TECHNICAL EVALUATION REPORT

Hydro International Up-Flo® Filter Stormwater Treatment System Performance Verification Project

Prepared for
Hydro International Inc.

Prepared by
Herrera Environmental Consultants, Inc.

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HYDRO INTERNATIONAL UP-FLO® FILTER STORMWATER TREATMENT SYSTEM PERFORMANCE VERIFICATION PROJECT

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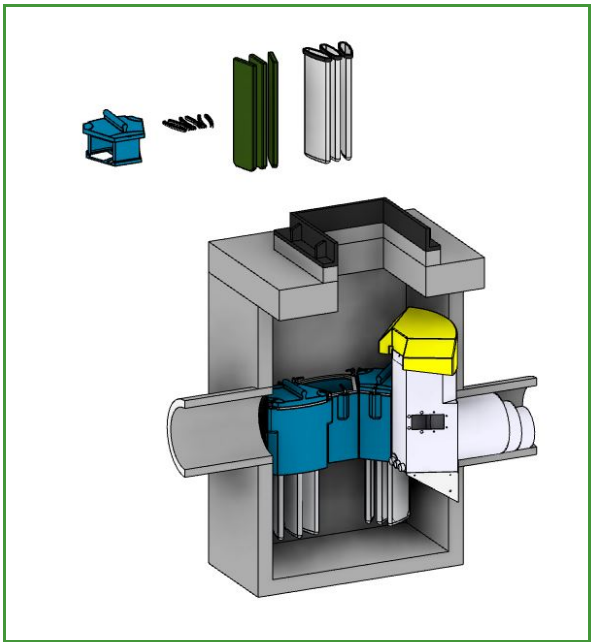
EXECUTIVE SUMMARY

The Hydro International Up-Flo® Filter is an emerging stormwater treatment technology consisting of an array of modules containing engineered woven fabric filters (filter Ribbons) wrapped around a permeable core that allows filtered water to pass upward and out of the treatment system.



Up-Flo Filter with Ribbon

From April 2017 through March 2018, Herrera Environmental Consultants, Inc. (Herrera) conducted hydrologic and water quality monitoring of an Up-Flo Filter for Hydro International, Inc. at an approved test facility in Seattle, Washington. Herrera conducted this monitoring to obtain performance data to support the issuance of a General Use Level Designation (GULD) for the Up-Flo Filter 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 2011).

This technical evaluation report (TER) was prepared by Herrera to demonstrate the Up-Flo Filter meets minimum treatment goals identified in the TAPE to obtain a GULD for basic and phosphorus treatment.

SAMPLING PROCEDURES

To evaluate the stormwater treatment performance of the Up-Flo Filter system based on Ecology's TAPE, a test system was installed at the Washington State Department of Transportation (WSDOT) Ship Canal Test Facility (SCTF), in Seattle, Washington (Figure 1 in the *Introduction* section). This test system is identified herein as the WSDOT Up-Flo Filter (WUFF) test system. Automated monitoring equipment was installed to continuously measure the WUFF test system's effluent and bypass flow volumes. Automated equipment was also used to collect flow-weighted composite samples of the WUFF test system's influent and effluent during 24 separate storm events over the monitoring period identified above.

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

- Total suspended solids (TSS)
- Total phosphorus (TP)
- Soluble reactive phosphorus (SRP)
- Particle size distribution (PSD)

Additional screening parameters required by the TAPE were also analyzed on the composite samples for a select number of events. The screening parameters were:

- Total and dissolved copper
- Total and dissolved zinc
- pH
- Hardness

In addition, analyses were conducted for total petroleum hydrocarbons, suspended solid concentration, and total volatile solids. The results for these parameters are included in the appendices to this TER; however, the main text of this report only addresses the primary water quality parameters listed above. The TSS and TP water quality data were subsequently analyzed in the following ways:

- Computation of pollutant removal efficiencies with bootstrap confidence intervals
- Statistical comparisons of influent and effluent concentrations
- Correlation analysis to examine the influence of treated flow rate on system performance

These results were then compared to the minimum treatment goals from the TAPE for basic and phosphorus treatment.

Hydraulic Performance

The hydraulic treatment goal for the test system was to capture and treat 91 percent of the average annual runoff volume. The WUFF test system was unable to consistently sustain peak treatment flow rates during the course of the study, which caused more bypass volume. As a result, even though the filter was tested for a year, it did not treat the annual runoff volume. However, three other stormwater treatment technologies installed in adjacent bays at the SCTF were also challenged with maintaining maximum treatment flow rates. The source of stormwater at the SCTF is primarily highway runoff; consequently, it is hypothesized that a combination of the large and well-trafficked catchment area with associated conveyance generated an unusual mixture of fine organic particulate matter, hydrocarbons, and other vehicular pollutants. It is likely this stormwater is specific to this site and not representative of the typical stormwater that manufactured stormwater treatment devices will encounter from other common urban catchment areas and land uses (e.g., residential or commercial development). The ramifications of this are discussed in the *Results* section.

Water Quality Performance

Basic Treatment

The basic treatment goal in the TAPE is ≥80 percent removal of total suspended solids for influent concentrations ranging from 100 to 200 milligrams per liter (mg/L). For concentrations less than 100 mg/L, facilities must achieve an effluent goal of 20 mg/L pursuant to the TAPE.

None of the influent total suspended solids concentrations in collected samples exceeded 100 mg/L, thus the percent reduction analysis was not conducted. Instead an analysis of effluent concentrations indicated that of the 20 qualifying events the minimum total suspended solids concentration was 2 mg/L and the maximum was 28 mg/L. The upper 95 percent confidence interval about the mean effluent concentration was 15.5 mg/L, below the 20 mg/L treatment goal from the TAPE. Analyses of flow and water quality data indicated that the treatment goal was met up to and through the tested flow rate of 90 gallons per minute (gpm) for six modules, 15 gpm per module or 0.8 gpm per square foot of filter ribbon.

Phosphorus Treatment

The phosphorus treatment goal in the TAPE is ≥50 percent removal of total phosphorus for influent concentrations ranging from 0.1 to 0.5 mg/L. Out of the 24 sampled events, samples from only 12 events had influent concentrations within this range.

The lower 95 percent confidence limit of the mean total phosphorus removal for these 12 samples was 50.0 percent. Consequently, it can be concluded the phosphorus treatment goal from the TAPE was met. The system also exhibited removal rates greater than this goal up to and through the tested surface area loading rate of 0.8 gpm per square foot of filter ribbon.

Recommendation

Based on the performance results presented above, it is recommended that the Up-Flo Filter system be granted a GULD for basic and phosphorus treatment when sized based on a surface loading rate of 0.8 gpm/square foot [ft^2] of filter ribbon surface area. Due to the unpredictable media longevity recorded at this atypical site, we propose that, if granted a GULD, an additional hydraulic assessment of an Up-Flo Filter be conducted at another location. Ideally, the site will have pollutant characteristics that will be more typical than what was encountered at the SCTF, and the assessment will demonstrate a more predictable service life. Once these data are collected, the maintenance requirements in the GULD for the Up-Flo Filter could be updated based on the associated findings. This approach to addressing the maintenance interval question was proposed and accepted by Ecology for the approval of the Oldcastle BioPod, which was tested in an adjacent bay at the SCTF and also encountered frequent bypass.

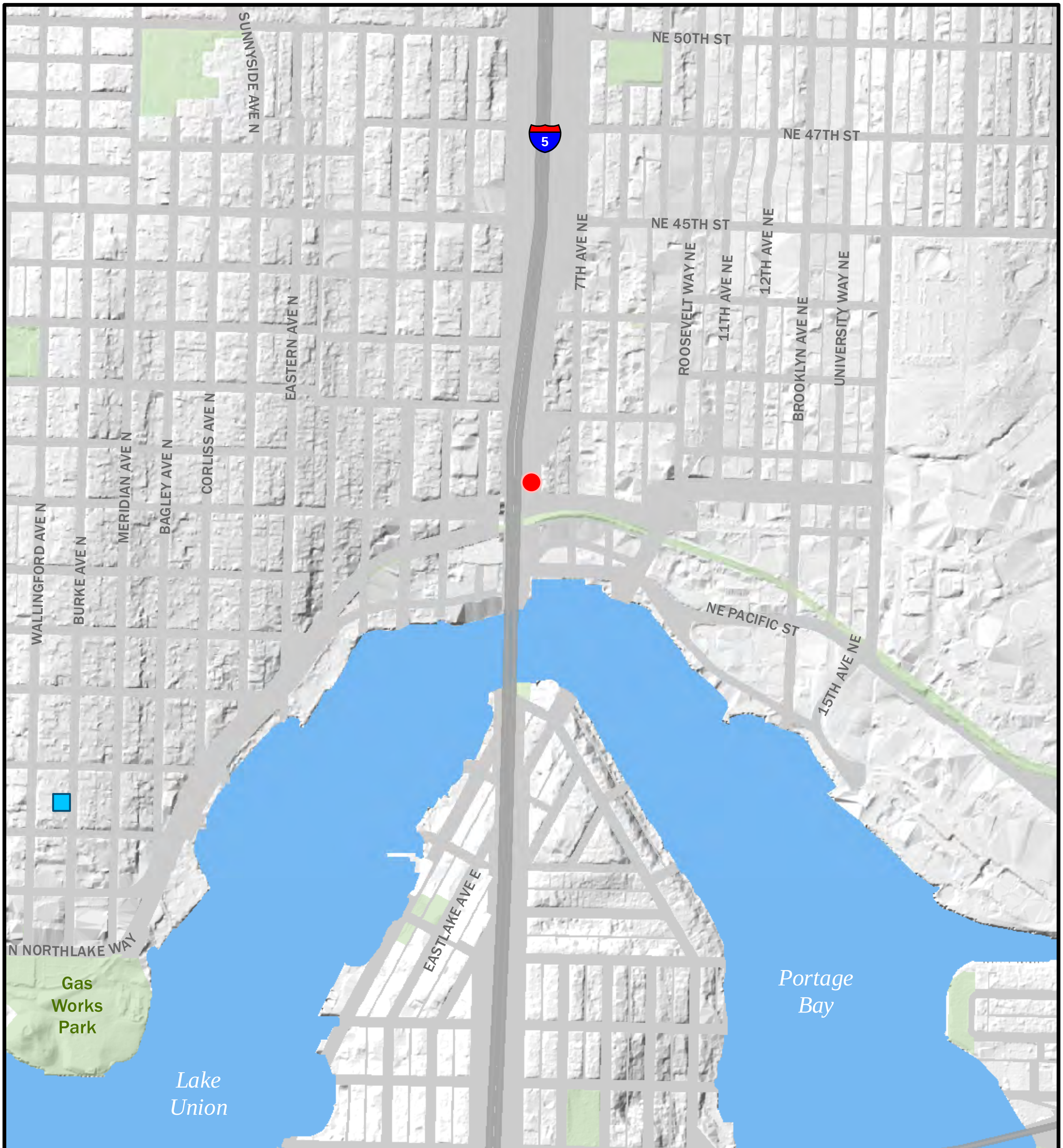
INTRODUCTION

The Up-Flo Filter is an emerging stormwater treatment technology developed by Hydro International, Inc. that incorporates gravitational separation of floating and settling materials, and filtration of polluted stormwater, to offer treatment train capabilities in a stand-alone device. The Washington State Department of Ecology (Ecology) has established specific use level designations for emerging stormwater treatment technologies like the Up-Flo Filter in accordance with guidelines that are identified by Ecology (2011) in the *Technical Guidance for Evaluating Emerging Stormwater Treatment Technologies: 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, Ecology may issue a general use level designation (GULD) for the treatment technology that permits its widespread use in Washington.

The TAPE requires a technical evaluation report (TER) be completed for any stormwater treatment system under consideration for a GULD. Specifically, the TER should document the treatment performance of a technology to show that it will achieve Ecology's performance goals for target pollutants, as demonstrated by field testing performed in accordance with the TAPE.

This document is the TER for the Up-Flo Filter, and was prepared by Herrera Environmental Consultants, Inc. (Herrera) to demonstrate that performance of the Up-Flo Filter system complies with goals specified in the TAPE guidelines for basic and total phosphorus treatment. It specifically presents data from field testing that was performed on an Up-Flo Filter test system installed at the Washington State Department of Transportation (WSDOT) Ship Canal Test Facility (SCTF) in Seattle, Washington (Figure 1). This field testing was performed over a 1-year period, from April 12, 2017, through March 22, 2018.

Prior to this field testing, an Up-Flo Filter with an alternative design configuration (filtration media instead of filter Ribbons) was also tested at the SCTF over the period from May 16, 2016, through February 8, 2017. However, data from testing at this site showed the performance expectations could not be met. Hence, monitoring of this design configuration was discontinued, and the associated results are not included herein.



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 Up-Flo Filter is an emerging stormwater treatment technology that combines gravitational separation and filtration of polluted stormwater to offer treatment train capabilities in a stand-alone device. This section describes the system's physical components, treatment processes, sizing methods, expected treatment capabilities, expected design life, and maintenance procedures.

System Overview

The Up-Flo Filter is a modular high-rate stormwater filtration device. The system can be installed in a typical manhole configuration or vaulted configuration. The Up-Flo Filter is available in a variety of standard sizes that can treat from approximately half an acre to 23 acres of impervious surface (based on MGSFlood [version 4.39] modeling). Figure 2 provides a cross section perspective of an Up-Flo Filter, while Figure 3 provides a cross section of an individual filter module. Appendix A provides design drawings of the test system deployed at the SCTF.

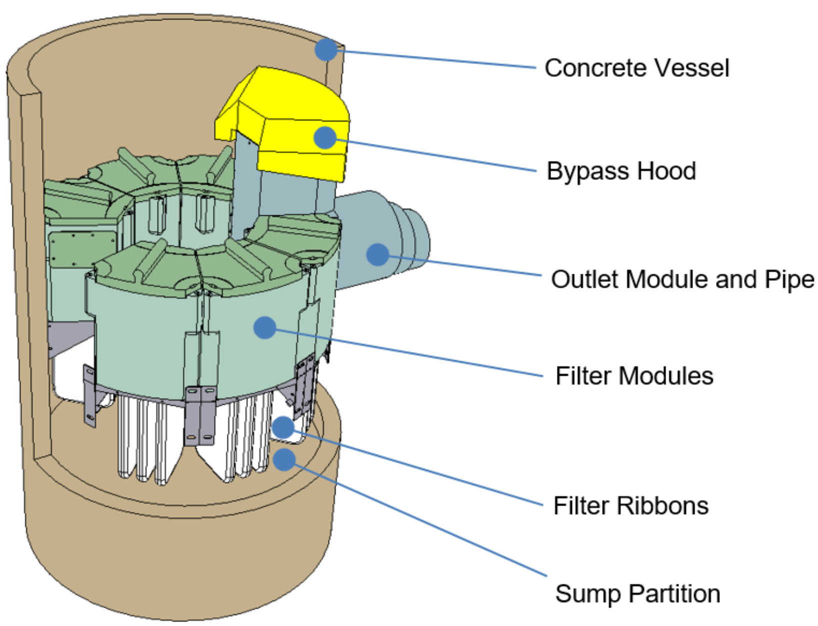


Figure 2. Up-Flo Filter Components.

