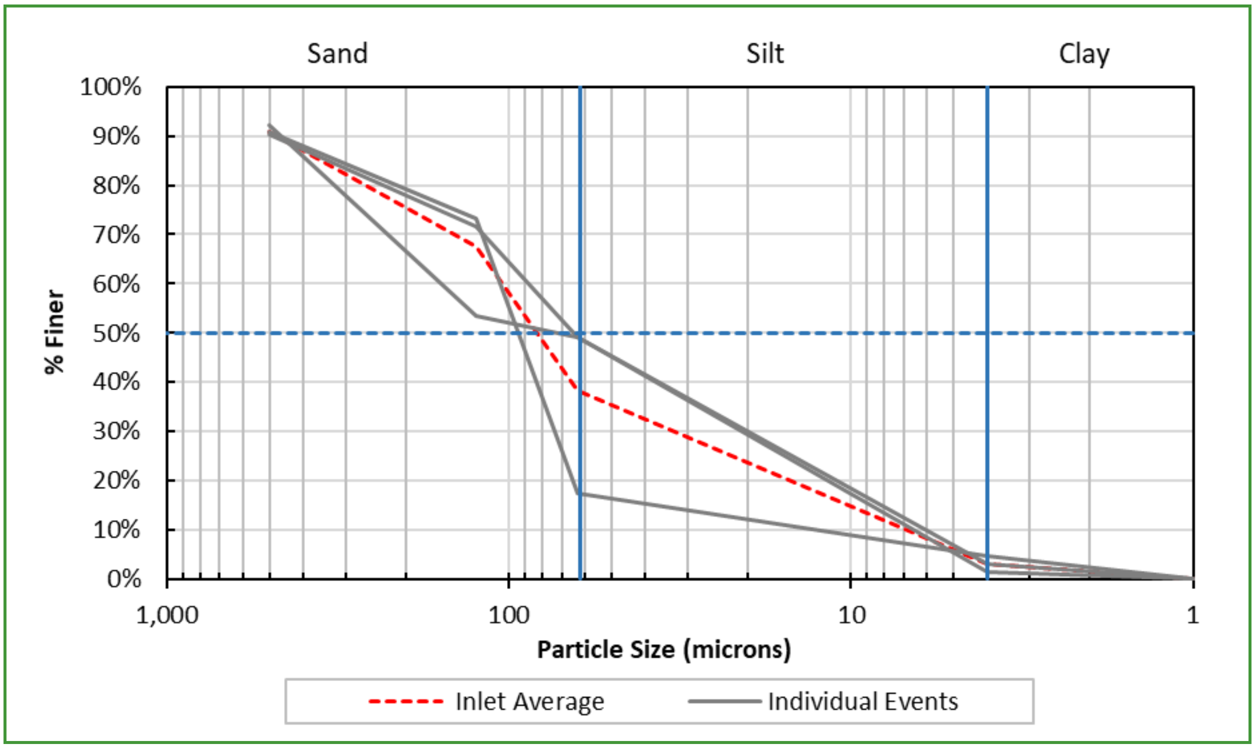

Figure 9. Influent Particle Size Distribution Results.

Upstream Catch Basin Effect on TSS

As noted in the *Site Location and System Sizing* section, the upstream type 2 catch basin was configured with a bypass in case there needed to be field adjustments to increase influent solid concentrations. It was anticipated that having the catch basin online would reduce influent TSS concentrations, but as indicated in Table 7 influent TSS actually decreased when the catch basin was taken offline between May 19, 2020 and July 2, 2020. Three of the four sampled events in the period when the catch basin was offline had TSS concentrations below 20 mg/L and thus could not be used for TAPE assessment (Table 7). When the bypass was removed and the catch basin put back online on July 2, 2020, influent TSS concentrations increased and never fell below 20 mg/L from that point forward.

Basic Treatment

The basic treatment goal from the TAPE guidelines indicates the bootstrapped LCL95 of the mean TSS removal must be ≥80 percent for influent concentrations ranging from 100 to 200 mg/L. For influent TSS concentrations ≤100 mg/L but > 20 mg/L, the UCL95 of the mean effluent concentration must be ≤20 mg/L. There is no specified goal for influent TSS concentrations <20 mg/L; consequently, those sample pairs (influent and effluent) are not used to assess TSS removal performance. For influent concentrations that exceed 200 mg/L, the treatment goal is an LCL95 of at least an 80 percent reduction. Additionally, a statistically significant difference between influent and effluent concentrations must be demonstrated. Finally, pollutant removals that meet the TAPE goals must be shown for sample pairs across a range of flow rates up to and including the design flow rate.

Influent composite samples from 26 of the 29 composite-sampled events sampled for TSS had concentrations above 20 mg/L. Samples with influent concentrations below this threshold could not be used in the analysis per the TAPE guidelines. One sample had an influent concentration greater than 100 mg/L and per TAPE guidelines was also excluded from effluent concentration analysis. A one-tailed Wilcoxon signed-rank test performed on the available TSS data ($n = 25$) indicated there was a statistically significant ($p < 0.001$) decrease in effluent TSS concentrations compared to influent TSS concentrations. Table 7 indicates the calculated UCL95 was 3.5 mg/L, well below the goal identified. Collectively, these data indicate the basic treatment goal was met. It should be noted that 3.5 mg/L is a very low TSS value relative to typical BMP effluent. An indication that the StormTree® system will perform well even when influent TSS concentrations are low, as is typical in residential basins.

