TECHNICAL EVALUATION REPORT

THE KRAKEN™ MEMBRANE FILTER

Prepared for

Bio Clean Environmental Services, Inc.

Prepared by

Herrera Environmental Consultants, Inc.

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Some pages in this document have been purposely skipped or blank pages inserted so that this document will copy correctly when duplexed.

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EXECUTIVE SUMMARY

The Bio Clean Environmental Services, Inc. (Bio Clean) Kraken™ Membrane Filtration System (the Kraken™ Filter) is an emerging stormwater treatment technology designed to provide a maximum amount of filtration surface area in a compact footprint. The system uses built-in pretreatment followed by high surface area membrane filtration to target particulate pollutants in stormwater.

The Kraken™ Filter

From October 2016 through April 2017, Herrera Environmental Consultants, Inc. (Herrera) conducted hydrologic and water quality monitoring of a Kraken™ Filter for Bio Clean 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 Kraken™ 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). A second Kraken™ Filter installed in Tacoma, Washington was monitored for hydraulic performance from January 2018 to May 2019. Data from both these studies are presented herein.

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

SAMPLING PROCEDURES

Ship Canal Test Facility

To evaluate the stormwater treatment performance of the Kraken™ Filter based on Ecology's TAPE, a test system was installed at the Ship Canal Test Facility (SCTF), in Seattle, Washington (Figure 1 in the *Introduction* section). This test system is identified herein as the WK Test System. Automated monitoring equipment was installed to continuously measure the WK Test System's effluent and bypass flow volumes. Automated equipment was also used to collect flow-weighted composite samples of the WK Test System's influent and effluent during 14 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 nitrate+nitrite, total Kjeldahl nitrogen, and suspended solid concentration. The results for these parameters are included in the appendices to this TER; however, the main text of this report only addresses the primary and screening water quality parameters listed above. The TSS and TP data from collected samples 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.

Tacoma Dome Site

The SCTF uses stormwater from Interstate 5 and consequently is characterized by high pollutant loading. To determine the maintenance frequency of the Kraken™ Filter in a setting more typical for manufactured stormwater treatment devices, a second Kraken™ Filter was installed in the parking lot immediately west of the Tacoma Dome in Tacoma, Washington in October of 2017.

The objective of the monitoring at this second location was to assess the required maintenance frequency or the Kraken™ Filter. Consequently, monitoring consisted of a simple grab sample routine to characterize influent suspended solids, effluent grab samples to verify removal, and periodic flow testing. Specifically, the following samples were collected:

- Nine influent samples for TSS, four of which were also analyzed for PSD
- Five effluent samples for TSS

Flow testing began in November 2018 and entailed discharging the design flow rate of 34 gallons per minute (gpm) into the filter with a water truck and then measuring the water level elevation relative to the internal bypass. If the system went into bypass at the design flow rate, this was considered an indication that the system was clogged and required maintenance. Results from this testing was used to verify the maintenance interval of a Kraken™ Filter under more typical applications, relative to the SCTF.

Hydraulic Performance

The hydraulic treatment goal for the test system was to capture and treat 91 percent of the average annual runoff volume. The WK Test System was unable to provide consistent treatment at the design flow rate over the course of the study, which resulted in more bypass volume. As a result, the system was only able to treat a volume equivalent to 8.3 percent of a typical water year for Seattle (as calculated by comparing treated flow rates versus theoretical annual treatment volume for a properly sized system) before it required maintenance. However, two other stormwater treatment technologies installed in adjacent bays at the SCTF were also unable to provide consistent treatment at their design flow rates and were only able to treat between 6.3 and 12.7 percent of a water year before clogging. 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 generates 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).

To address this issue, a hydraulic assessment of a second Kraken™ Filter installed in a Tacoma, Washington parking lot was conducted. Based on three quarterly flow tests conducted between November 6, 2018, and May 6, 2019, it was determined that the Kraken™ Filter treated a volume equivalent to between 36 and 56 percent of a water year before its maximum treatment flow rate fell below the design flow rate of 34 gpm (8.5 gpm per cartridge).