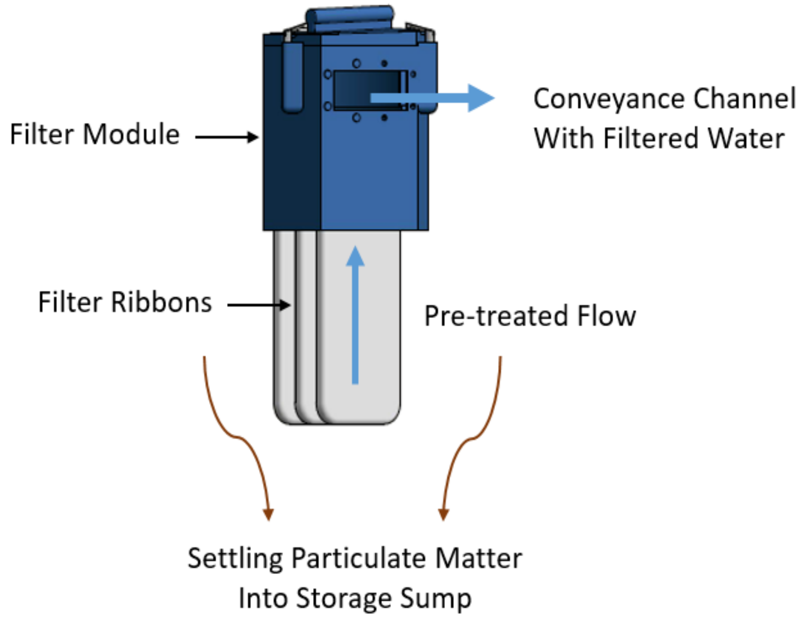


Figure 3. Up-Flo Filter Module with Filter Ribbons.

Operation of the Up-Flo Filter is initiated during a rainfall event when stormwater is conveyed into the chamber from a pipe or grated inlet. As flow enters the chamber, internal components act as baffles to force gross debris and sediment to settle into the sump and floating debris to rise to the surface.

Depending on the runoff rate entering the chamber, a water column builds within the concrete vessel until it reaches a bypass weir elevation. This water column provides the potential energy to drive flow upward through the Ribbon Filters (Figure 3). Filtered water exits the Filter Module(s) into the Outlet Module via a conveyance channel located above the filter Ribbons. Flow in excess of the design filtration capacity discharges over a bypass weir located inside the manhole or adjacent to the vault installation. After a storm event, the water column drops to the bottom of the Conveyance Channel at which point there is no longer any head to drive flow.

Physical Components

The Up-Flo Filter is designed as a modular filtration system that can accommodate a variety of hydraulic conditions. This section describes each component of the technology.

Concrete Vessel

The Up-Flo Filter exterior container is typically precast concrete, but can also be manufactured from polymer materials, plastics, and or field constructed. A typical unit is designed for HS-20 traffic. The structure can range in size from a 4-foot manhole to a 15-foot-long by 13-foot-wide vault (Table 1). An internal bypass is typical, but the Up-Flo Filter can also be provided for use with an external bypass structure. Total unit height is 6.5 feet with a drop of 11.5 inches between the inlet and outlet pipes (piped inlet configuration).

Table 1. Up-Flo Filter Configurations, Design Flow Rates, and Typical Contributing Impervious Areas for Western Washington.

Configuration	Model	Maximum Number of Filter Modules	Flow Rate[a] (gallons/minute)	Contributing Area[b] (acres)
Manhole	**UFF-MH-400R**	**6**	**90**	**2.5**
Vault	UFF-ZV-19-400R	19	285	7.8
Vault	UFF-ZV-38-400R	38	570	15.5
Vault	UFF-ZV-57-400R	57	855	23.3

[a] Assuming 0.8 gallons per minute per square foot of filter.

[b] Basin area modelled using MGS Flood 4.40, Seattle 38-inch MAP, 100 percent impervious basin, default HSPF values, off-line

Bold indicates the size of the test system used in this study.
Sizing table intended for planning level use. The design engineer must use WWHM, MGS Flood, or approved equivalent and the site location mapping to calculate the appropriate facility size for each installation in western Washington.

Inlet

The Up-Flo Filter has multiple inlet configurations:

- Grated Inlet: The grated inlet configuration allows flow to enter through a surface grate in a catch basin installed in the adjacent gutter line. The inlet grate elevation is typically at grade level and can vary from about 12-inches above the top of the module lids to about 12-inches above the top of the bypass hood.

- Piped-In Inlet: The piped-in inlet configuration allows flow to enter through a pipe that discharges into the structure. For piped inflow, flow enters in a place where there is no filter module or is above the filter modules. In either case, the water elevations vary from the outlet pipe invert to the bypass weir elevation.

Filter Modules

The filter modules contain a set of three brackets from which the filter Ribbons (described below) are suspended. The modules are constructed of roto-molded plastic and are hydraulically connected to each adjacent module (Figure 2) to convey filtered water after it passes through the filter Ribbons to the outlet module (described below).

Filter Ribbons

The filter Ribbons consist of a woven inert polymer wrapped around a permeable core that allows filtered water to pass through the filter and then upward and out of the system. Each tubular ribbon is 45 inches in length and is rated to pass 0.8 gpm of stormwater per square foot of ribbon. With a surface area of 6.25 ft^2 per ribbon and three Ribbons per module (Figure 3), this equates to 15 gpm per module. The only way for water to enter the filter modules is through the filter Ribbons. Pressure head from the water in the sump outside of the filter modules drives water through the Ribbons.

Outlet Module and Pipe

After filter water passes through the Ribbons and the filter modules, it is collected in the outlet module. The outlet module (also roto-molded plastic) has a horizontal effluent pipe and a vertical bypass conveyance. Under non-bypass conditions, filtered water passes horizontally through the module and out the effluent pipe. When bypass is occurring, untreated water in the sump outside the modules passes under the bypass hood (described below) and down the vertical bypass conveyance into the outlet module where it mixes with treated water and exits through the effluent pipe. During the testing described herein, the bypass was reconfigured to prevent this mixing to provide a representative location for collecting effluent samples.

Bypass Hood

The Up-Flo Filter has an internal bypass weir with a floatables exclusion hood (Figure 2). The bypass weir invert elevation is 3 feet above the invert of the outlet pipe. This bypass hood was sealed and vented (see Figure 8 in the *Sampling Procedures* section) for the duration of testing at the SCTF and a separate bypass pipe was installed at the hood invert elevation on the opposite side of the manhole (Figure 4).

Site Installation Requirements

Necessary Soil Characteristics

Specific underlying soil characteristics are not required for the Up-Flo Filter, since it is a self-contained, watertight system and is fully enclosed. However, Hydro-International suggests following standard local municipal guidelines, which typically require compaction of the bedding under a vault or comparable water treatment device.

Hydraulic Grade Requirements

The minimum elevation between the inlet and outlet pipe inverts to prevent a submerged inlet is 11.5 inches. However, the system requires a maximum of 3 feet of operating head, so if backwatering of the inlet pipe is not desirable, then the invert of the inlet pipe should be located 3 feet above the invert of the outlet.

Depth to Groundwater Limitations

The Up-Flo Filter vaults are sealed so that they are water tight; therefore, they do not have depth to groundwater limitations.

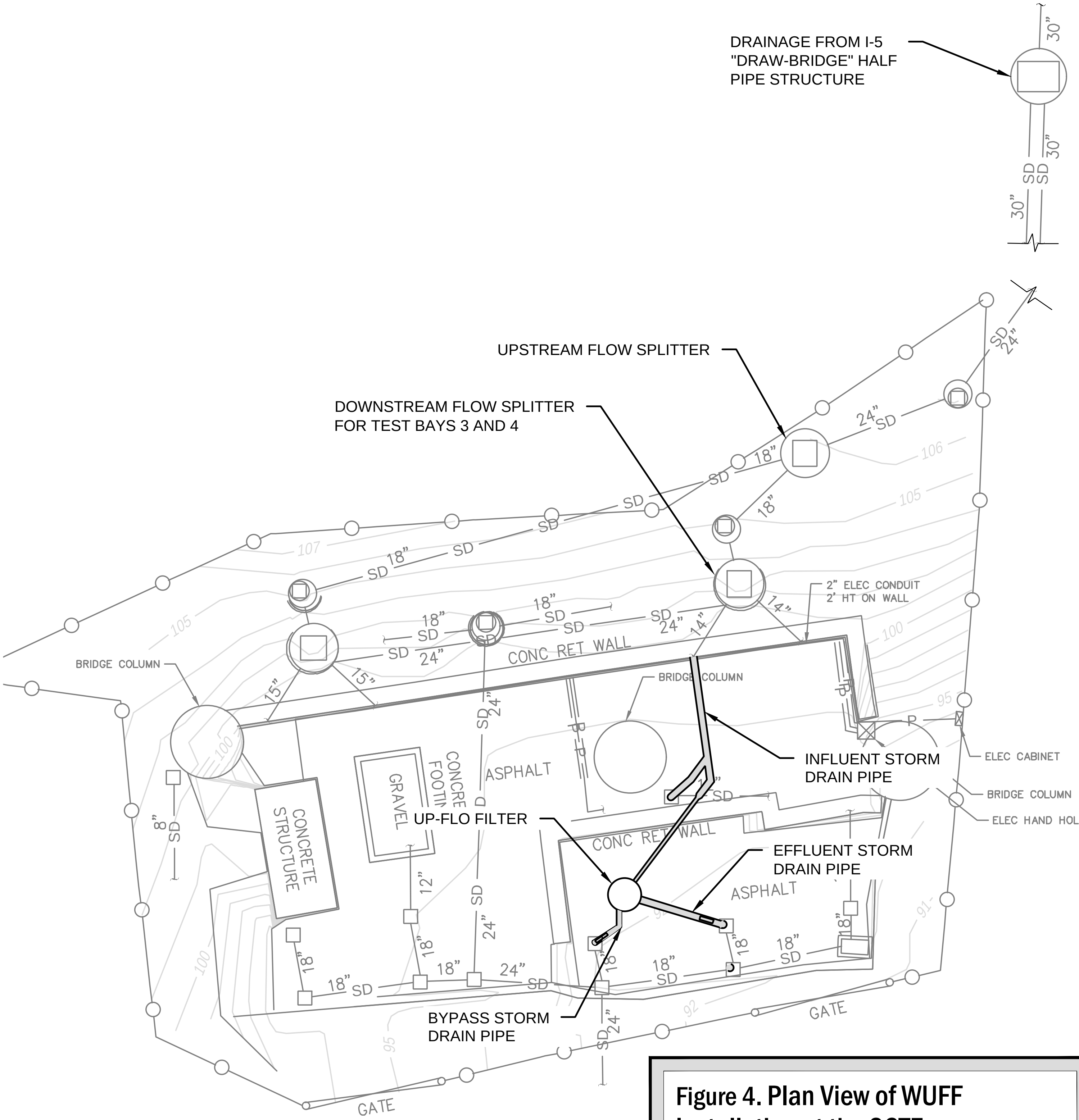
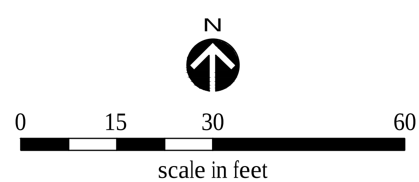


Figure 4. Plan View of WUFF Installation at the SCTF.



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Utility Requirements

The Up-Flo Filter is a passive system that requires no power and has a free-draining outlet.

Treatment Processes

The Up-Flo Filter removes pollutants from runoff through settling, screening, and filtration.

Settling

The internal components of the Up-Flo Filter act as baffles to force gross debris and sediment to settle into the sump.

Screening

The only flow path out for large floating debris is to pass under the bypass hood. The hood is designed to pass bypass water while preventing floatables from exiting.

Filtration

Filtration of stormwater occurs as the flow is forced through the filter Ribbons and then up and out of the outlet module.

Sizing Methodology

The Up-Flo Filter is available in a variety of standard models (Table 1), ranging from a one module system for retrofit in a 4-foot manhole and sized to treat approximately 0.36 acres to a 15-foot-long by 13-foot-wide vault that can treat approximately 23.3 acres. Each filter module in the Up-Flo Filter holds three ribbon filters. The Ribbons are 45 inches in length and have a filter surface area of 6.25 ft^2. This equates to 18.75 ft^2 of media per module. The design flow rate per module is 15 gpm and the hydraulic loading rate is 0.8 gpm/ft^2. For preliminary sizing purposes, sizing tables were developed that provide maximum contributing areas for each of the standard sizes of Up-Flo Filter for both western (Table 1) and eastern Washington (Table 2). The following sections describe the modeling used to generate the tables for western and eastern Washington, respectively.

Table 2. Up-Flo Filter Configurations, Design Flow Rates, and Typical Contributing Impervious Areas for Eastern Washington.				
Configuration	**Model**	**Maximum Number of Filter Modules**	**Flow Rate[a] (gallons/minute)**	**Contributing Area[b] (acres)**
Manhole	**UFF-MH-400R**	**6**	**90**	**0.372**
Vault	UFF-ZV-19-400R	19	285	1.23
Vault	UFF-ZV-38-400R	38	570	2.46
Vault	UFF-ZV-57-400R	57	855	3.7

[a] Assuming 0.75 gallons per minute per square foot of filter.

[b] Basin area modelled using HydroCAD 10.00-16, SCS Method, Region 3 – Spokane, 6-month 3-hour event depth of 0.337 inch, curve number = 98.

Bold indicates the size of the test system used in this study.

Sizing table intended for planning level use. The design engineer must use HydroCAD, StormSHED, or approved equivalent and the site location mapping to calculate the appropriate facility size for each installation in eastern Washington.

Western Washington

Up-Flo Filter systems designed for use in western Washington are sized using MGS Flood, the Western Washington Hydrology Model (WWHM), or another continuous hydrologic model approved by Ecology, to treat a minimum 91 percent of the annual stormwater volume (Ecology 2012). The remaining 9 percent of the annual stormwater volume bypasses the treatment system through either external bypass along the curb line or the internal weir wall. The design calculations for each size system are determined with a hydraulic loading rate of 0.8 gpm/ft^2.

For preliminary flow-based sizing purposes, a sizing table was developed that provides maximum contributing areas for each of the standard sizes of the Up-Flo Filter (Table 1). The basin sizes were generated using MGS Flood version 4.40 with a 100 percent impervious basin, off-line treatment, Seattle 38-inch map, and default Hydrological Simulation Program – FORTRAN (HSPF) values. This sizing table is to be used for planning level use only. The design engineer must use a continuous model with the site-specific drainage area and precipitation to confirm that the unit will treat the required volume. As part of the design process, Hydro-International's engineering department reviews the water quality requirements and confirms the system is sized correctly and according to the approved loading rate and project treatment flow.