To evaluate how TSS treatment efficiency may vary as a function of influent flow rate, analyses were performed to determine the influent flow rate at the time each aliquot was collected. The 90th percentile of the influent aliquot flow rates was then calculated per TAPE guidelines. Figure 10 displays effluent concentrations versus the 90th percentile influent flow rate for all 25 qualifying events. The TAPE guidelines state that a regression analysis should be conducted to evaluate whether treatment efficiency for TSS varies as a function of influent flow rate. Results from this analysis indicated no significant relationship between treatment efficiency and influent flow rate ($p = 0.111$). As is apparent from Figure 10, the StormTree® system reduced effluent concentrations to below 20 mg/L TSS at flow rates up to and including the target design flow rate of 36.9 gpm.

Taken together, this analysis of the monitoring data indicates that the basic treatment goals from the TAPE guidelines were met by the tested StormTree® system.

Table 7. Water Quality Results and Comparison to TAPE Criteria.

Date	Total Suspended Solids (mg/L)			Total Phosphorus (mg/L)			Dissolved Copper (µg/L)			Dissolved Zinc (µg/L)			90th Percentile Sampled Treated Flow (gpm)	Peak Inflow (gpm)
	IN	OUT	Percent Reduction	IN	OUT	Percent Reduction	IN	OUT	Percent Reduction	IN	OUT	Percent Reduction[e]		
3/24/20	38	4	89	0.18	0.062	66	18.9 J	8.99 J	52	47.3 J	7.52 J	84	20	27
3/28/20	78	3	96	0.142	0.048	66	8.65 J	4.54 J	48	26.4 J	7.07 J	73	10	11
3/30/20	47	3	94	0.108	0.048	56	6.72 J	4.02 J	40	18 J	4.57 J	75	11	12
4/22/20	49 J	5 J	90	0.11 J	0.064 J	42	16.6 J	10.6 J	36	34.9 J	8.3 J	76	39	40
5/2/20	31 J	2 J	94	0.14 J	0.052 J	63	12.7 J	7.61 J	40	27.2 J	6.51 J	76	24	20
Maintenance 5/11/20 – Mulch Replaced														
5/16/20	68	3	96	0.162	0.05	69	9.73 J	6.91 J	29	21 J	6.57 J	69	22	24
Upstream CB bypassed 5/19/20														
5/20/20	16	3[a]	81	0.086	0.054	37[c]	10.9 J	8.1 J	26	27.1 J	9.46 J	65	18	30
5/30/20	23	1	96	0.088	0.05	43[c]	10.3 J	6.92 J	33	22.8 J	6.85 J	70	18	19
6/8/20	17	3[a]	82	0.078	0.06	23[c]	12.2 J	7.42 J	39	23.4 J	7.52 J	68	25	33
6/12/20[f]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
6/15/20[h]	18	1[a]	94	0.074	0.04	46[c]	10.4	6.24	40	23	9.25	60	16	17
Upstream CB bypass removed 7/2/20														
9/18/20	131 J	12[b] J	91	0.338 J	0.152 J	55	23.9 J	18.2 J	24[g]	63.3 J	29.1 J	54	17	19
9/23/20	55	3	95	0.168	0.064	62	13.1 J	9.1 J	31	24.6 J	11.6 J	53	8	27
9/25/20	30	3	90	0.062	0.044	29[c]	11.6 J	9.23 J	20	25.3 J	7.94 J	69	19	22
10/9/20	20	3	85	0.072	0.058	19[c]	10 J	6.16 J	38	18.2 J	5.15 J	72	16	20
10/13/20	28	2	93	0.07	0.044	94[c]	8.47 J	6.35 J	25	18.9 J	4.93 J	74	12	13
11/3/20	55	6	89	0.172	0.054	69	11.6 J	8.5 J	27	27 J	8.25 J	69	12	31
11/24/20	67	5	93	0.191	0.043	77	–	–	–	–	–	–	10	10
12/8/20	47	4	91	0.156	0.052	67	–	–	–	–	–	–	17	20
12/15/20	29	2	93	0.092	0.035	62[c]	–	–	–	–	–	–	5	5.5
12/16/20	37	2	95	0.134	0.03	78	–	–	–	–	–	–	7	9.5
Maintenance 12/20/20 – Mulch Replaced														
12/21/20	39	2	95	0.084	0.037	56[c]	–	–	–	–	–	–	17	18
12/29/20	41	2	95	–	–	–	–	–	–	–	–	–	16	34
1/11/21	29	2	93	–	–	–	–	–	–	–	–	–	28	29