In addition to the above hydraulic performance testing, the Kraken™ Filter has also been approved through the New Jersey Corporation for Advanced Technology (NJCAT) protocol. Lab testing indicated that the system could retain 600 pounds of synthetic sediment before requiring maintenance. This loading is comparable to numerous TAPE approved devices which have gone through the same lab protocol.

Water Quality Performance

Basic Treatment

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

Only 4 of the 14 influent samples collected at the SCTF had TSS concentrations that exceeded 100 mg/L, thus an evaluation of the percent removal goal was not performed. Instead, an evaluation of the effluent concentration goal was performed based on 13 influent samples with TSS concentrations ranging from 31 to 162 mg/L (one sample pair was excluded due to influent concentration being below 20 mg/L); effluent concentrations from these samples ranged from 2 to 23 mg/L and the upper 95 percent confidence interval about the mean effluent concentration was 10.1 mg/L. This demonstrates the Kraken™ Filter met the goal for basic treatment. An analysis of treatment performance as a function of treated flow rate showed the system was able to meet this goal at flow rates up to 136 gpm (8.5 gpm per cartridge).

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 14 sampled events at the SCTF, samples from only 11 events had influent concentrations for total phosphorus within this range. Samples from the remaining three events had influent concentrations below 0.1 mg/L; however, the associated data were included in the final analysis to increase the n-value while providing a conservative estimate of treatment performance. The lower 95 percent confidence interval of the mean total phosphorus removal for these samples was 64.2 percent. Consequently, it can be concluded the Kraken™ Filter met the goal for phosphorus treatment. An analysis of treatment performance as a function of treated flow rate showed the system was able to meet this goal at flow rates up to 119 gpm (7.4 gpm per cartridge).

Tacoma Dome Performance

The mean influent TSS concentration from samples (n = 10) collected at the Tacoma Dome site was 57.4 mg/L while the mean effluent concentration was 6.1 mg/L (n = 6). Because the influent samples were generally collected when the parking lot was empty, it is likely that the data obtained from the Tacoma Dome site may underestimate the TSS load delivered to the Kraken™ Filter given the parking lot is in frequent use on the weekends when sampling crews were not typically present. Only two of the six paired influent samples had TSS concentrations that exceeded 20 mg/L, making them usable for TAPE assessment. Both of these samples met the TAPE TSS removal criteria.

Recommendations

Based on the performance results presented above, it is recommended that the Kraken™ Filter system be granted a GULD for basic treatment when sized based on a hydraulic loading rate of 8.5 gpm per cartridge. Furthermore, it is recommended that the system be granted a GULD for phosphorus treatment when sized based on a hydraulic loading rate of 7.4 gpm per cartridge. When sized using these loading rates, the data obtained from the Tacoma Dome site indicate that the system will last between 36 and 56 percent of a typical water year before requiring maintenance. However, a site-specific maintenance frequency is recommended for each new installation.

INTRODUCTION

The Washington State Department of Ecology (Ecology) has established specific use level designations for emerging stormwater treatment technologies in accordance with guidelines from the Technology Assessment Protocol-Ecology (TAPE) (Ecology 2011). 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 this 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 technology, permitting its more 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 Kraken™ Membrane Filtration System (the Kraken™ Filter), and was prepared by Herrera Environmental Consultants, Inc. (Herrera) to demonstrate that performance of the Kraken™ Filter 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 a Kraken™ Filter test system installed at the Washington State Department of Transportation (WSDOT) Ship Canal Test Facility (SCTF) in Seattle, Washington (Figure 5). This field testing was performed over a 7-month period, from October 2016 through April 2017. In addition, follow up testing was conducted at the Tacoma Dome, in Tacoma, Washington over a 16-month period from January 23, 2018, through May 25, 2019.

The SCTF is a dedicated facility for testing the pollutant removal effectiveness of emerging stormwater treatment devices. Up to four systems can be tested in parallel. Each system can receive runoff from a 31.6-acre basin, the majority of which is highway runoff from Interstate 5 (I-5). The flows are divided with a series of adjustable flow splitters and valves such that design storms can be directed to each device. The goal with the splitting was to divert approximately 3.5 acres of the basin to the filter.