Eastern Washington

Up-Flo Filter systems designed for use in Eastern Washington are sized to treat the 6-month, 3-hour storm using HydroCAD, StormSHED, or another approved single-event model (Ecology 2004). For preliminary sizing purposes, a sizing table was developed that provides maximum contributing areas for each of the standard sizes of the Up-Flo Filter system in Region 3 – Spokane (Table 2). This sizing table is to be used for planning level use only. The design engineer must use an approved single event model with the site-specific drainage area and precipitation to confirm that the unit will treat the required volume.

Expected Treatment Capabilities

Based on 2016 laboratory testing, the Up-Flo Filter is capable of removing 84.2 percent of influent total suspended solids with an average influent concentration of 206 mg/L (sil-co-sil synthetic silica sediment). The results are reported by NJCAT as part of the systems NJCAT verification (Hydro-International 2016). Table 3 presents a summary of the water quality results from the testing.

Table 3. Summary Results from NJCAT Lab Testing.

Run Number	Influent TSS mg/L	Adjusted Effluent TSS mg/L	Volume of Test Water L	Drawdown TSS mg/L	Volume of Drawdown L	Removal Efficiency Percent
1	220	42	1,676	46	4	81.0%
2	192	44	1,663	45	4	77.1%
4	198	41	1,696	44	4	79.5%
5	219	45	1,693	46	4	79.2%
7	206	39	1,677	40	4	80.6%
8	212	38	1,683	39	4	82.3%
9	204	31	1,663	35	4	85.0%
10	197	35	1,664	37	4	82.3%
11	195	32	1,676	33	5	83.8%
12	192	33	1,650	34	5	83.0%
13	214	31	1,673	32	5	86.0%
14	210	31	1,675	32	6	85.0%
15	203	24	1,686	25	6	88.0%
16	200	26	1,677	29	6	87.0%
17	209	28	1,681	30	8	87.0%
18	212	32	1,673	36	10	85.0%
19	209	31	1,685	32	17	85.0%
20	199	25	1,677	26	22	87.0%
21	206	29	1,672	29	35	86.0%
22	216	24	1,677	30	43	89.0%
23	210	22	1,680	30	56	90.0%
Mean	206	33	1,676	35	12	84.2%

mg/L = milligrams per liter

Estimated Design Life

The non-consumable structural components of the Up-Flo Filter system are designed to last 25 years or more before needing maintenance or replacement of internal components. The manufacturer recommends that, on average, the system be maintained every 6 to 12 months. If the system is inadvertently undersized for the basin or sediment loading is very high, it is expected that more frequent maintenance will be required. Due to the high variation of loading conditions from site to site, it is recommended that first-year inspections be performed to assess the loading condition of the site on the Up-Flo Filter. Based upon this first year of observation, a site-specific maintenance frequency can be established.

Installation

The Up-Flo Filter is designed for ease of installation. The internal components are pre-assembled prior to delivery to the installation site. The system is delivered on a flatbed truck. The installer or contractor will need to provide a crane capable of off-loading the unit and placing it into the ground. Prior to delivery, the appropriate excavation should be completed, and the bottom 6 inches backfilled and leveled using the appropriate and recommended material compacted to 95 percent of maximum density.

Prior to installation, all inlets are blocked and covered to prevent contamination by construction sediment from the site. Backfilling should be performed in a careful manner, bringing the appropriate fill material up in 6-inch lifts on all sides. Precast sections shall be set in a manner that will result in a watertight joint. In all instances, installation of the Up-Flo Filter shall conform to ASTM specification C891 *Standard Practice for Installation of Underground Precast Utility Structures*, unless directed otherwise in contract documents.

Operation and Maintenance Requirements

Maintenance activities can be categorized by those that can be performed from outside the Up-Flo vessel and those that are performed inside the vessel. Maintenance performed from outside the vessel includes removal of floatables and oils that have accumulated on the water surface and removal of sediment from the sump via Vactor truck. Maintenance performed inside the vessel includes removal and washdown or replacement of the filtration Ribbons. Occupational Safety and Health Administration (OSHA) confined space entry procedures need to be followed when entering the Up-Flo vessel.

Inspection

The frequency of inspection and maintenance can be determined in the field after installation. Based on the rainfall characteristics (when and how much), site characteristics such as contributing area, types of surfaces (e.g., paved and/or landscaped), site activities (e.g., short-term or long-term parking), and site maintenance (e.g., sanding and sweeping), inspections should follow every significant rainfall event or what is practical; and maintenance should be dependent on the inspection findings.

It is possible to determine if the filter Ribbons are occluded during the inspection by removing the manhole cover and observing the water level in the manhole or vault. If the water elevation is at the bypass weir elevation and not decreasing over 24 hours, then the Ribbons are occluded and should be replaced. If the water elevation is below the bypass weir and decreases to the top of the media in less than 24 hours then the Ribbons do not need to be replaced or cleaned. Otherwise, scheduled inspections will determine when one or more of the following maintenance thresholds have been reached:

- Sediment depth at sump storage capacity; a minimum 6 inches should separate the bottom of the filtration Ribbons and top of the sediment captured in the sump. A simple probe, such as the Sludge-Judge, can be used to determine the depth of the solids in the sump.

- Clogged filter Ribbons; the water elevation in the vault is above the bypass weir and is not decreasing 24 hours after a storm event.

- Slime and debris covering the filter Ribbons.

- Oil forming a measurable thickness on the surface of the water; the amount of accumulated oils should be minimized.

- Floatables completely covering the surface of the water; like oils, the amount of accumulated floatables should be minimized to prevent trash and loose debris from bypassing during the larger and less frequent storm events.

After completion of the first year of operation, the inspection and maintenance intervals for cleaning the sump and replacing Ribbons will be established to keep the solids loading within the respective limits of these treatment components. Keeping to the established maintenance intervals will minimize the annual bypass volume.

Reliability

The Up-Flo Filter system is a robust water quality system designed to withstand a variety of conditions in the field. Hydro International warranties that the materials used to manufacture its products will be able to withstand and remain durable to environmental conditions for a period of 5 years from the date of purchase. The ribbons consist of a robust woven polymer membrane which will not degrade under saturated conditions. If left unmaintained, the ribbons would become coated with sediment until water could no longer pass through the membrane at which point all flow would enter the sump, bypass the ribbons, and exit through the internal bypass. Consequently, there should be no concern over the ribbons degrading and impacting water quality if the system is left unmaintained.

Other Benefits and Challenges

The filter ribbon treatment component of the Up-Flo Filter is washable and replaceable. In this way, maintenance costs and the environmental footprint of maintaining the system are reduced.

SAMPLING PROCEDURES

This section describes the sampling procedures that were used to evaluate the performance of the Up-Flo Filter. It begins with a general overview of the monitoring design and describes the specific goals Ecology has established for the types of treatment that are being sought under the GULD. Separate sections then describe in more detail the site location, test system, monitoring schedule, and the 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 discussed.

MONITORING DESIGN

To facilitate performance monitoring pursuant to the TAPE, six Up-Flo Filter Modules that contain three filter Ribbons per module were installed for testing purposes at the SCTF located at the corner of Pasadena Place Northeast and Northeast 40th Street (Figure 1). This system is identified herein as the Hydro International Up-Flo Filter test system (WUFF test system).

Automated equipment was installed in conjunction with the WUFF test system to facilitate continuous monitoring of influent, effluent, and bypass flow volumes over a 12-month period extending from April 12, 2017, through March 22, 2018. In association with this hydrologic monitoring, automated samplers were also employed to collect flow-weighted composite samples of the influent and effluent to the WUFF test system during discrete storm events for subsequent water quality analyses.

Using the data obtained from the WUFF test system monitoring, removal efficiencies and effluent concentrations were characterized for targeted monitoring parameters. These data were subsequently compared to goals identified in the TAPE to support the issuance of a GULD for the Up-Flo Filter. These treatment goals are described below for the two types of treatment that are under consideration for inclusion in the GULD:

1. **Total Suspended Solids (Basic) Treatment:** 80 percent removal of total suspended solids 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 concentrations less than 100 mg/L, the facilities are intended to achieve an effluent goal of 20 mg/L total suspended solids.

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

Site Location

The WUFF test system 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 “drawbridge” half-pipe structure and a series of flow splitters. First, flow from the drawbridge 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 4). 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 gate valve located at the inflow to each test bay. To fine tune the flow into the test bay even further, a bypass valve was installed immediately upstream of the influent pipe to the filter unit that can divert water around the structure without changing the flow rate into the neighboring test bay.

Ecology approved the use of this site for field testing under the TAPE guidelines and entered into an agreement with WSDOT on October 23, 2015, to allow testing at the facility. Hydro International subsequently entered into a property use agreement with Ecology (Appendix B) for the duration of the monitoring.

Because influent flow rates can be fine-tuned with the upstream valves and flow splitters, the peak influent flow rate was set to range between 50 and 100 percent of the design flow rate; for a six-module unit this equates to between 45 and 90 gpm (design flow rate = 90 gpm). Storms had a natural hydrograph form except when the valve became clogged with gross solids, which resulted in decreased flows independent of rainfall in the basin. The ramifications of this are discussed in more detail in the *System Hydraulic Performance* section.

Monitoring Schedule

Hydrologic and water quality monitoring was conducted at the WUFF test system over a 12-month period from April 12, 2017, through March 22, 2018. During this monitoring period, 24 separate storm events were successfully sampled.

TEST SYSTEM DESCRIPTION

The WUFF test system consists of a 4-foot-diameter vault with six Filter Modules that contain three filter Ribbons per module (Figure 3). The water enters the system via a 6-inch-diameter PVC pipe (see Figure 5) and exits the system from a 12-inch pipe. A plan view schematic of the test system is shown in Figure 4 (also see Appendix A).

Although Up-Flo Filters are typically installed subgrade, the system at the SCTF was installed above grade for ease of installation. The above grade installation does not affect the hydraulics or treatment performance of the system. To access the top of the system, a platform and railing were installed with an attached ladder (Figure 5). A description of the monitoring equipment employed at the site is provided in *Monitoring Procedures* sections below.

TEST SYSTEM SIZING

Because the field testing was conducted at an Ecology approved facility for the TAPE where the flow rate entering the system can be controlled, there was no need to run a model to size the system for the basin. Instead six filter modules containing a total of 18 filter Ribbons were selected and the upstream valves and splitters were adjusted so that the system received flows between 50 and 100 percent of the design flow rate.

TEST SYSTEM MAINTENANCE SCHEDULE

Maintenance of the six filter modules consists of dewatering the system with a sump pump, vacuuming out the sediment with a shop vacuum, and replacing the filter Ribbons. The frequency of these maintenance activities is a function of solids loading from the drainage basin. When field testing commenced on April 12, 2017, it quickly became apparent that the stormwater entering the SCTF was rapidly clogging the filter Ribbons installed in the WUFF test system. At the same time three different systems, a pleated fabric filter and two different tree-box style media filters were having similar clogging issues in adjacent bays.

After analyzing the data, it was not apparent what specific factor was leading to the rapid clogging of three very different filtration technologies. The particle size distribution was highly variable with samples from some events characterized by suspended solids with a median particle diameter (D_{50}) of only 2 to 3 microns (see *Water Quality Results* section). It is our hypothesis that suspended solids with this clay sized distribution, combined with oils from the highway drainage are contributing to the rapid clogging.

Herrera formally brought this clogging issue to Ecology's attention on June 8, 2017. The TAPE indicates that the duration of field testing must span 1.5 maintenance cycles. Due to the rapid clogging, the WUFF test system was maintained four times from April 11, 2017, to March 6, 2018; hence, this requirement of the TAPE was met. However, we understand Ecology may request that additional flow testing be conducted at an alternate site with more typical pollutant loading to provide additional data for assessing maintenance requirements (see email correspondence on this topic in Appendix C). The specific details of this additional flow testing would be described by Ecology in the GULD, if issued.

Figure 5. Photo of the WUFF Test System at the SCTF.

Hydrologic Monitoring Procedures

Generalized schematics of the equipment that was installed in association with the WUFF test system are provided in Figures 6 and 7. Figure 8 provides photographs of the filter Ribbons used in the WUFF test system as well as images of other system components and monitoring equipment. The equipment installation was completed on January 27, 2016. Continuous hydrologic monitoring was performed in conjunction with the WUFF test system at four separate monitoring stations: WUFF-BP, WUFF-OUT, Wall-RG, and WUFF-IN (Figures 1, 6, and 7). WUFF-BP was a bypass flow monitoring station, WUFF-OUT was an effluent flow monitoring station located at the outlet, and the combined flows from WUFF-BP and WUFF-OUT were used to estimate the influent flows at WUFF-IN. Wall-RG was a precipitation monitoring station located 4,000 feet southwest of the SCTF in a residential backyard (the SCTF is located under a highway overpass so precipitation monitoring at the facility is not feasible). These hydrologic monitoring stations are discussed in separate subsections below, followed by a summary of the maintenance procedures performed on the monitoring equipment. These monitoring procedures are also described in greater detail within the quality assurance project plan (QAPP) that was prepared for this study (Herrera 2018).

Hydrologic monitoring instruments at each of the stations discussed below were all interfaced with a Campbell Scientific CR1000 datalogger, which served to record data, run simple algorithms based on those data, and control the automated sampling equipment. The datalogger was programmed to scan every 10 seconds and record average readings on a 5-minute time step. The datalogger was interfaced with an Airlink Raven XTV digital cellular modem. This communication system was configured to automatically download data on a 5-minute basis and send text message alarms to field technicians and project managers. Power to the system was supplied using on-site 120 volt AC power.

The datalogger, digital cell phone link, and automated samplers were housed in a Knaack box model 3068 enclosure. Conduit was installed to convey pressure transducer cabling and autosampler suction lines from the base of the enclosure to each station.

Bypass Flow Monitoring (WUFF-BP)

Bypass flows were monitored at the terminus of a 12-inch PVC pipe that routed flows from the internal bypass points to a downstream storm drain inlet. The photo in Figure 5 and the Figure 6 and 7 schematics shows this pipe configuration.

A 12-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 ID polyethylene tubing. The other end of the tubing was connected to a stilling well that was constructed from 3-inch-diameter PVC pipe. An INW PS-9805 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 Campbell Scientific CR1000 datalogger described above. When bypass occurred, the datalogger converted bypass weir water level readings to estimates of discharge based on standard hydraulic equations (Walkowiak 2006).

Effluent Flow Monitoring Station (WUFF-OUT)

To facilitate continuous monitoring of effluent flow rates, a monitoring station, designated WUFF-OUT, was established at the end of the 12-inch outlet pipe (Figures 6, 7, and 8). All other components used to measure the bypass flows as described above (WUFF-BP) were used to measure the effluent flows.