Table 7 (continued). Water Quality Results and Comparison to TAPE Criteria.														
Date	**Total Suspended Solids (mg/L)**			**Total Phosphorus (mg/L)**			**Dissolved Copper (µg/L)**			**Dissolved Zinc (µg/L)**			**90th Percentile Sampled Influent Flow (gpm)**	**Peak Inflow (gpm)**
	IN	**OUT**	**Percent Reduction**	**IN**	**OUT**	**Percent Reduction**	**IN**	**OUT**	**Percent Reduction**	**IN**	**OUT**	**Percent Reduction[e]**		
Maintenance 12/20/20 – Mulch Replaced (continued)														
1/24/21	30	1	97	0.085	0.028	67[c]	–	–	–	–	–	–	10	11
1/31/21	44	3	93	0.116	0.03	74	–	–	–	–	–	–	21	25
3/4/21	68	4	94	0.208	0.058	72	–	–	–	–	–	–	11	13
3/20/21	54	3	94	0.118	0.035	70	–	–	–	–	–	–	20	21
3/22/21	38	3	92	0.120	0.028	77	–	–	–	–	–	–	23	32
5/27/21	31 J	5 J	84	0.156 J	0.077 J	51	15.5 J	9.4 J	39	43.2 J	6.74 J	84	13	14
Summary (all data)														
Maximum	131	12	97	0.338	0.152	94	23.9	18.2	52	63.3	29.1	84	39	40
Median	38	3	93	0.118	0.049	62.5	11.6	7.61	36	25.3	7.52	70	17	20
Minimum	16	1	81	0.062	0.028	19	6.72	4.02	20	18	4.57	53	5.3	5.5
Total n-value	29	29	29	27	27	27	17	17	17	17	17	17	29	29
TAPE Summary (screened data)														
Criteria		<20	≥80			≥50			≥30			≥60		
Qualifying n-value[d]		25	1			17			15			17		
UCL95 Mean		**3.5**				69.2			38.6			73.4		
LCL95 Mean		2.64				**61.6**			**31.4**			**66.7**		

[a] Value excluded from calculated TAPE effluent TSS concentration screened summary statistics because the influent concentrations were less than 20 mg/L, which is below the TAPE acceptable range.

[b] Value excluded from calculated TAPE effluent TSS concentration screened summary statistics because the influent TSS was >100 mg/L.

[c] Value excluded from calculated TAPE TP screened summary statistics because influent TP was <0.100 mg/L.

[d] The n-value indicates the number of samples used to calculate summary statistics for each parameter after excluding samples based on influent and special case screening. Minimum require n-value per TAPE (2018) is 15. Full description of screening is provided in the other footnotes to this table and in the *Performance Evaluation* section.

[e] Dissolved zinc screening criteria not applied due to high dissolved zinc removals even with influent concentrations below the TAPE threshold of 20 ug/L.

[f] No composite samples analyzed for this event.

[g] Value excluded from calculated TAPE dissolved copper screened summary statistics because influent was >20 ug/L.

[h] Values from this event excluded from analysis due to low sample coverage.

J = estimate due to lab QA (see Appendix G).

Note: Design flow rate = 36.9 gallons per minute, or 120 inches per hour. **Bold** values meet the performance target from the TAPE guidelines for the associated parameter.