Testing of a Kraken™ Filter at the SCTF began in October 2016 with the goal of obtaining at least 12 qualifying paired samples pursuant to requirements from the TAPE. After this testing was initiated, it quickly became apparent that the stormwater entering the system contained fine organic-rich suspended solids and oils which resulted in premature filter occlusion. This rapid occlusion was also observed in three other filters installed at the facility during the same period; hence, it is likely that the issue is related to the pollutant profile of highway runoff rather than the filter design.

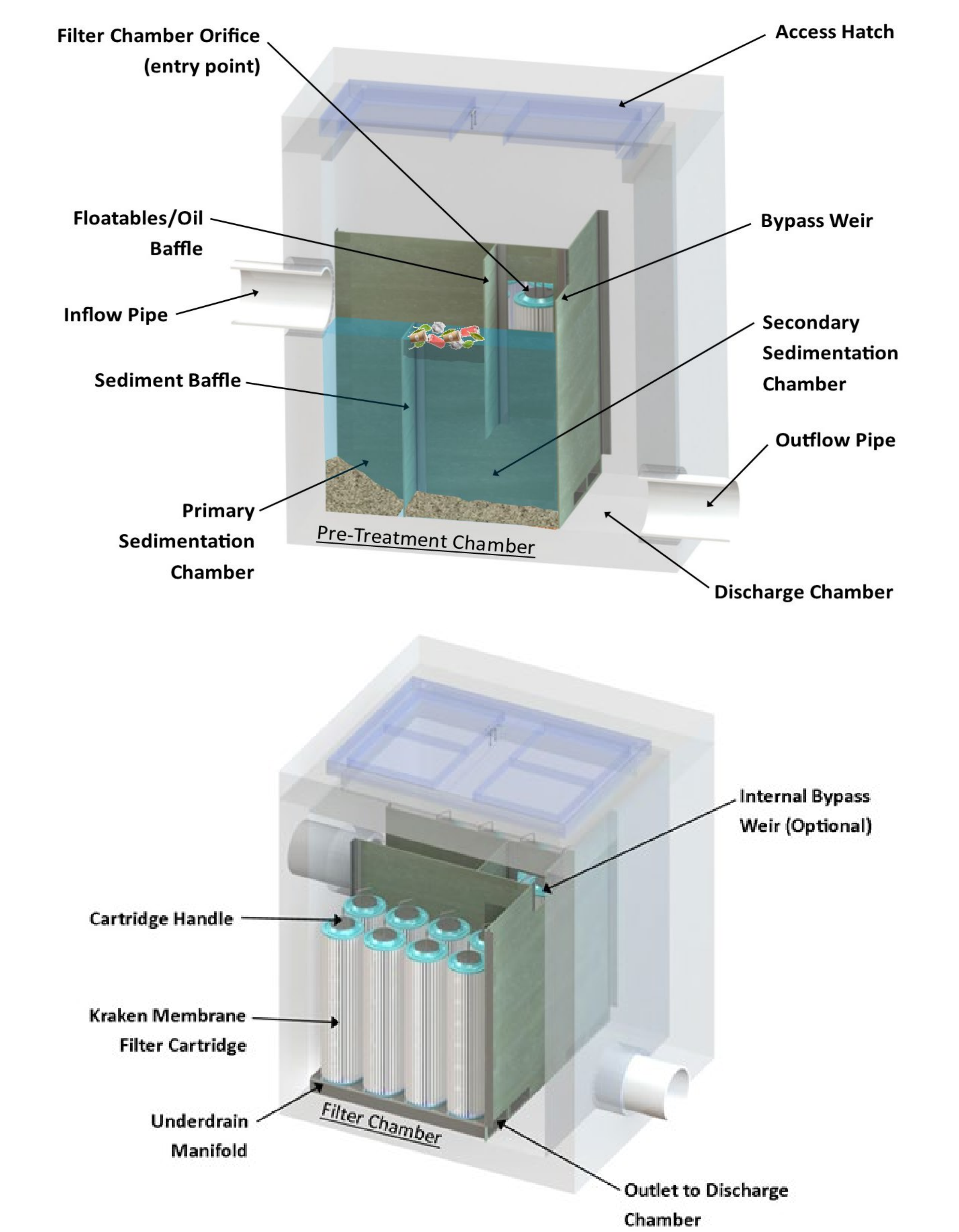


Figure 1. The Kraken™ Filter Design.