Influent Flow Monitoring Station (WUFF-IN)

Inflow to the WUFF test system was estimated by adding the flow rate at WUFF-BP with the flow rate at WUFF-OUT. Due to the low residence time within the WUFF test system, this approach was deemed accurate enough for inlet autosampler pacing. This approach to estimating inflow has been used in previous field testing studies that were conducted pursuant to the TAPE and has been deemed acceptable by Ecology for these types of systems.

Precipitation Monitoring Station (Wall-RG)

In addition to the flow monitoring stations, a third hydrologic station, designated Wall-RG, was installed approximately 4,000 feet southwest of the equipment enclosure in a residential yard (Figure 1) to facilitate continuous monitoring of precipitation depths. Precipitation monitoring cannot be conducted at the SCTF because it is located beneath a highway overpass. 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 an Airlink Raven XTV digital cell phone link to allow communication with the WUFF-OUT and WUFF-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.

Monitoring Equipment Maintenance and Calibration

Maintenance and calibration of the rain gauge and flow monitoring equipment was conducted 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 D. In addition, on March 3, 2016 and April 10, 2017, a dynamic flow test at WUFF-BP and WUFF-OUT was conducted using known flow rates from a nearby fire hydrant. The hydrant flows were used to calibrate the Thel-Mar weir equations at these stations. Results from the dynamic flow testing are presented in Appendix D. The adjusted rating curves from the second flow test were deemed more accurate and were applied to the entire dataset prior to final analysis.

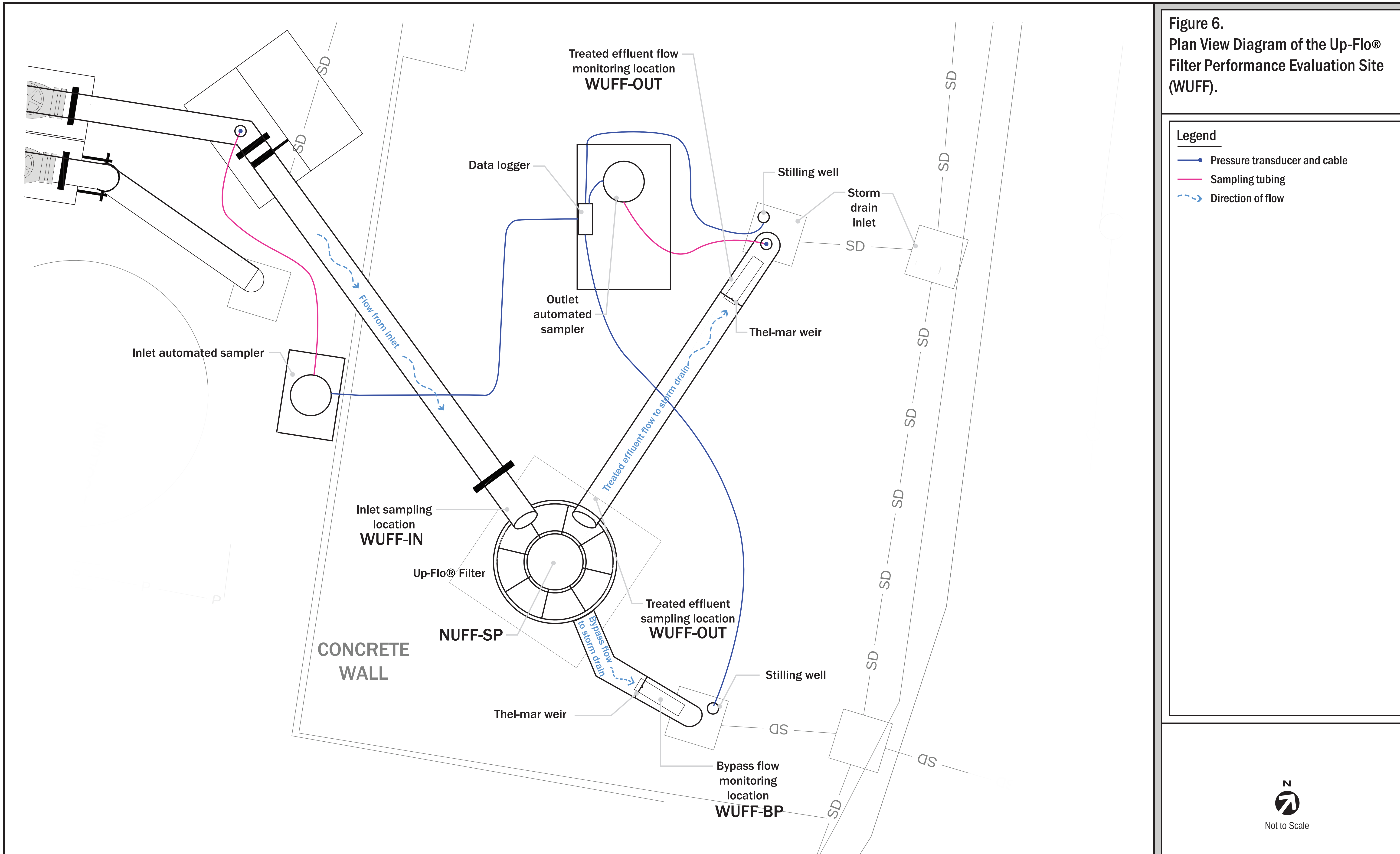
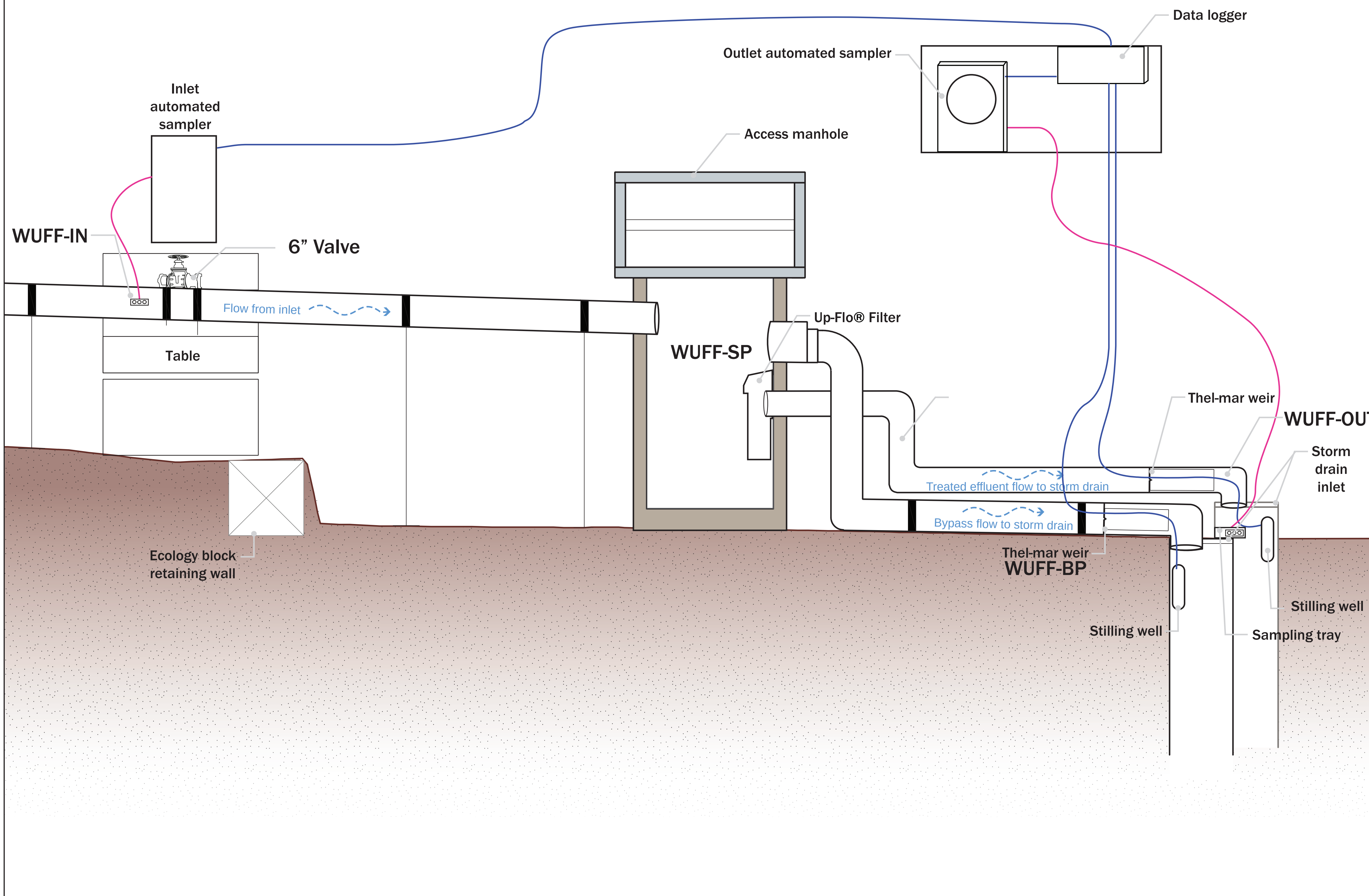


Figure 6. Plan View Diagram of the Up-Flo® Filter Performance Evaluation Site (WUFF).

G:\Graphics\13-05605-000\plan_view.ai (09/17/2015)

Figure 7.
Cross Section Diagram of the Up-Flo Filter Test System (WUFF).



Legend

- Pressure transducer and cable
- Sampling tubing
- Direction of flow

Not to Scale

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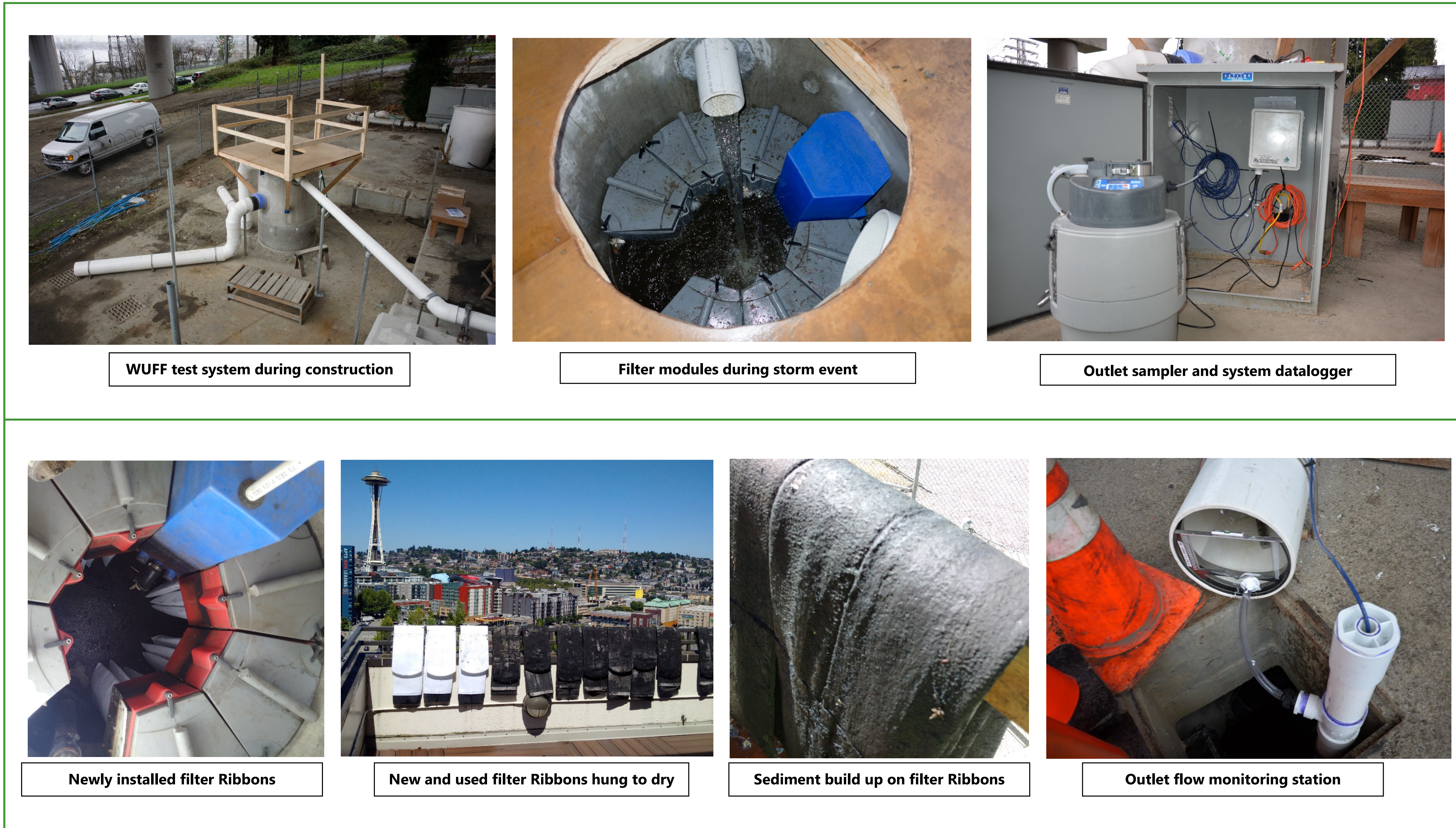

Figure 8. Photos of Monitoring at the Up-Flo Filter Test System (WUFF).

WATER QUALITY MONITORING PROCEDURES

To evaluate the water quality treatment performance of the WUFF test system, water quality sampling was conducted at the influent (WUFF-IN) and effluent (WUFF-OUT) stations (Figures 6 and 7) during 24 discrete storm events over the period from April 2017 through March 2018. A general description of the procedures used for this monitoring is provided herein. A more detailed description of these procedures can also be obtained from the QAPP that was prepared for this study (Herrera 2018). To facilitate water quality sampling for this study, ISCO 6712 portable automated samplers were installed in association with WUFF-IN and WUFF-OUT. The intake strainer for the automated sampler at WUFF-IN was positioned at the bottom of the inlet pipe above the 6-inch valve, which controlled flow to the WUFF test system (Figure 7); the intake strainer for the automated sampler at WUFF-OUT was in a sampling tray located below the invert of the outlet pipe (Figure 7). In each case, 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 for defining the acceptability of specific storm events for sampling:

- **Target storm depth:** A minimum of 0.15 inches of precipitation over a 24-hour period
- **Antecedent conditions:** A period of at least 6 hours preceding the event with less than 0.04 inches of precipitation
- **End of storm:** A continuous period of at least 6 hours after the event with less than 0.04 inches 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 and to start the sampling program. A clean 20-liter polyethylene carboy and crushed ice were also placed in the sampling equipment at this time. 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. During the storm event sampling, the datalogger was programmed to enable the sampling routine in response to a predefined increase in water level (stage) at WUFF-OUT. The automated samplers were then programmed to collect 220-milliliter sample aliquots at preset flow increments. Based on the expected size of the storm, the flow increment was adjusted prior to the event to ensure that the following criteria for acceptable composite samples were met at each station:

- A minimum of **10 aliquots**.
- Sampling was targeted to capture **at least 75 percent** of the hydrograph.
- Due to sample holding time considerations, the maximum duration of automated sample collection was **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 composites 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°C using ice during transport to the laboratory. All samples were delivered to the laboratory with appropriate chain-of-custody documentation. Collected flow-weighted composite samples were then analyzed for the following parameters:

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

In addition, total volatile suspended solids (TVSS), suspended sediment concentration (SSC), and total petroleum hydrocarbons (TPH) were measured (see Appendix F), but this report only addresses those parameters that are pertinent to the basic and phosphorus treatment GULD.