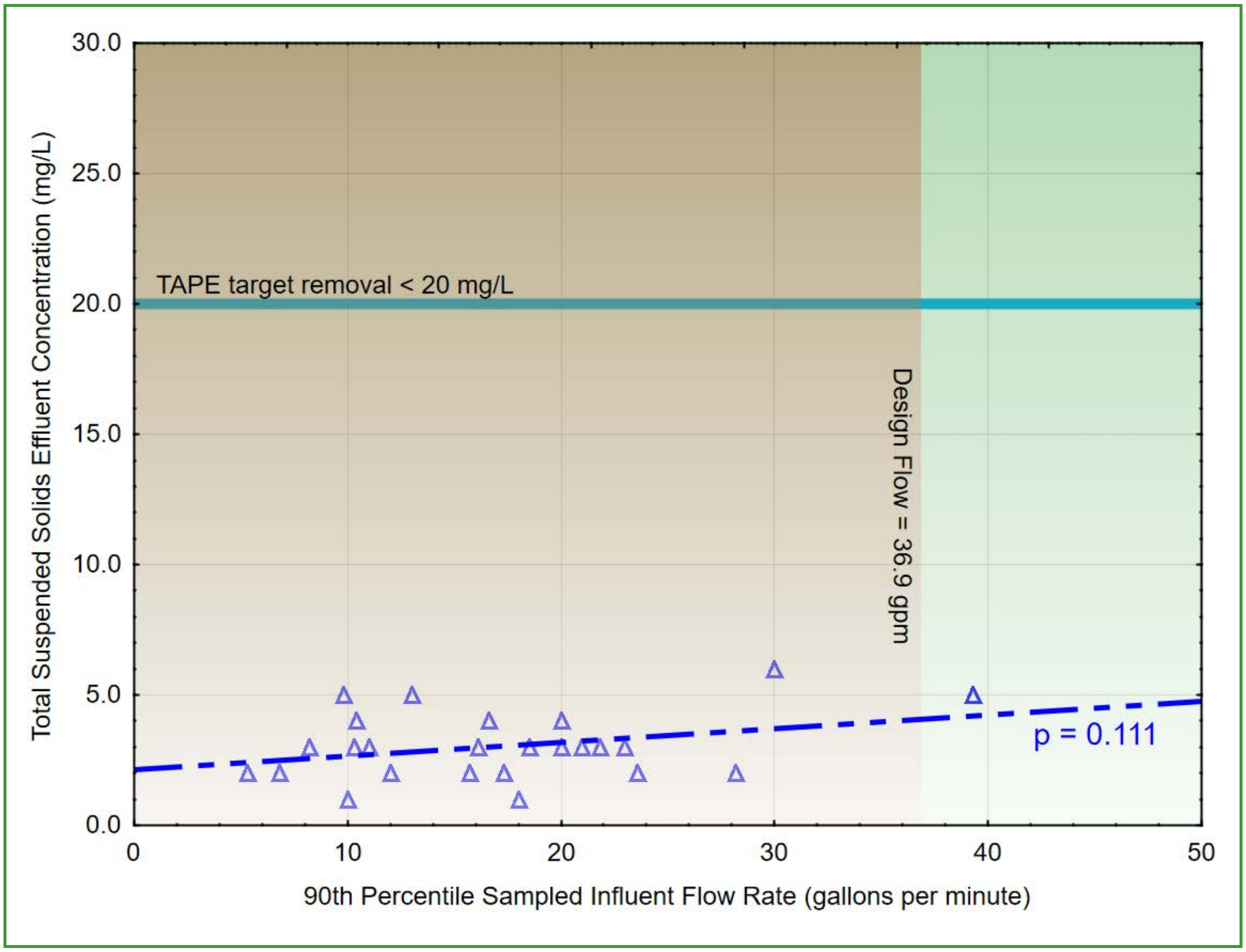

Figure 10. TSS Effluent Concentration as a Function of Average Sampled Influent Flow Rate.

Enhanced Treatment

The TAPE enhanced treatment criteria indicate that the LCL95 of the mean dissolved zinc removal must be ≥60 percent for influent concentrations ranging from 0.02 to 0.30 mg/L. In addition, the LCL95 of the mean dissolved copper removal must be ≥30 percent for influent concentrations ranging from 0.005 to 0.02 mg/L. In addition, it must be shown that a statistically significant difference between influent and effluent concentrations exists. Finally, pollutant removals that meet the TAPE goals must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate. Separate subsections for copper and zinc below describe the sampling results in relation to these criteria.

Copper Treatment

As shown in Table 7, influent composite samples from 15 sampled storm events had dissolved copper concentrations between 0.005 and 0.02 mg/L and were therefore used in calculations.

A one-tailed Wilcoxon signed-rank test applied to the data from these samples indicated there was a statistically significant ($p < 0.001$) decrease in effluent dissolved copper concentrations compared to influent concentrations. Consequently, this component of the dissolved copper treatment goal from the TAPE guidelines was met.

Table 7 indicates that the calculated LCL95 of the mean dissolved copper reduction for this dataset was 31.4 percent, which exceeds the percent removal goal identified above. Consequently, this component of the dissolved copper treatment goal from the TAPE guidelines was also met.

Finally, analyses were performed to evaluate dissolved copper treatment efficiency as a function of influent flow rate as described above for basic treatment. Figure 11 displays percent removal versus the 90th percentile influent flow rate for all 15 qualifying events. Results from the regression analysis performed on these data indicated there was no significant relationship between treatment efficiency and treated flow rate (p = 0.794). As is apparent from Figure 11, the StormTree® test system removed greater than 30 percent of the influent dissolved copper at flows rates up to and including the design target flow rate of 36.9 gpm.

Taken together, analyses of the monitoring data indicate the tested StormTree® system was able to meet the Enhanced treatment goals for dissolved copper.