Due to this issue, Bio Clean submitted an interim dataset to Ecology to support the issuance of a CULD for the Kraken™ Filter; the CULD was subsequently granted in September 2017. As a condition for obtaining a GULD, the CULD required Bio Clean to conduct flow testing (not full TAPE testing) of the Kraken™ Filter at an additional site with runoff more representative of an urban setting. The data obtained from this additional site would be used to verify that the maintenance cycle of the system conforms with Bio Clean's expectations. A site in the Tacoma Dome west parking lot in Tacoma, Washington was identified for this purpose. The results from this monitoring are presented in the Results section of this TER and further documented in the Appendices.

The combined water quality dataset from the SCTF and the flow dataset from the Tacoma Dome site are presented and discussed herein to support the issuance of a GULD for the Kraken™ Filter.

TECHNOLOGY DESCRIPTION

The Kraken™ Filter provides water quality treatment of captured flows through several physical processes. This section describes the system's physical components, treatment processes, sizing methods, expected treatment capabilities, expected design life, and maintenance procedures. Note that the test system installed at the SCTF for the monitoring pursuant to the TAPE was designed with a separate bypass outlet for monitoring purposes, which is discussed in more detail below (also see detailed design drawings Appendix A).

The Kraken™ Filter is an engineered stormwater quality treatment device that utilizes a reusable membrane filter designed to remove total suspended solids (TSS), hydrocarbons, metals, and nutrients found in contaminated stormwater. Each filter contains a large surface area that is designed to deal with high TSS and particulate concentrations. The large surface area of each filter allows it to operate at a loading rate from one-fourth to one-twentieth the loading rate of other media filtration devices to improve longevity.

Figure 1 shows cutaway views of the system's pretreatment, filtration, and discharge chambers. The pretreatment chamber is partitioned into primary and secondary sedimentation chambers divided by a baffle wall. The secondary sedimentation chamber contains a floatables/oil baffle wall that extends upward. That wall directs water to pass underneath it, thereby trapping floatables and free floating hydrocarbons. After water passes under the floatables/oil baffle wall, it travels upward to the filter chamber weir and enters the filter chambers.

By filtering out the coarser material prior to reaching the membrane filters, the efficiency of the system is increased and maintenance requirements are reduced. The physical height of both sedimentation chambers is 2.5 feet for units with a 30.75-inch-tall cartridge. The floatables/oil skimmer wall in the middle that protrudes down to a level of 1.25 feet off the floor of the chamber and up several feet above the pretreatment chamber. Entering stormwater must pass over a baffle separating the primary and secondary sedimentation chambers, and then pass under the floatables/oil skimmer wall before being directed back up to the exit point.

Once stormwater exits the pretreatment chamber of the Kraken™ Filter, it passes through the filter chamber weirs and into the filtration chambers where the membrane filters are located. The membrane is made of a pleated paper material designed specifically for treatment of stormwater. There are no additives, algaecides, or other compounds in the membrane that could impart toxicity to the effluent stormwater.

Figures 2 and 3 illustrate the operation of the Kraken™ Filter once water enters the filtration chamber. The membrane filters sieve out finer micron sediments and associated contaminants.