Sediment Monitoring Procedures

Sediment sampling for the Up-Flo Filter was used to assess the sediment accumulation and sediment composition within the system. Sediment depth monitoring occurred monthly and samples were collected annually (for a total of two samples).

Sediment depth was measured at three different locations within the sumps. The average of the three depths was used to calculate the volume of sediment captured in the sump. The sediment samples were collected from three separate areas of the sump and composited. Sediment was collected by extending a wide mouth bottle to the bottom of the sump. The sediment sample was analyzed for total solids, grain size, total volatile solids, total phosphorus, total copper, and total zinc.

Analytical Methods

Analytical methods for this project are summarized in Tables 4 and 5. Analytical Resources, Inc. in Tukwila, Washington performed the analyses for all parameters except total suspended solids and particle size distribution; these parameters were analyzed by ETS, Inc. in Petaluma, California. Analytical Resources, Inc. is certified by Ecology, and participates in audits and inter-laboratory studies by Ecology and the US Environmental Protection Agency. These 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 WUFF test system evaluation are discussed in the following sections. Quality assurance memorandums discussing hydrologic and water quality data can be found in Appendices D and E, respectively.

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

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 blanks were collected on February 4, 2016, at both monitoring locations. A second set of field blanks was collected on November 6, 2017, after nine storm events had been sampled. Finally, a third set was collected on December 4, 2018 after the completion of the study. 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.

Field Duplicate Samples

Field duplicates were collected for approximately 10 percent of the samples. The field duplicates were collected at the influent station to ensure that analyte concentrations were not near the detection limit. 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 these samples were used to assess variation in the analytical results that is attributable to environmental (natural) and analytical variability.

Flow Measurements

The accuracy and precision of the automated flow measurement equipment were tested prior to the first monitoring round and periodically throughout the project. Level calibration data can be found in the hydrologic data quality assurance memorandum in Appendix D. In addition a dynamic flow test was conducted on April 10, 2017, using known flow rates from a nearby hydrant. The results of these QA procedures are presented in Appendix D.

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. and ETS, Inc. were responsible for conducting internal quality control and quality assurance measures in accordance with their own quality assurance plans.

Water quality results were first reviewed at the laboratory 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 quality assurance procedures were followed. The review, verification, and validation by the laboratory were documented in a case narrative that accompanied the analytical results.

Data were also reviewed and validated by Herrera prior to data analysis. This review was performed to ensure that all data were consistent, correct, and complete, and that all required quality control information was provided. Specific quality control elements for the data were also examined to determine if the method quality objectives (MQOs) for the project were met. Results from these data validation reviews were summarized in quality assurance worksheets prepared for each sample batch. Values associated with minor quality control problems were considered estimates and assigned *J* qualifiers. Values associated with major quality control problems were rejected and qualified with an *R*. Estimated values were used for evaluation purposes, but rejected values were not used. The results from this data quality assessment are presented in Appendix E.

Data Management Procedures

Flow and precipitation data were uploaded after each storm event remotely using telemetry systems (i.e., Raven cell link modem) and transferred to a database (LoggerNet and Aquarius software) for all subsequent data management tasks.

Table 4. 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		12 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
pH	Field meter (potentiometric)	NA		NA	NA		NA	0.01	0.01	std. units
Copper, dissolved	ICP-MS	EPA 200.8		12 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		12 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	

[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] 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 flow-weighted sampling. A more practical proxy goal of 12 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.

°C = degrees Celsius

HDPE = high-density polyethylene

ICP-MS = inductively coupled plasma/mass spectrometry

mg/L = milligrams per liter

NA = not applicable

Table 5. Sediment Quality Analysis Methods and Detection Limits.									
Parameter	**Analytical Method**	**Method Number[a]**	**Field Sample Container[b]**	**Total Holding Time[c]**	**Field Preservation**	**Laboratory Preservation**	**Actual Reporting Limit/Resolution**	**Target Reporting Limit/Resolution**	**Units**
Percent total solids	Gravimetric	SM 2540 B	8 oz glass jar	14 days; 6 months if frozen	Maintain ≤ 6°C	Maintain ≤ 6°C	NA	NA	%
Grain size	Sieve and Pipette	PSEP 1986	16 oz plastic jar	6 months			NA	NA	%
Total volatile solids	Combustion/Gravimetric	SM 2540 E	8 oz glass jar	6 months			0.1	0.1	%
Total phosphorus	Manual ascorbic acid	EPA 365.3		28 days			0.01	NA	mg/kg
Total copper	ICP-MS	EPA 6020		6 months; 2 years if frozen			0.1	0.1	mg/kg
Total zinc							5.0	5.0	

[a] SM method numbers are from APHA et al. (1998); EPA method numbers are from USEPA (1983, 1984); PSEP method number is from PSEP (1986); and ASTM method number is from ASTM (2007).

[b] Sample bottles that share the same numeric notation will be used for multiple parameters.

[c] Holding time specified in the referenced methods.

°C = degrees Celsius.

ICP-MS = inductively coupled plasma/mass spectrometry.

mg/kg = milligrams per kilogram.

NA = not applicable.

Analytical Resources, Inc. and ETS, Inc. reported the analytical results within 30 days of receipt of the samples. The laboratories provided sample and quality control data in standardized reports suitable for evaluating project data. These reports included all quality control 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 was subsequently entered into a Microsoft Access 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, all of the sample values in the database were crosschecked to confirm they were consistent with the laboratory reports.

Data Analysis Procedures

Analysis procedures that were 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 this 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 test system. The specific procedures that were used in these analyses are as follows:

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

Each of these procedures is described in more detail in the following subsections.

Statistical Comparisons of Influent and Effluent Concentrations

Pollutant concentrations in paired influent and effluent samples were compared 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 controlled for in the statistical analyses. A 1-tailed test was used to evaluate the specific hypothesis that effluent pollutant concentrations in effluent samples were significantly lower than those in influent samples. 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} = Flow-weighted influent pollutant concentration

C_{eff} = Flow-weighted effluent pollutant concentration

After the percent removal for each qualifying event was calculated, the mean percent removal 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 estimating confidence intervals around a measure of central tendency. The generality of bootstrapped confidence intervals means they are well suited for non-normally distributed data or datasets that are too small for more powerful tests of normality.

To perform the bootstrapping analysis, the percent removal values for each valid event were sampled randomly with replacement until a new synthetic percent removal dataset of equivalent size was generated. The median percent removal was then calculated on the synthetic dataset and the process was repeated. Repetition generates a distribution of possible values for the mean. Quantiles of this distribution are confidence intervals of the statistic. For example, in the analysis the mean was replicated 10,001 times; after sorting the replications, the 250th and 9,750th elements constituted the 95 percent confidence interval of the median, while the reported mean was the 5,000th ranked value.

The results from this test were used to determine if the mean percent removal was significantly different from percent removal goals identified in the TAPE (e.g., 80 percent total suspended solids removal).

Calculation of Pollutant Removal Efficiency as a Function of Flow

Analyses were performed to determine if pollutant removal performance varies as a function of influent flow rate. The first step in these analyses involved calculations to determine the average influent flow rate across individual sample aliquots that were composited to provide an estimate of the influent event mean pollutant concentration. Specifically, the instantaneous influent flow rates associated with the sample aliquots from the composites were averaged to generate an average sampled flow rate over the event; this process was repeated for each event. The average sampled flow rate for each event was then plotted against the measured pollutant percent removal to facilitate the detection of potential relationships between these variables (e.g., pollutant percent removal decreases as the average sampled flow rate increases). A regression analysis was performed on these data to determine if any observed relationships were statistically significant. In all cases, the statistical significance was evaluated at an alpha level (α) of 0.05.

DATA SUMMARIES AND ANALYSIS

This section summarizes data collected during the April 2017 through March 2018 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 D, while Appendix E presents results from the validation review that was performed on the water quality 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 some context for interpreting the hydrologic performance of the WUFF test 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 (April 1, 2017, through March 31, 2018) were anomalous. The NWS rain gauge is located at Sand Point, approximately 4.25 miles northeast of the WUFF rain gauge. The analysis specifically involved a comparison of rainfall totals measured at the Sand Point rain gauge over the monitoring period to averaged totals for the same gauge from the past 29 years. These data are summarized in Table 6 along with data from the rain gauge associated with the SCTF (Wall-RG) and data from the back up rain gauge (City of Seattle RG-03).

Results from this analysis showed the average April through March rainfall total at the Sand Point rain gauge from 1981 through 2010 was 35.96 inches. In comparison, the rainfall total at the same rain gauge over the monitoring period was 40.10 inches. This indicates that this was an above average wet period when compared with long term averages. Because flow was not continuously monitored across all rain events during the monitoring period (i.e., the valves were not always open to let water into the WUFF test system), this factor did not affect the representativeness of the results.

Table 6 also indicates that precipitation measured at the City of Seattle RG-03 gauge (located 3,700 feet southeast of the SCTF) was similar to rainfall measurements at Wall-RG during the monitoring period. The difference between these gauges was only 1.27 inches. The discrepancy between the Sand Point and Wall-RG was much less (0.05 inches). 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.

Table 6. Monthly Precipitation Totals at the WUFF Test Site Compared to Historical Totals at Sand Point.				
Month	Monthly Averages from Monitoring Period: April 1, 2017, through March 31, 2018			Monthly Averages from Historical Data: 1981–2010
	Wall-RG Rain Gauge from April (inches)	RG-03 Rain Gauge[a] (inches)	Sand Point NWS Station[b] (inches)	Sand Point NWS Station[b] (inches)
April 2017	4.12	3.99	4.12	2.84
May 2017	2.76	2.57	2.25	2.10
June 2017	1.08	1.06	1.63	1.68
July 2017	0.01	0.03	0.00	0.97
August 2017	0.19	0.15	0.02	0.97
September 2017	1.06	1.17	0.59	1.71
October 2017	3.35	3.28	4.80	3.32
November 2017	8.66	8.36	8.62	4.92
December 2017	4.65	4.47	5.38	5.45
January 2018	8.67	8.27	8.12	4.49
February 2018	3.33	3.13	2.04	3.67
March 2018	2.17	2.30	2.53	3.84
Total	40.05	38.78	40.10	35.96

[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.

System Hydraulic Performance

The water budget for the WUFF test system was analyzed to determine influent volume, effluent volume, and bypass frequency and volume. Using this water budget, additional analyses were performed to meet the following objectives:

- Determine whether treatment goals for the test system were met based on the volume treated and bypassed
- Determine site specific maintenance frequency by examining bypass over the course of the study

The data used in these analyses are presented in their entirety in Appendix F.

Performance in Relation to Design Treatment Goal

The water quality treatment goal for the WUFF test system was to capture and treat 91 percent of the average annual runoff volume. Due to the rapid filter clogging discussed in the *Test*

System Maintenance Schedule section, the 6-inch valve upstream of the test system was closed for some large event which were not targeted for sampling. This was done to limit the amount of maintenance events required to complete the monitoring. Table 7 presents the hydraulic results for the WUFF test system for the events that were sampled (n = 24) for water quality over the period from April 12, 2017, to March 22, 2018. Appendix F presents the results for all the sampled and unsampled events (n = 118) for this same period for events when the 6-inch valve was open and the system was online.

Table 7 indicates that flows equivalent to 2.0 percent of a water year were treated before the system required its first maintenance. The system required maintenance an additional three times before the end of the study with a maximum of 12.7 percent of a water year passing through the system before maintenance was required (Table 7). Maintenance entail dewatering the sump with a pump, removing sediment from the sump (see *Sediment Monitoring Results* section), and replacing the ribbons with either new or previously washed ribbons. By the end of the study on March 22, 2018, flows equivalent to 25 percent of a water year had passed through the system during, this value is below the goal of 91 percent treatment.

As described in the *Maintenance Schedule* subsection above, stormwater used for testing at the SCTF is derived primarily from highway drainage. The Influent samples collected at the WUFF test system showed the particle size distribution of this stormwater was highly variable with samples from some events characterized by suspended solids with a median particle diameter (D_{50}) of only 2 to 3 microns (see *Water Quality Results* section). It is our hypothesis that suspended solids with this clay sized distribution, combined with oils from the highway drainage are contributing to the excessive bypass. We also understand that Ecology may request supplemental flow testing be conducted at an alternate site with more typical pollutant loading to provide additional data for assessing maintenance requirements. The specific details of this additional flow testing would be described by Ecology in the GULD, if issued. Once these data are collected, the maintenance requirements in the GULD for the Up-Flo Filter could be updated based on the associated findings.

Hydrograph Form and Sample Distribution

Due to progressive clogging of the 6-inch valve conveying stormwater to the WUFF test system, the hydrograph form was not always correlated with the hyetograph form (see the individual storm report—Appendix H—for the June 15, 2017, event as an example). This resulted in a sample distribution across the hydrograph, which is more skewed toward the beginning of the storm when the valve was not clogged. Because both the inlet and outlet samplers were pacing off flow data estimated downstream of the valve, they were equally affected by this bias. Consequently, the data were deemed usable for the purposes of this paired comparison of influent and effluent pollutant concentrations.

Water Quality Data

This section summarizes water quality data collected during the monitoring period at the WUFF test system, including a comparison of data compiled over this period with guidelines identified by Ecology (2011) for assessing data acceptability. Monitoring results for each parameter are summarized and discussed in separate sections. Field forms completed by staff during each sampling visit are presented in Appendix G. Individual Storm Reports showing sample collection times in relation to influent and effluent hydrographs are presented in Appendix H for all sampled storm events. In addition, laboratory reports for each sampled event are presented in Appendix I.

Comparison of Data to TAPE Criteria

The TAPE identify criteria for determining data acceptability based on the characteristics of sampled storm events and the collected samples. The data collected through this monitoring effort are evaluated relative to these criteria in the following subsections.

Storm Event Criteria

During the April 12, 2017, through March 22, 2018, monitoring period, 24 storm events were sampled to characterize the water quality treatment performance of the WUFF test system. Precipitation data from the sampled storm events in this period were compared to the following criteria from the TAPE for determining their acceptability:

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

Summary data related to these criteria are presented in Table 8 for each of the 24 sampled storm events. These data show the criterion for minimum precipitation depth (0.15 inch) was met during all storm events. The minimum, median, and maximum precipitation depths across all 24 sampled storm events were 0.19, 0.41, and 1.64 inches, respectively. The criterion for minimum antecedent dry period (6 hours) was met for every event except the March 22, 2018, event, which had an antecedent dry period of 5.8 hours. Due to the fact that this is only 12 minutes below the threshold, data from this storm was deemed valid and included in further analyses. Antecedent dry periods during the sampled storm events ranged from 5.8 to 276.9 hours, with a median value of 30.1 hours. The storm duration criterion (1 hour) was met for all 24 storm events. Storm durations ranged 3.0 to 37.5 hours, with a median value of 13.3 hours (Table 8).