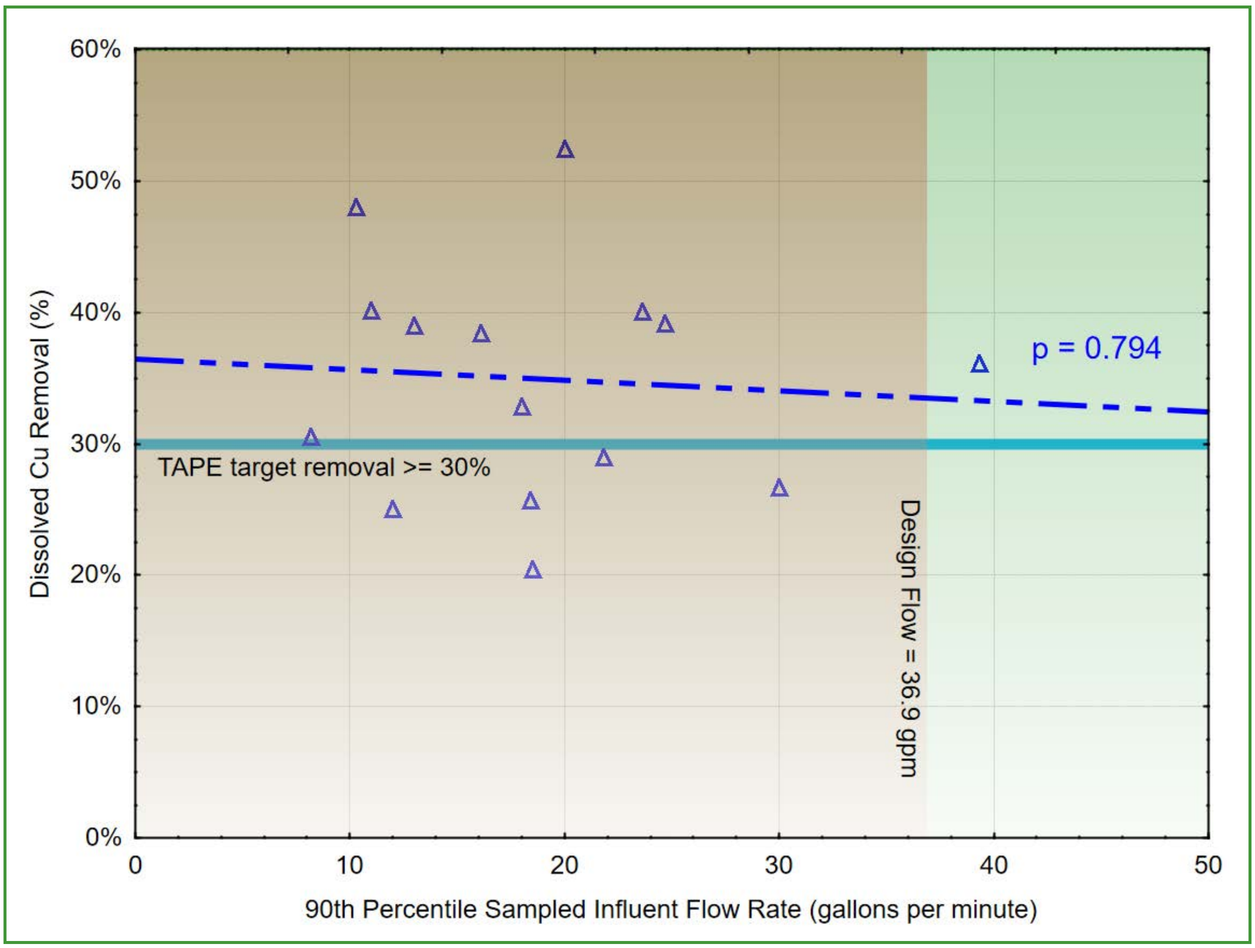

Figure 11. Dissolved Cu Removal (percent) as a Function of 90th Percentile Sampled Influent Flow Rate.

Zinc Treatment

As shown in Table 7, composite samples from 14 of the 17 events sampled for dissolved zinc had influent dissolved zinc concentrations between 0.02 to 0.30 mg/L. Samples from three events had influent concentrations below 0.02 mg/L; however, as indicated in Table 7, the StormTree system was still able to reduce those concentration by greater than 60 percent. Consequently, the dissolved zinc results from all 16 samples were used in this analysis.

A one-tailed Wilcoxon signed-rank test applied to the data from these samples indicated there was a statistically significant ($p < 0.001$) decrease in effluent dissolved zinc concentrations compared to influent concentrations. Consequently, this component of the dissolved zinc treatment goal from the TAPE guidelines was met.

Table 7 indicates that the calculated LCL95 of the mean dissolved zinc reduction for this dataset was 66.7 percent, which exceeds the percent removal goal identified above. Consequently, this component of the dissolved zinc treatment goal from the TAPE guidelines was also met.

Analyses were performed to evaluate dissolved zinc treatment efficiency as a function of influent flow rate as described above. Figure 12 displays percent removal versus the 90th percentile influent flow rate for all 17 events. Results from the regression analysis performed on these data indicated there was no significant relationship between treatment efficiency and treated flow rate ($p = 0.438$). As is apparent from Figure 12, the StormTree® system removed greater than 60 percent of the influent dissolved zinc at flows rates up to and including the target design flow rate of 36.9 gpm.

Taken together, analyses of the monitoring data indicate the tested StormTree® system was able to meet the TAPE Enhanced treatment goals for dissolved zinc.