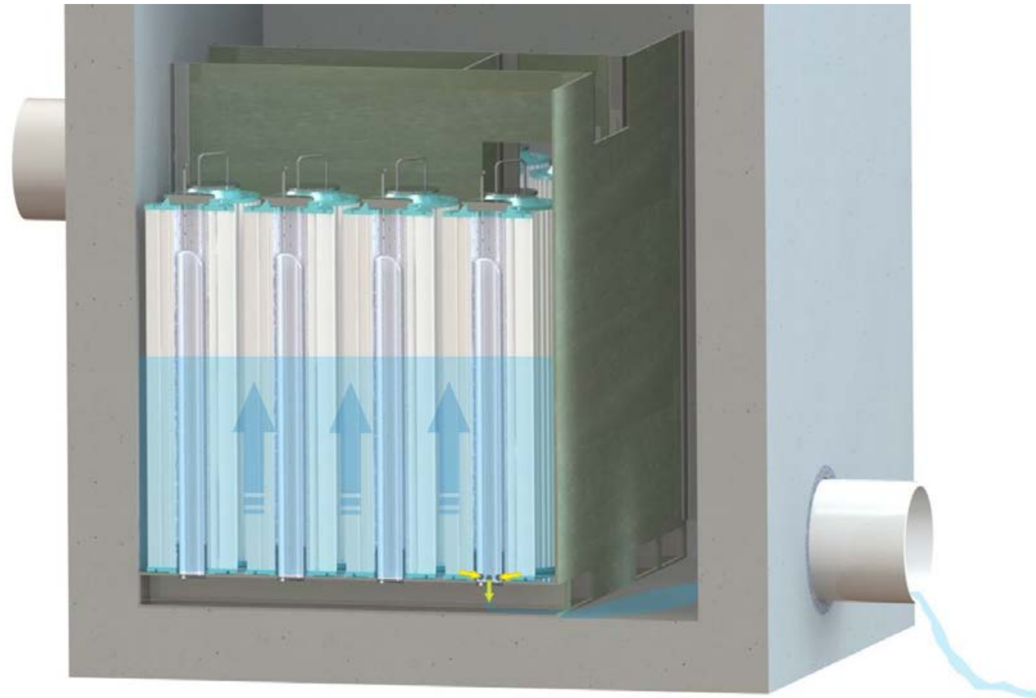


Figure 2. Fill-Up Period – Less Than Peak Treatment Capacity.

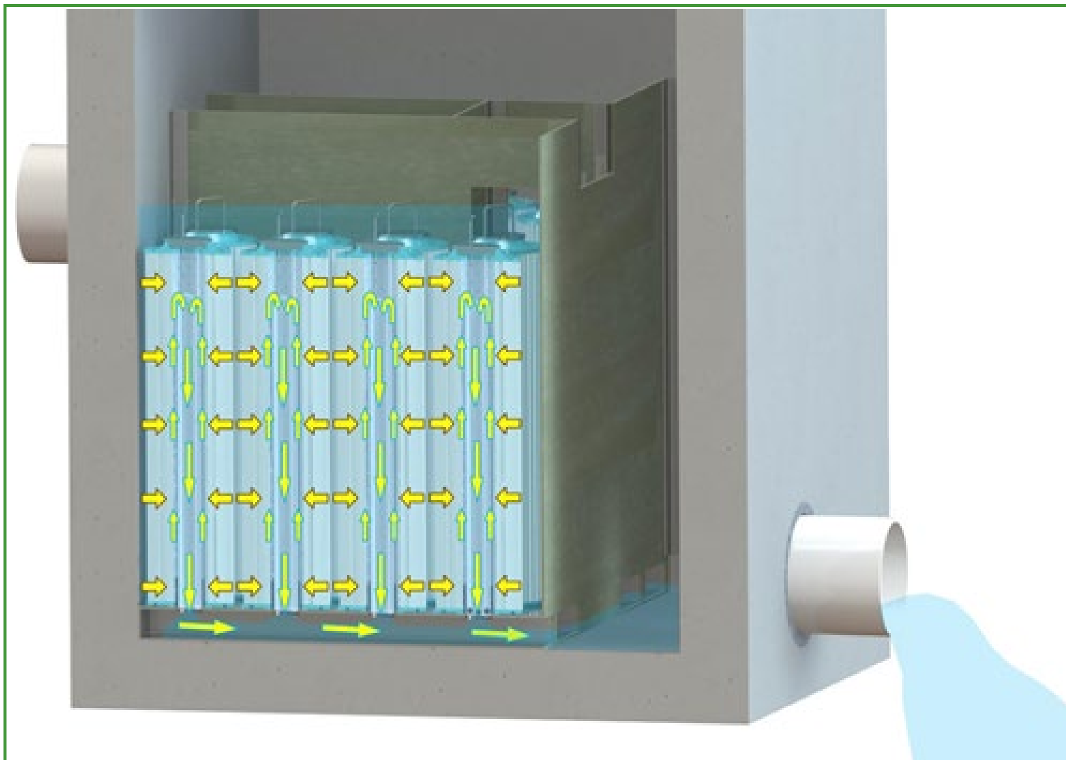


Figure 3. Max Operating Head – At Peak Treatment Capacity.