Table 7. Hydraulic Performance of the Sampled Events at the WUFF Test System.											
Date	**Inlet Storm Volume (gallons)**	**Outlet Storm Volume (gallons)**	**Bypass Storm Volume (gallons)**	**Average Inlet Sampled Flow (gpm)**	**Average Outlet Sampled Flow (gpm)**	**Peak Inflow (gpm)**	**Peak Outflow (treated) (gpm)**	**Peak Bypass Flow (gpm)**	**Averaged Treated Flow During Bypass (gpm)**	**Cumulative Percent of a Water Year Monitored**	**Percent Water Year Treated Between Maintenance Events**
4/11/17 New Ribbons installed, system goes online											
4/12/2017	20,576	20,576	-	56.8	56.8	92.1	92.1	–		0.5	0.5
4/19/2017	21,991	6,386	15,605	56.4	14.0	68.8	55.7	60.7	7.1	2.0	2.0
5/9/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)											
5/11/2017	9,913	9,913	-	11.8	11.6	30.6	30.6	–		3.5	1.5
5/15/2017	28,994	26,899	2,095	22.5	20.6	30.3	30.3	8.8	19.5	5.1	3.1
6/8/2017	13,097	13,097	-	28.3	25.4	39.5	39.5	–		6.8	4.8
6/15/2017	4,831	4,831	-	4.7	4.7	9.3	9.3	–		7.7	5.7
7/25/17 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)											
10/18/2017[a]	11,762	11,752	9	86.6	86.6	89.1	89.1	0.7	89.1	9.0	1.3
10/24/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)											
11/2/2017	10,043	10,043	-	10.8	10.1	33.0	33.0	–		10.5	1.5
11/4/2017	8,851	8,851	-	6.3	6.3	7.7	7.7	–		10.9	1.9
11/8/2017	15,460	15,460	-	8.4	7.9	13.6	13.6	–		11.7	2.7
11/12/2017	5,255	5,255	-	24.4	21.4	35.4	35.4	–		13.3	4.3
11/13/2017	1,593	1,593	-	9.9	9.6	18.5	18.5	–		13.9	4.9
11/19/2017	3,764	3,764	-	27.1	25.4	39.2	39.2	–		14.4	5.4
12/28/2017[a]	6,451	6,451	-	91.4	91.6	94.2	94.2	–		16.3	7.3
1/4/2018	8,518	8,518	-	30.2	26.9	39.7	39.7	–		17.7	8.7
1/7/2018	12,024	12,024	-	8.2	8.0	9.3	9.3	–		19.1	10.1
1/8/2018	4,633	4,616	17	31.0	28.0	35.4	34.0	1.4	33	19.4	10.4
1/26/2018	15,710	15,547	163	34.2	32.3	44.2	38.9	5.4	38	19.7	10.7
2/3/2018	7,422	7,422	-	16.8	16.7	20.0	20.0	–		21.2	12.2
2/13/2018	5,061	5,061	-	26.5	26.4	31.2	31.2	–		21.6	12.6
2/28/2018	17,488	17,488	-	30.3	30.5	61.6	61.6	–		21.7	12.7
3/6/18 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)											
3/8/2018	9,441	9,441	-	21.6	21.4	35.3	35.3	–		23.6	1.9
3/13/2018	1,881	1,881	-	8.5	7.2	10.5	10.5	–		23.7	2.0
3/22/2018	16,627	16,627	-	37.3	33.6	53.2	53.2	–		25.1	3.4
Mean	10,891	10,145	2,982	28.1	25.4	38.5	37.7	15.4	37.3	NA	NA

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold.

gpm = gallons per minute

Table 8. Comparison of Precipitation Data from Sampled Storm Events at the WUFF Test System to Storm Event Guidelines in the TAPE.				
Storm Start Date and Time[a]	Storm Precipitation Depth (inches)	Storm Antecedent Dry Period (hours)	Storm Precipitation Duration (hours)	Average Storm Intensity (inches/hour)[b]
4/12/2017 20:00	0.26	9.0	6.3	0.04
4/19/2017 8:45	0.42	13.8	15.0	0.03
5/11/2017 3:30	0.25	121.5	15.5	0.02
5/15/2017 14:00	0.73	41.1	20.8	0.04
6/8/2017 1:05	0.32	171.0	9.5	0.03
6/15/2017 6:30	0.69	165.9	15.3	0.05
10/18/2017 9:55[b]	1.64	22.8	37.5	0.04
11/2/2017 11:40	0.67	276.9	26.6	0.03
11/4/2017 13:55	0.97	24.3	23.8	0.04
11/8/2017 16:00	0.48	75.3	28.4	0.02
11/12/2017 3:45	0.25	15.8	5.2	0.05
11/13/2017 15:05	0.26	12.4	3.0	0.09
11/19/2017 15:55	0.32	77.1	13.3	0.02
12/28/2017 19:45[b]	1.31	55.2	24.5	0.05
1/4/2018 22:20	0.24	149.8	7.2	0.03
1/7/2018 6:25	0.49	19.4	19.2	0.03
1/8/2018 22:20	0.20	23.7	5.6	0.04
1/26/2018 18:30	0.78	29.9	17.7	0.04
2/3/2018 10:55	0.35	30.3	11.3	0.03
2/13/2018 21:05	0.27	96.6	3.4	0.08
2/28/2018 12:05	0.65	13.0	12.4	0.05
3/8/2018 6:05	0.48	7.2	13.4	0.04
3/13/2018 14:55	0.19	117.9	5.0	0.04
3/22/2018 6:50	0.40	**5.8**	13.3	0.03
Criteria	≥0.15	≥6	≥1	≥0.03[c]
Minimum	0.19	5.8	3.0	0.02
Median	0.41	30.1	13.3	0.04
Maximum	1.64	276.9	37.5	0.09

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

[a] Flow-weighted composited sample collected during all events unless indicated otherwise.

[b] Discrete sample collected during this event above a peak flow rate threshold.

[c] Majority of events exceeded the 0.03 inches per hour rainfall intensity criteria.

The criterion for minimum average storm intensity (0.03 inches per hour) was met for 83 percent of the sampled storm events (Table 8). The TAPE require this threshold be met for at least half of the sampled storms; consequently, this criterion was also met.

Sample Collection Guidelines

As described in the methods section, automated samplers were programmed with the goal of meeting the following criteria for acceptable composite samples that are identified in the TAPE:

- A minimum of 10 aliquots were collected for each event.
- Sampling was 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 was 36 hours.

It should be noted that 2 of the 24 sampled events involved the collection discrete samples during peak flows; flow-weighted composite sample were collected during all other events. The TAPE indicates that samples must represent a wide range of treated flows including the system's design flow rate; to obtain representative samples at this threshold, discrete sampling at the peak flow was required.

The criterion for minimum number of sample aliquots (10) was met for all of the flow-weighted composite samples except for the November 13, 2017, event (see Table 9). The TAPE indicates that events with between 7 to 10 aliquots will be accepted if an explanation for the low aliquot count is provided. This event was forecast a much larger storm so the pacing for the composite sample was set at too high a volume.

The criterion for minimum portion of storm volume covered by sampling (75 percent) was met for all events except the two peak flow sample events and at the influent station for the April 19, 2017, event (see Table 9). The peak flow sample events were not intended to cover the entire hydrograph; hence, the criterion is not applicable. The April 19, 2017, event came in two pulses (Appendix H) and the storm was larger than forecast. The automated sampler at WUFF-IN filled after 70.1 percent of the hydrograph volume had been captured. Given all other sampling and storm criteria were met and that the coverage was only 4.9 percent shy of the goal, the data from this event were deemed valid for subsequent use in analyses.

The sampling duration did not exceed 36 hours for any of the 24 events.

Table 9. Comparison of Sampling Data from Storm Events at the WUFF Test System to Sample Event Guidelines in the TAPE.

Storm Start Date and Time[a]	Sample Aliquots (number)		Storm Coverage (percent)		Sampling Duration (hours)	
	WUFF-IN	WUFF-OUT	WUFF-IN	WUFF-OUT	WUFF-IN	WUFF-OUT
4/12/2017 20:00	100	100	89.1	89.1	6.9	6.9
4/19/2017 8:45	100	47	**70.1**	93.7	11.1	17.2
5/11/2017 3:30	56	71	93.1	91.3	19.0	18.7
5/15/2017 14:00	90	90	94.5	94.5	22.3	22.5
6/8/2017 1:05	33	42	82.8	92.8	7.9	11.4
6/15/2017 6:30	19	19	93.1	93.1	18.8	18.8
10/18/2017 9:55[b]	35	31	**14.4**	**14.3**	0.3	0.3
11/2/2017 11:40	35	60	88.3	87.5	23.6	23.5
11/4/2017 13:55	34	56	93.4	93.8	21.0	21.2
11/8/2017 16:00	69	100	95.8	95.8	32.2	32.2
11/12/2017 3:45	11	14	90.1	90.1	2.7	4.5
11/13/2017 15:05	**8**	**9**	75.9	85.5	2.3	2.6
11/19/2017 15:55	24	38	89.3	96.3	5.4	5.8
12/28/2017 19:45[b]	22	23	**14.0**	**14.0**	0.2	0.2
1/4/2018 22:20	72	100	86.2	92.6	6.1	6.5
1/7/2018 6:25	96	100	75.4	73.9	21.2	20.8
1/8/2018 22:20	43	51	82.0	97.1	2.0	3.1
1/26/2018 18:30	100	100	87.4	79.4	9.3	7.1
2/3/2018 10:55	49	49	97.8	97.8	7.7	7.7
2/13/2018 21:05	72	72	96.7	96.8	3.1	3.3
2/28/2018 12:05	100	100	75.3	75.8	8.8	8.8
3/8/2018 6:05	54	54	96.4	97.8	8.6	8.9
3/13/2018 14:55	11	15	84.8	91.8	4.3	4.8
3/22/2018 6:50	81	93	75.3	75.8	9.4	9.4
Criteria	≥10		≥75		≤36	
Minimum	8	9	14.0	14.0	0.2	0.2
Median	52	55	86.8	92.2	8.3	8.3
Maximum	100	100	97.8	97.8	32.2	32.2

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

NA = not applicable

[a] Flow-weighted composited sample collected during all events unless indicated otherwise.

[b] Discrete sample collected during this event above a peak flow rate threshold. These events are not required to meet sampling guidelines.

PERFORMANCE EVALUATION

This section evaluates water quality data relative to treatment goals identified in the TAPE. Over the monitoring period from April 12, 2017, to March 22, 2018, a total of 25 storm events were targeted for sampling; however, one of these events only involved the collection of a grab sample for analysis of total petroleum hydrocarbons. Data from this storm (November 21, 2018) are not included in the analyses presented in this section. Of the remaining 24 sampled events, 22 involved the collection of flow-weighted composite samples and 2 involved the collection of discrete samples during peak flows. The discrete samples were collected on October 18, 2017, and December 28, 2017, by opening the upstream valve conveying stormwater to the SCTF until the treated flow rate was equivalent to the design flow rate for the WUFF test system; at this point the automated samplers at WUFF-IN and WUFF-OUT were manually activated until an adequate volume of stormwater was collected for sample analysis at both station. This method was used to collect chemistry data at the design flow rate, which was not possible by collecting flow-weighted composite samples alone (due to the collection of sample aliquots for compositing across the rising, peak, and falling limbs of the hydrograph).

PARTICLE SIZE DISTRIBUTION

The TAPE states that Pacific Northwest stormwater typically contains mostly silt-sized particles; thus, PSD results should be provided to indicate whether the stormwater runoff analyzed is consistent with particle sizes typically found in urban runoff in this region.

In Figure 9, it is apparent that suspended solids in stormwater discharged to the SCTF are mostly comprised of silt sized particles; the mean D_{50} across all influent samples collect at WUFF-IN was 11 microns. However, the variability from event to event was high with the D_{50} for individual influent samples ranging from 2 to 106 microns. As discussed in the *Maintenance Schedule* subsection above, it is our hypothesis that periodic events with very fine PSD (6 of the 24 events had a D_{50} in the clay range) led to the premature clogging of the WUFF test system.

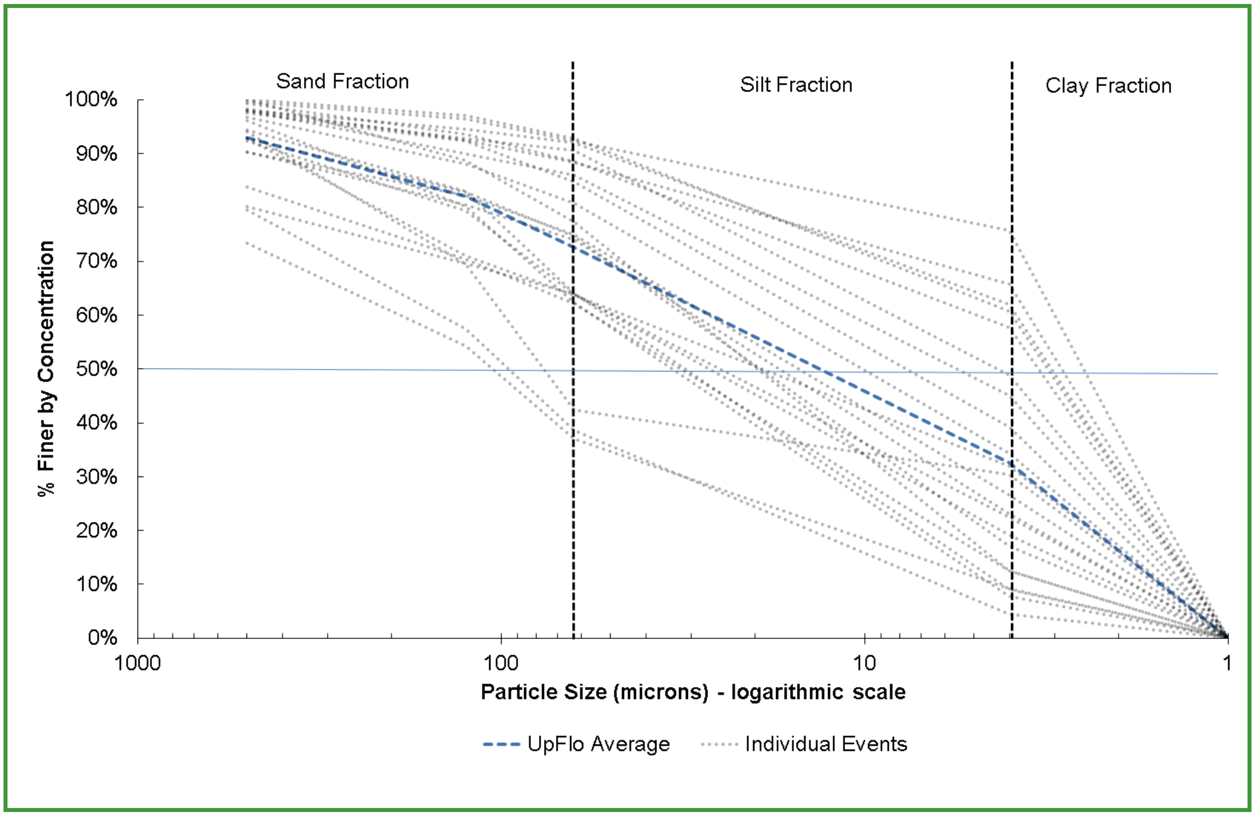

Figure 9. Influent PSD Results.