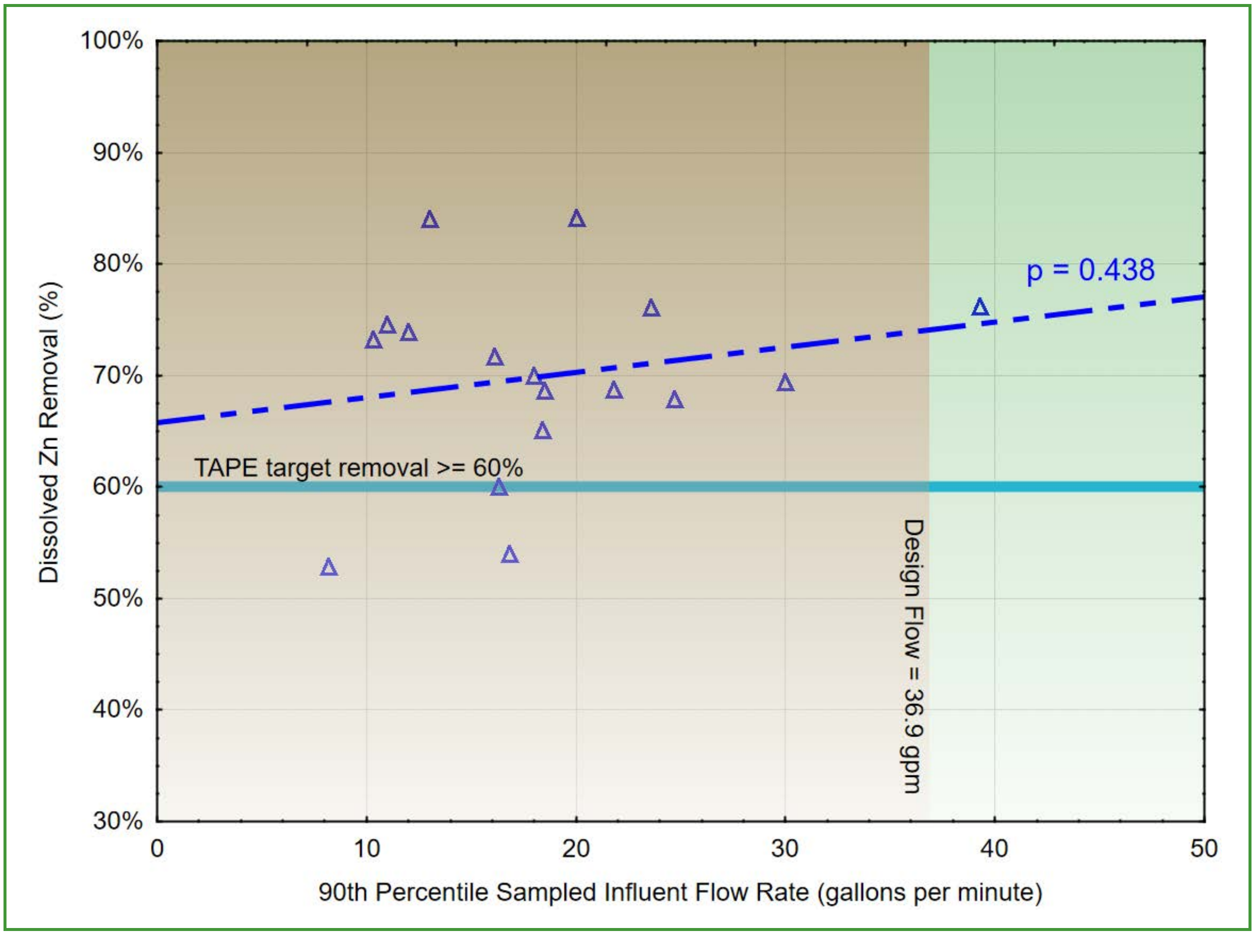

Figure 12. Dissolved Zn Removal (percent) as a Function of 90th Percentile Sampled Influent Flow Rate.

Phosphorus Treatment

The phosphorus treatment goal from the TAPE guidelines indicates that the LCL95 of the mean removal must be ≥50 percent for influent TP concentrations ranging from 0.1 to 0.5 mg/L. In addition, a statistically significant difference between influent and effluent concentrations must be demonstrated. Finally, pollutant removals that meet the TAPE goals must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate.

As shown in Table 7, influent composite samples from 17 of the 27 events sampled for TP had concentrations between 0.1 and 0.5 mg/L; while the remaining 10 samples had concentrations <0.1 mg/L. Per the TAPE guidelines, the latter sample pairs should be omitted from subsequent analyses of treatment performance because influent concentrations below the 0.1 mg/L threshold are deemed too difficult to treat relative to the percent reduction goal identified above.

A one-tailed Wilcoxon signed-rank test applied to the data from the subset of 17 samples indicated there was a statistically significant ($p < 0.001$) decrease in effluent TP concentrations compared to influent concentrations. Consequently, this component of the phosphorus treatment goal from the TAPE guidelines was met.

Table 7 indicates that the calculated LCL95 of the mean TP reduction for this dataset was 61.6 percent, which exceeds the percent removal goal identified above. Consequently, this component of the phosphorus treatment goal from the TAPE guidelines was also met.

Analyses were performed to evaluate TP treatment efficiency as a function of influent flow rate as described above for basic treatment. Figure 13 displays percent removal versus the 90th percentile influent flow rate for all 16 qualifying events. Results from the regression analysis performed on these data indicated there is a statistically insignificant relationship between treatment efficiency and treated flow rate (p = 0.171). Although removal efficiency decreases with an increase in flow rate, the results show removal efficiency is above TAPE removal goal of 50 percent for flows at the target design flow rate of 36.9 gpm.

Taken together, analyses of the monitoring data indicate the tested StormTree® system was able to meet the phosphorus treatment goals from the TAPE guidelines at flow rates up to and including the design flow rate of 36.9 gpm.