Basic Treatment

The basic treatment goal listed in the TAPE indicates the bootstrapped 95 percent lower confidence interval (LCL95) of the mean TSS removal must be greater than or equal to 80 percent for influent concentrations ranging from 100 to 200 mg/L. For influent TSS concentrations less than or equal to 100 mg/L but greater than 20 mg/L, the upper 95 percent confidence interval (UCL95) of the mean effluent concentration must be less than or equal to 20 mg/L. There is no specified criterion for influent TSS concentrations less than 20 mg/L; consequently, those sample pairs (influent and effluent) are generally not used for assessment of TSS removal performance. For influent concentration that exceed 200 mg/L, the treatment goal is an LCL95 of greater than an 80 percent reduction. Additionally, it must be shown there is a statistically significant difference between TSS concentrations in influent and effluent samples. Finally, pollutant removals that meet the basic treatment goals in the TAPE must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate. This section describes the sampling results in relation to these goals based on data collected from the WUFF test system.

A one-tailed Wilcoxon signed-rank test was performed on TSS concentrations from the paired influent and effluent samples. Three of the 24 paired samples had influent concentrations below 20 mg/L; hence, they were not included in this analysis. For the remaining 20 paired samples, the test indicated there was a significant decrease in effluent TSS concentrations ($p < 0.001$)

compared to influent concentrations. Consequently, this aspect of the basic treatment goal from the TAPE was met.

All of the influent samples collected from the WUFF test system had TSS concentrations below 100 mg/L (Table 10). Out of the 24 sampled events, influent samples from 4 events had concentrations below 20 mg/L; the associated sample pairs were excluded from this analysis per the TAPE. Using the paired samples from the remaining 20 events, the calculated UCL95 of the mean effluent concentration was 15.5 mg/L, meeting the basic treatment goal of <20 mg/L.

As described in the *Data Analysis Procedures* subsection above, analyses were performed to determine if pollutant removal performance varies as a function of influent flow rate. Discrete samples were collected on two events (October 18, and December 28, 2018) to obtain results that reflect TSS treatment efficiency near the design flow rate. Figure 10 displays effluent TSS concentrations versus the average samples flow rate for all 20 qualifying events. The results of the regression analysis performed on these data indicated there is no significant relationship between treatment efficiency and average sampled flow rate (p = 0.861). As is apparent from Figure 10, the WUFF test system exhibited effluent concentrations below the 20 mg/L threshold up to the design flow rate of 90 gpm.

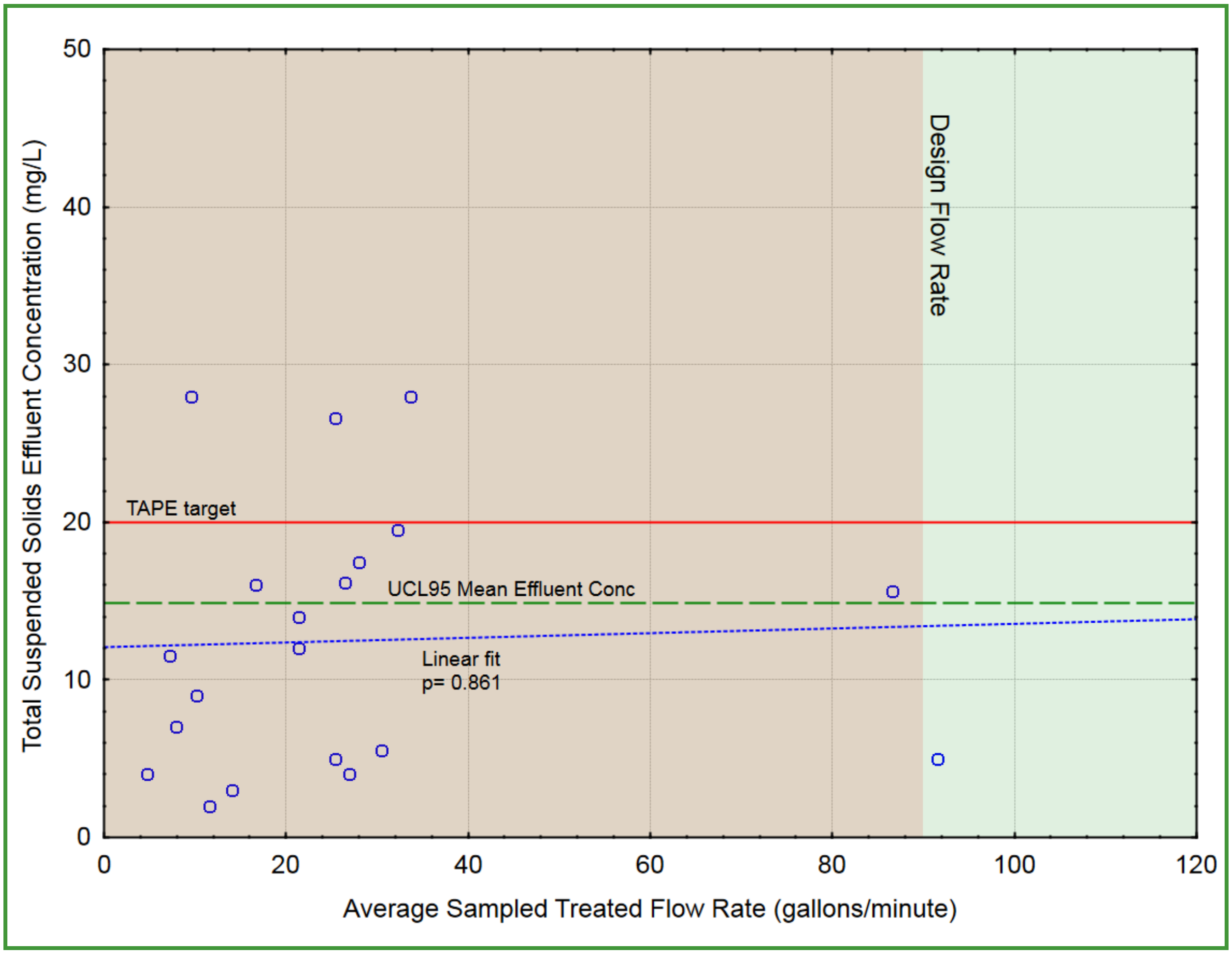

Figure 10. TSS Effluent Concentration as a Function of Average Sampled Treated Flow Rate.

Table 10. Water Quality Results and Comparison to TAPE Criteria.								
	Total Suspended Solids (mg/L)			**Total Phosphorus (mg/L)**				
Date	**IN**	**OUT**	**Percent Reduction**	**IN**	**OUT**	**Percent Reduction**	**Sampled Treated Flow (gpm)**	**Peak Treated Flow Rate (gpm)**
4/11/17 New Ribbons installed, system goes online								
4/12/2017	8	2	75%	0.046	0.042	9%	56.8	92.1
4/19/2017	**35**	**3**	**91%**	**0.154**	**0.022**	**86%**	14.0	55.7
5/9/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)								
5/11/2017	**27**	**2**	**93%**	**0.105**	**0.046**	**56%**	11.6	30.6
5/15/2017	6	2	67%	0.052	0.040	23%	20.6	30.3
6/8/2017	**98**	**5**	**95%**	**0.360**	**0.100**	**72%**	25.4	39.5
6/15/2017	**55**	**4**	**93%**	0.054	0.068	-26%	4.7	9.3
7/25/17 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)								
10/18/2017[a]	**87.3**	**15.6**	**82%**	**0.204**	**0.068**	**67%**	86.6	89.1
10/24/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)								
11/2/2017	**40**	**9**	**78%**	**0.188**	**0.064**	**66%**	10.1	33.0
11/4/2017	17	2	88%	0.044	0.028	36%	6.3	7.7
11/8/2017	**21**	**7**	**67%**	0.082	0.038	54%	7.9	13.6
11/12/2017	**28**	**14**	**50%**	0.070	0.042	40%	21.4	35.4
11/13/2017	**74**	**28**	**62%**	**0.148**	**0.096**	**35%**	9.6	18.5
11/19/2017	**44.6**	**26.6**	**40%**	0.082	0.090	-10%	25.4	39.2
12/28/2017[a]	**20**	**5**	**75%**	**0.142**	**0.070**	**51%**	91.6	94.2
1/4/2018	**30**	**4**	**87%**	**0.122**	**0.048**	**61%**	26.9	39.7
1/7/2018	13.5	8	41%	0.030	0.048	-60%	8.0	9.3
1/8/2018	**23**	**17.5**	**24%**	0.038	0.034	11%	28.0	34.0
1/26/2018	**24**	**19.5**	**19%**	0.032	0.048	-50%	32.3	38.9
2/3/2018	**27.5**	**16**	**42%**	0.084	0.046	45%	16.7	20.0
2/13/2018	**28**	**16.2**	**42%**	0.096	0.086	10%	26.4	31.2
2/28/2018	**46**	**5.5**	**88%**	**0.112**	**0.056**	**50%**	30.5	61.6

Table 10 (continued). Water Quality Results and Comparison to TAPE Criteria.								
Date	**Total Suspended Solids (mg/L)**			**Total Phosphorus (mg/L)**			**Sampled Treated Flow (gpm)**	**Peak Treated Flow Rate (gpm)**
	IN	**OUT**	**Percent Reduction**	**IN**	**OUT**	**Percent Reduction**		
3/6/18 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)								
3/8/2018	**60**	**12**	**80%**	**0.138**	**0.058**	**58%**	21.4	35.3
3/13/2018	**58**	**11.5**	**80%**	**0.140**	**0.064**	**54%**	7.2	10.5
3/22/2018	**74.5**	**28**	**62%**	**0.140**	**0.100**	**29%**	33.6	53.2
Mean [b]	39.4	11.0	68%	0.111	0.058	32%	26.0	38.4
n-value	20 qualifying events (**bolded**)			12 qualifying events (**bolded**)				
LCL95 of the mean percent reduction						50%		
UCL95 of the mean effluent concentration		15.5						

Note: design flow rate = 90 gpm

Bold values meet the influent sample criteria and are used in the LCL95 or UCL95 mean removal calculations.

[a] All sampled events were flow-weighted composite sampled except these events, which consisted of samples collected above a high flow rate threshold. These events are not required to meet sampling guidelines.

[b] The mean value represents the mean of all 24 measured values (i.e., the mean value before screening the data per the TAPE requirements). This is provided as a reference for the overall chemistry of the site.

Taken together, the above analyses indicate that the goals for basic treatment from the TAPE were met based on the data collected from the WUFF test system.

Phosphorus Treatment

The phosphorus treatment goal listed in the TAPE indicates that the LCL95 of the mean removal must be greater than or equal to 50 percent for influent TP concentrations ranging from 0.1 to 0.5 mg/L. In addition, it must be shown there is a statistically significant difference between TP concentrations in influent and effluent samples. Finally, pollutant removals that meet the phosphorus treatment goals in the TAPE must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate. This section describes the sampling results in relation to these goals based on data collected from the WUFF test system.

As indicated in Table 10, 12 of the 24 sample pairs had influent TP concentrations above 0.1 mg/L. The remainder of the sample pairs had influent TP concentrations below the 0.1 mg/L threshold and were not used in these analyses per the TAPE.

A one-tailed Wilcoxon signed-rank test performed on the data from the qualify samples pairs indicated there was a statistically significant ($p = 0.001$) decrease in effluent TP concentrations compared to influent concentrations. Consequently, this aspect of the Phosphorus Treatment criteria from the TAPE guidelines was met.

The LCL95 of the mean percent reduction for the 12 qualifying sample pairs was 50.0 percent (Table 10), which meets the goal of ≥50 percent; consequently, these samples also show the phosphorus treatment goal from the TAPE was met.

Analyses performed to evaluate how TP treatment efficiency may vary as a function of influent flow rate as described above in the results section for TSS. Figure 11 displays percent removal versus average sampled rate for all 12 qualifying sample pairs. As is apparent, there is no significant trend in TP performance ($p = 0.946$). The data indicate that the 50 percent removal goal was met across the range of measured flows up to the design flow rate of 90 gpm.

Taken together, the above analyses indicate that the phosphorus treatment goal from the TAPE were met based on the data collected from the WUFF test system.