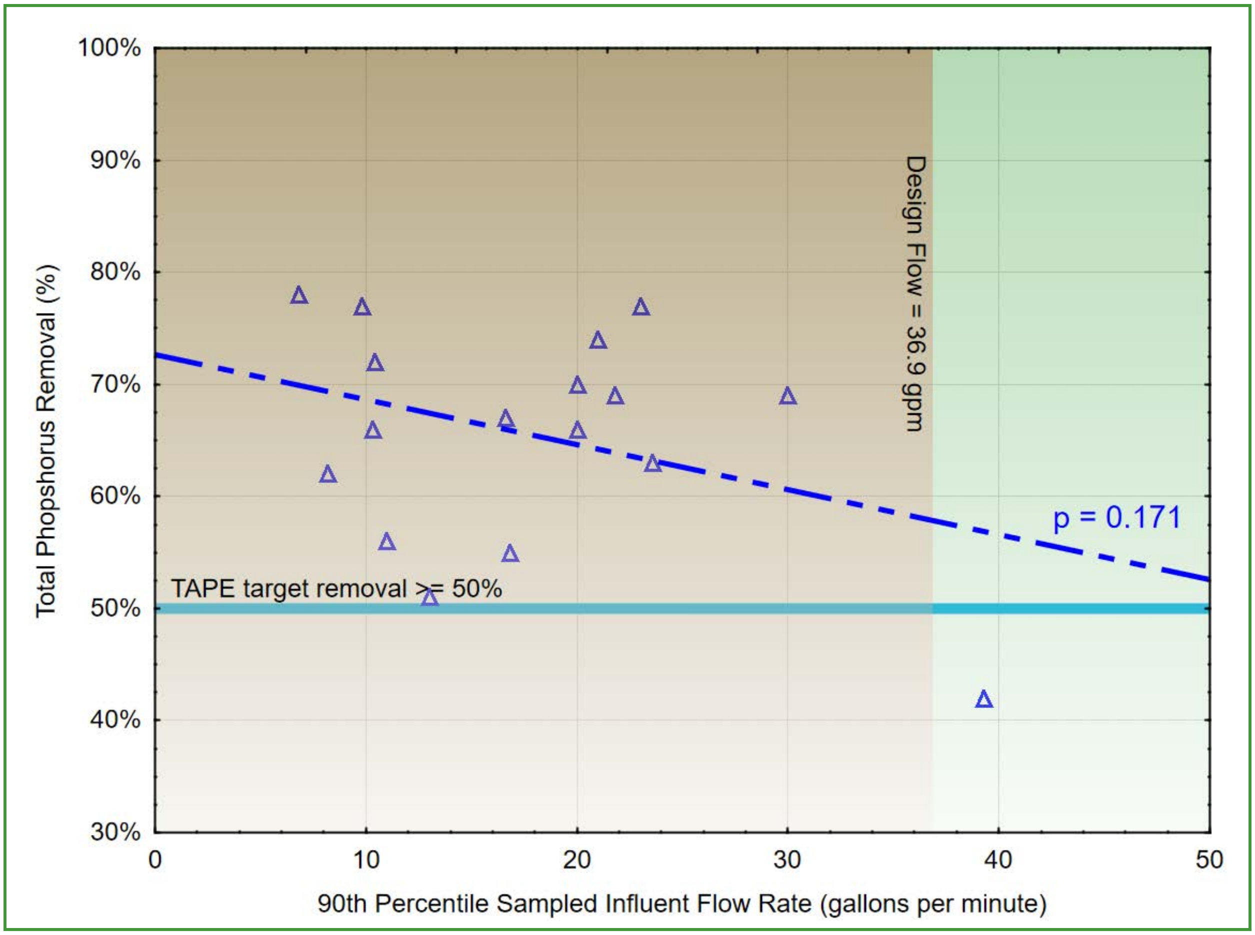

Figure 13. TP Removal (percent) as a Function of 90th Percentile Sampled Influent Flow Rate.

Other Factors

In addition to the required parameters addressed above, the TAPE guidelines indicate additional parameters consisting of hardness, orthophosphorus, pH, total and dissolved copper, fecal coliform, e. Coli, and total and dissolved zinc should also be analyzed. Results for those parameters are presented in Table 8. The median hardness concentrations were 46.9 and 51.3 mg/L of calcium carbonate ($CaCO_3$) from influent and effluent samples, respectively. The median pH levels were 7.14 and 7.56 from influent and effluent samples, respectively. A slight increase in hardness and pH is typical for stormwater filters with granular media. The TAPE guidelines indicate that the test system should not increase or decrease pH by more than one unit for any given event and should not discharge effluent with pH levels less than 4 or greater than 9. The pH data presented in Table 8 indicate that those conditions were met for each sampled event.

Total metals reductions mirrored the dissolved metals reductions reported above. Median influent concentrations were 21.7 and 64.4 ug/L for total copper and total zinc, respectively, while median effluent concentrations were only 9.09 and 10.7 ug/L for the same parameters.

Bacteria is typically difficult to treat with passive stormwater filters; however, the StormTree was moderately effective at removing both fecal coliform and E. coli. Median influent concentrations were both 2,300 colony forming units (CFU)/100 mL for fecal coliform and E. coli, respectively, while median effluent concentrations were only 1,600 and 1,580 (CFU)/100 mL.

The StormTree system acted as a source of nitrogen species and orthophosphorus. Nitrogen export is typical from stormwater filters without an anoxic zone designed to promote denitrification. The orthophosphorus export was likely a function of the very low influent orthophosphorus concentrations (median = 0.014 mg/L). The International BMP database indicates that the lowest median <u>effluent</u> concentrations for any BMP category is 0.015 mg/L (ISBMPD 2020), greater than the median influent concentration measured at the SCTF. This indicates that influent orthophosphorus concentrations measured during this study were likely irreducible using typical unit process in passive stormwater treatment systems, so the observed export was not a surprise.

Table 8. Results of Other Parameters.