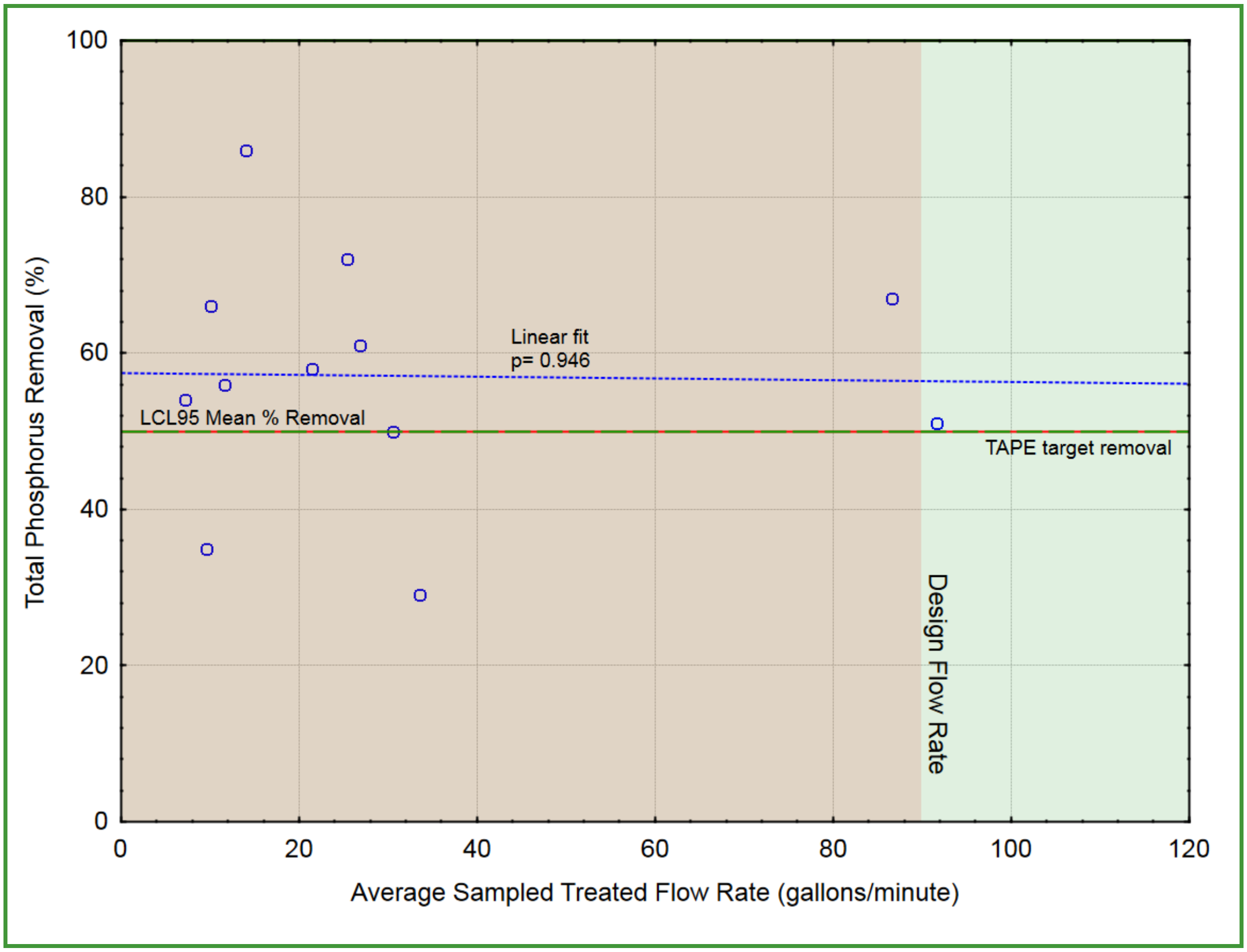

Figure 11. TP Removal (percent) as a Function of Average Sampled Treated Flow Rate.

OTHER PARAMETERS

The TAPE indicates that in addition to the parameters mentioned above, additional screening parameters should also be analyzed. To fully assess the basic and phosphorus treatment goals, the following parameters must be analyzed during at least three storm events:

- Hardness
- pH
- Total and dissolved copper
- Total and dissolved zinc

Orthophosphate is also a required screening parameter to assess the phosphorus treatment goal and must be analyzed during every event. The results for these parameters are presented in Table 11.

Table 11. Results of Other Required Parameters.														
	Hardness (mg as $CaCO_3$/L)		Orthophosphorus (mg/L)		pH (standard units)		Total Zinc (ug/L)		Dissolved Zinc (ug/L)		Total Copper (ug/L)		Dissolved Copper (ug/L)	
Date	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
4/11/17 New Ribbons installed, system goes online														
4/12/2017	38.8	43.8	0.011	0.009	–	–	51.3	43.1	31	28.6	21.8	18.5	14.6	14
4/19/2017	40.7	53.9	0.006	0.004	–	–	90.8	37.4	27.2	29.4	36.2	11.3	14.2	10.4
5/9/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)														
5/11/2017	110	90.1	0.011	0.019	7.48	7.87	95.7	46.2	37.9	36.4	29.8	20.4	15.2	17.6
5/15/2017	52.7	54.3	0.008	0.009	–	–	62.3	48	29	28.3	23.1	17.8	13.2	10.6
6/8/2017	66.3	61	0.01	0.024	–	–	329	66.7	50.3	50.5	79.7	34.9	25.3	26.9
6/15/2017	105	122	0.017	0.025	–	–	107	22.2	30.3	20.7	35.5	10.9	13	9.77
7/25/17 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)														
10/18/2017[a]	–	–	0.019	0.022	–	–	234	54.4	45.7	36.2	62.5	20.5	12.3	13.9
10/24/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)														
11/2/2017	72.1	69.3	0.022	0.021	–	–	112	53.2	36.5	36.2	26.8	18.9	12.2	14.1
11/4/2017	51.8	49.8	0.025	0.013	7.12	7.11	57.3	36.5	25.7	27.2	16.3	11.2	8.47	8.79
11/8/2017	78.5	96.4	0.01	0.007	–	–	88.6	51.8	40.6	34.8	26.9	17	12.3	11
11/12/2017	37	40.2	0.009	0.007	–	–	71.7	62.9	24.2	24.6	22	18.1	7.14	7.18
11/13/2017	34	50.6	0.014	0.018	–	–	41	36.5	158	86.5	12.8	12.6	49.1	34.2
11/19/2017	33.8	37.1	0.004	0.004	6.11	6.30	93.9	94.6	37.1	33	30.4	28.2	10.1	10.5
12/28/2017[a]	–	–	0.017	0.011	–	–	–	–	–	–	–	–	–	–
1/4/2018	49.5	59.9	0.012	0.012	–	–	96.1	51.4	36.3	39.2	30.5	16.4	11.7	12
1/7/2018	70.2	74.9	0.008	0.007	–	–	64.8	62.5	36.1	38.5	19.2	18.2	9.88	10.3
1/8/2018	39.2	51.5	0.005	0.007	–	–	66.2	60.7	28.2	30	21.4	18.3	8.28	8.48
1/26/2018	–	–	0.005	0.006	–	–	–	–	–	–	–	–	–	–
2/3/2018	40.1	39.2	0.01	0.013	–	–	99.9	63	31.3	31.1	33	22.7	10.7	10.6
2/13/2018	–	–	0.017	0.015	–	–	–	–	–	–	–	–	–	–
2/28/2018	–	–	0.016	0.022	–	–	138	65.7	–	–	41.1	20.3	–	–

Table 11 (continued). Results of Other Required Parameters.														
	Hardness (mg as $CaCO_3$/L)		Orthophosphorus (mg/L)		pH (standard units)		Total Zinc (ug/L)		Dissolved Zinc (ug/L)		Total Copper (ug/L)		Dissolved Copper (ug/L)	
Date	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
3/6/18 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)														
3/8/2018	–	–	0.012	0.014	–	–	142	77.4	–	–	45.9	26.6	–	–
3/13/2018	–	–	0.013	0.011	–	–	182	77.8	–	–	47.5	23.8	–	–
3/22/2018	–	–	0.012	0.011	–	–	151	106	–	–	51.4	36.3	–	–
Mean	57.5	62.1	0.012	0.013	6.90	7.09	113.1	58.0	41.5	36.0	34.0	20.1	14.6	13.5

Mean hardness concentrations measured in influent and effluent samples (n = 16) were 57.5 and 62.1 mg $CaCO_3$/L, respectively. Mean pH levels measured in influent and effluent samples (n = 3) were 6.90 and 7.09, respectively. TAPE guidelines indicate that the test system should not increase or decrease pH by more than one unit for any given event or discharge effluent with pH levels less than 4 or greater than 9. The pH data presented in Table 11 indicate that these conditions were met for each sampled event.

Orthophosphorus concentrations measured in influent and effluent samples (n = 24) were nearly identical, with a mean influent concentration of 0.012 mg/L and a mean effluent concentration of 0.013 mg/L.

For the 16 paired influent and effluent samples that were analyzed for metals, copper and zinc concentrations were generally reduced by the WUFF test system (Table 11). Mean total zinc concentrations measured in influent and effluent samples were 113.1 and 58.0 ug/L, respectively; mean dissolved zinc concentrations measured in these same samples were 41.5 and 36.0 ug/L. Mean total copper concentrations measured in influent and effluent samples were 34.0 and 20.1 ug/L, respectively; mean dissolved copper concentrations measured in these same samples were 14.6 and 13.5 ug/L.

Sediment Monitoring Results

As indicated in the Sampling Procedures section sediment depth and quality were assessed as part of this study. This section presents the results from the sediment depth analysis followed by results from the two samples collected for sediment quality.

Sediment depth never exceeded an average of 2.5 inches in the sump (Table 12). Sediment accumulation between maintenance events was evident, particularly between the October 24, 2017, maintenance event and the March 6, 2018, event. The mean sediment depth over the duration of the study was 1.3 inches.

Two sediment quality samples were collected, one on April 10, 2017, and a second on October 27, 2017. As mentioned in the *Introduction* section the Up-Flo Filter was online with a different configuration prior to the commencement of monitoring with the ribbon media on April 11, 2017. Consequently, the sediment sampled on April 10, 2017, was deposited in the sump when the different media configuration was in place.

The first sediment sample was mistakenly analyzed for total solids, volatile solids, and total petroleum hydrocarbons (which was not the list of parameters indicated in the QAPP), the second sediment sample was correctly analyzed for total solids, volatile solids, total phosphorus, grain size, copper and zinc. The results are reported in Table 13 along with Model Toxics Control Act (MTCA) disposal criteria limits for total petroleum hydrocarbons and the metals. As is apparent the limits were exceeded for total petroleum hydrocarbons, which indicates that the sediment may need to be disposed of in a landfill. This is typical of accumulated sediments in stormwater treatment devices.

Table 12. Sediment Depth Measurements in Sump.	
Date	**Sediment Depth (inches)**
4/10/2017	1.5
4/11/17 New Ribbons installed, system goes online	
5/8/2017	1
5/9/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)	
6/9/2017	1
7/24/2017	1.5
7/25/17 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)	
8/23/2017	1
9/20/2017	1
10/23/2017	1
10/24/17 Ribbons removed, cleaned, and replaced (sump hand vacuumed)	
11/16/2017	1
12/21/2017	1.5
1/17/2018	1.5
2/8/2018	2
3/5/2018	2.5
3/6/18 Ribbons removed and replaced with new Ribbons (sump hand vacuumed)	
Mean	1.3

Table 13. Summary of Sediment Sample Chemistry Results.				
Sample Date	**Units**	**4/10/2017**	**10/27/2017**	***MTCA - Method A (Unrestricted) Cleanup Level (mg/kg)***
Total Solids	%	23.7	40.7	–
Volatile Solids	%	41.1	30.2	–
Total Phosphorus	mg-P/kg dry	–	2010	–
Pebbles and greater	%	–	0.2	–
Very coarse sand	%	–	2.2	–
Coarse sand	%	–	3.8	–
Medium sand	%	–	3.9	–
Fine sand	%	–	5.7	–
Very fine sand	%	–	4.6	–
Coarse silt	%	–	18.5	–
Medium silt	%	–	33.5	–
Fine silt	%	–	15.1	–
Very fine silt	%	–	7.1	–
Clay	%	–	3.3	–
Colloidal	%	–	2.0	–
Total fines	%	–	79.6	–
Diesel Range Organics	mg/kg dry	4,750	–	*2,000*
Lube Oil Range Organics	mg/kg dry	19,900	–	*2,000*
Copper	mg/kg dry	–	456	*3,200*[a]
Zinc	mg/kg dry	–	1,700	*24,000*[a]

[a] MTCA Method B, non-cancer.

CONCLUSIONS

To obtain performance data to support the issuance of a GULD for the Up-Flo Filter, Herrera oversaw installation of the WUFF test system at the WSDOT SCTF in Seattle, Washington. Herrera then conducted hydrologic and water quality monitoring of this system from April 12, 2017, to March 22, 2018. Over this monitoring period, 24 separate storm events were sampled to characterize influent and effluent pollutant concentrations for this test system. At the end of this period, flows equivalent to 25 percent of a water year had passed through the system after four required maintenance events.

Out of the 24 sampled events, paired influent and effluent samples from 20 events met criteria specified in the TAPE for evaluating the basic treatment goal. The UCL95 of the mean effluent concentration from these samples was 15.5 mg/L; below the goal of ≤20 mg/L. In addition, concentrations below this threshold were observed at flow rates up to and including the design flow rate of 90 gpm for all six modules. Based on these results, we recommend the Up-Flo Filter be granted a basic treatment GULD for influent flow rates up to this design flow rate (equivalent to 0.08 gpm/ft^2 of filter surface area).

Paired samples from 12 of 24 sampled events met the criteria specified in the TAPE for evaluating the phosphorus treatment goal. The LCL95 of the mean percent removal was 50.0; above the goal of ≥50 percent removal. Treatment above this threshold was evident at flow rates up to and including the design flow rate of 90 gpm. Based on these results, we also recommend the Up-Flo Filter be granted a phosphorus treatment GULD for influent flow rates up to the design flow rate.

Although the WUFF test system demonstrated satisfactory performance relative to the goals in the TAPE for basic and phosphorus treatment, the system did not meet the maintenance interval goals. It is our hypothesis that suspended solids with a clay-sized distribution, combined with oils from the highway drainage, significantly influenced the hydraulic performance of the filter. However, we understand Ecology may request supplemental flow testing be conducted at an alternate site with more typical pollutant loading to provide additional data for assessing maintenance requirements. The specific details of this additional flow testing would be described by Ecology in the GULD if issued.

REFERENCES

APHA, AWWA, and WEF. 1992. Standard Methods for the Examination of Water and Wastewater. 18th edition. Edited by A. Greenberg, A.D. Eaton, and L. Clesceri. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC.

APHA, AWWA, and WEF. 1998. Standard Methods for the Examination of Water and Wastewater. 20th edition. Edited by A. Greenberg, A.D. Eaton, and L. Clesceri. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC.

Ecology. 2004. Stormwater Management Manual for Eastern Washington. Washington State Department of Ecology, Olympia, Washington.

Ecology. 2011. Technical Guidance for Evaluating Emerging Stormwater Treatment Technologies: Technology Assessment Protocol – Ecology (Tape). Publication No. 11-10-061, Washington State Department of Ecology, Olympia, Washington.

Ecology. 2012. 2012 Stormwater Management Manual for Western Washington: Volume III – Hydrologic Analysis and Flow Control Design/BMPs. Washington State Department of Ecology, Olympia, Washington.

Helsel, D.R. and R.M. Hirsch. 2002. Statistical Methods in Water Resources. Elsevier, Amsterdam.

Herrera. 2018. Quality Assurance Project Plan: Up-Flo® Filter – Stormwater Treatment System. Prepared for Hydro International, Inc., Portland, Maine by Herrera Environmental Consultants, Inc., Seattle, Washington.

Hydro-International, Inc. 2016. NJCAT Technology Verification: Up-Flo® Filter with Filter Ribbon Media. Hydro-International, Portland, Maine. <http://www.njcat.org/uploads/newDocs/UpFloFilterVerificationReportFinal.pdf>.

US EPA. 1983. Methods for Chemical Analysis of Water and Wastes. EPA 600/4-79-020, US Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Washington, DC.

US EPA. 1984. Guidelines Establishing Test Procedures for the Analysis of Pollutants under the Clean Water Act; Final Rule and Interim Final Rule. CFR Part 136. US Environmental Protection Agency, Washington, DC.

Walkowiak, D.K. (Editor), 2006. Isco Open Channel Flow Measurement Handbook. Teledyne Isco, Inc., Lincoln, Nebraska.