Date	Orthophosphorus (mg/L)		Hardness (mg/L as $CaCO_3$)		Total Copper (µg/L)		Total Zinc (µg/L)		pH (Std Units)		Fecal Coliform (CFU/100mL)		E. coli (CFU/100mL)		Total Kjeldahl Nitrogen (mg/L)		Nitrate+Nitrite N (mg/L)		90 percentile Sampled Influent Flow	Peak Inflow (gpm)
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT		
3/24/2020	0.023	0.034	86.5	79.4	34.6	10.1	120	10.7	-	-	-	-	-	-	-	-	-	-	20	27
3/28/2020	0.009	0.028	63.2	56.1	40.3 D	5.98	168 D	9.09	-	-	-	-	-	-	-	-	-	-	10	11
3/30/2020	0.011	0.028	30.5	25	21.7	4.97	82.4	7.37	-	-	-	-	-	-	-	-	-	-	11	12
4/22/2020	0.006	0.018	36.1 J	30 J	47.1 D J	14.7 J	140 D J	16 J	-	-	-	-	-	-	-	-	-	-	39	40
5/2/2020	0.006	0.017	-	-	28.8 J	9.09 J	70.9 J	8.93 J	-	-	-	-	-	-	-	-	-	-	19	20
5/16/2020	0.008	0.021	-	-	28.3 D	8.06	107 D	9.46	-	-	-	-	-	-	-	-	-	-	22	24
5/20/2020	0.021	0.023	56.6	59.7	20.8	10.5	64.4	14.8	7.11	7.56	2300	1600	2300	1580	0.8	1.0	0.376	0.52	18	30
5/30/2020	0.02	0.026	40.6	41.6	18.5	8.09	54.7	9.57	-	-	-	-	-	-	-	-	-	-	17	19
6/8/2020	0.016	0.029	77.7	81.8	22.3	10.1	58.9	12.5	7.21	7.92	12000	3800	12000	3480	0.9	0.6	0.649	0.679	25	33
6/12/2020	-	-	-	-	-	-	-	-	-	-	92	390	74	387	-	-	-	-	-	123 [a]
6/15/2020	0.026	0.026	99.6	104	13.7	6.73	40.1	9.58	-	-	-	-	-	-	0.6	0.5 U	0.773	0.763	16	17
9/18/2020	0.027	0.044	64.4 J	54.2 J	100 J	26.5 J	381 J	46.2 J	7.14 J	7.29 J	-	-	-	-	-	-	-	-	17	19
9/23/2020	0.01	0.014	51	51.3	33.4 J	11	98.6 J	14.1	-	-	-	-	-	-	-	-	-	-	8.7	27
9/25/2020	0.025	0.02	33.8	31.4	27.2	12.7	79.1	14.6	-	-	-	-	-	-	-	-	-	-	19	22
10/9/2020	0.024	0.027	39.9	42.1	16.4	7.5	39.1	7.74	-	-	-	-	-	-	-	-	-	-	16	20
10/13/2020	0.021	0.024	30.2	32.2	19.3	7.57	59.2	9.12	-	-	-	-	-	-	-	-	-	-	12	13
11/3/2020	0.028	0.026	28.2	29.6	35.1	13.5	99.7	16.4	-	-	-	-	-	-	0.5 U	1.0	0.33	0.404	30	31
11/24/2020	0.01	0.017	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	10
12/8/2020	0.012	0.018	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17	20
12/15/2020	0.014	0.017	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.3	5.5
12/16/2020	0.01	0.012	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.6	9.5
12/21/2020	0.011	0.016	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17	18
12/29/20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15	34
1/11/21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	28	29
1/24/21	0.016	0.012	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	11
1/31/21	0.013	0.016	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	21	25
3/4/21	0.015	0.017	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11	13
3/20/21	0.007	0.012	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20	21
3/22/21	0.010	0.011	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24	32
5/27/21	0.024	0.034	107	123	26.8	11.7	78.5	10.6	-	-	-	-	-	-	-	-	-	-	13	14
Summary (all data)																				
Maximum	0.028	0.044	107	123	100	26.5	381	46.2	7.21	7.92	12000	3800	12000	3480	0.9	1.0	0.773	0.763	39	40
Median	0.014	0.020	51.0	51.3	27.2	10.1	79.1	10.6	7.14	7.56	2300	1600	2300	1580	0.7	0.8	0.513	0.600	17	20
Minimum	0.006	0.011	28.2	25	13.7	4.97	39.1	7.37	7.11	7.29	92	390	74	387	0.5 U	0.6	0.33	0.404	5.3	6
Total n-value	27	27	15	15	17	17	17	17	3	3	3	3	3	3	4	4	4	4	29	30

[a] Erroneously high value due to treated effluent weir being overtopped. Maximum flow weir can measure = 86 gpm.

U = non-detect J = estimate due to lab QA D = Sample analyzed on a dilution

µg/L = micrograms per liter mg/L = milligrams per liter

CONCLUSIONS

To obtain performance data to support the issuance of a GULD for the StormTree® system, Herrera conducted hydrologic and water quality monitoring at a test system located in Seattle, Washington, from March 24, 2020, to May 27, 2021. During the monitoring period, 30 separate storm events were sampled. The sampling yielded 29 paired influent and effluent composite samples and three paired grab samples, with one of the grab sample pairs collected during an event where no composite samples were collected.

Of the 29 paired composite samples collected, 25 were suitable for use in evaluating the StormTree® test system's performance relative to the basic treatment goal from the TAPE guidelines. The UCL95 of mean effluent TSS concentration from the 24 samples was 3.5 mg/L, and the goal for basic treatment from the TAPE program is ≤20 mg/L; therefore, the StormTree® system met this goal for basic treatment. The StormTree® system also meets the goal of effluent TSS concentrations at flow rates up to and including the design flow rate of 36.9 gpm (120 in/hr).

The LCL95 mean percent dissolved copper removal from the 15 qualifying samples was 31.4 percent, meeting the goal for enhanced treatment from the TAPE guidelines of ≥30 percent. The LCL95 mean percent dissolved zinc removal from the 17 qualifying samples was 66.7 percent, also meeting the goal for enhanced treatment from the TAPE guidelines of ≥60 percent. A regression analysis also indicated that the StormTree® system was able to meet the treatment goals for dissolved copper and dissolved zinc at flow rates up to and including the design flow rate of 36.9 gpm (120 in/hr).

Of the 27 storm events analyzed for TP, 10 had influent concentrations below 0.10 mg/L, and were screened from further analysis relative to TAPE phosphorus goals. For the remaining 17 sample pairs, the LCL95 mean percent TP removal was 61.6 percent, which meets the TAPE goal of ≥50 percent removal. A regression also indicated that the StormTree® system to meet the treatment goal for TP at flow rates up to and including the design flow rate of 36.9 gpm (120 in/hr).

Taken together, the sampling results present strong evidence that the StormTree® Bio-Filtration System should receive a GULD for basic, enhanced, and phosphorus treatment.

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