The Kraken™ Filter is a unique design in that the filter's hydraulic efficiency is controlled by an internal riser tube, so the filters begin to process and discharge only when the water level reaches the top of the filter column, which is close to the maximum hydraulic grade line in the filtration chamber. The riser tubes also control the flow rate to a level substantially less than the maximum flow capacity of the membrane filters, which creates a built-in safety factor and promotes longevity of the system's treatment capacity. It also helps guard against clogging by ensuring the sediment loading is evenly distributed along the full height of the cartridge. Once the water level nears the top of the cartridge, it starts passing through the membrane and collecting in the center effluent tubing of each cartridge. Treated water then passes down the center of the riser tube, collects in the horizontal underdrain manifold, and flows toward the discharge chamber. After water enters the discharge chamber, it exits the system via the outflow pipe.

An optional, internal bypass weir, located at the effluent end of the pretreatment chamber, is available (Figure 4). The Kraken™ Filter can be used in a traditional setup (that is, without the internal bypass feature) that uses an external flow splitter/diversion weir structure (not pictured). The optional, internal bypass weir allows runoff to pass directly from the pretreatment chamber to the discharge chamber without passing through the filtration chamber. Figure 4 illustrates the bypass flow path within the system. Water passes over the bypass weir once incoming flow exceeds the system's treatment capacity, thereby preventing scouring of fine sediment and other pollutants previously captured in the filtration chamber. Because the system has a three–chamber design (pretreatment, filtration, and discharge) and internal bypass occurs directly from pretreatment to discharge without passing through the filtration chambers, the filter cartridges operate in the same manner with or without the optional, internal bypass weir.

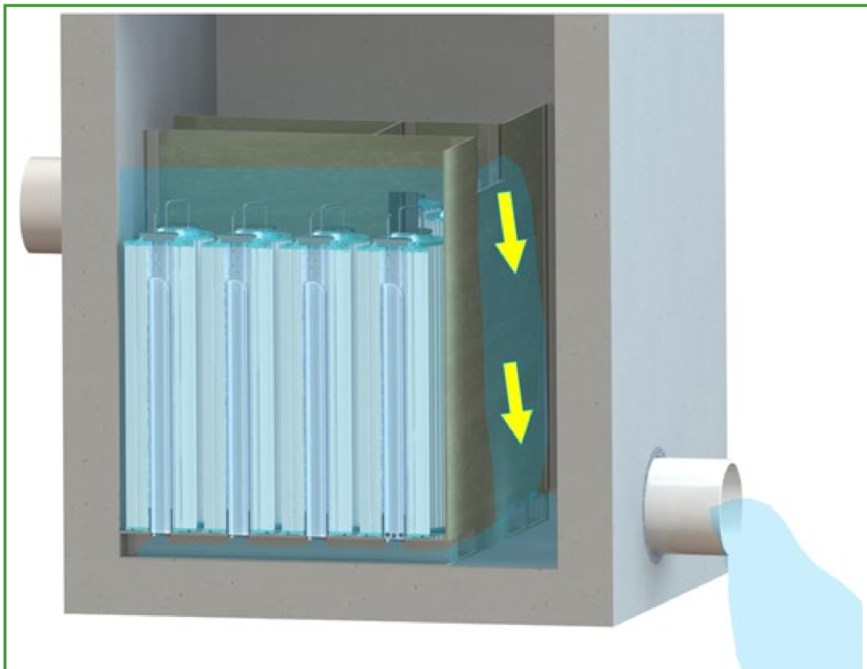


Figure 4. The Kraken™ Filter During Bypass Flow.

For the Kraken™ Filter installed at the SCTF for monitoring pursuant to the TAPE, an 8-inch pipe replaced the bypass weir to route bypass water directly from the filtration chamber through the downstream vault wall (Appendix A). This design change was included to prevent bypass water from mixing with treated water so the two flow rates could be measured independently (a TAPE requirement). Based on the designer's calculations, the head above the weir during bypass would be 1.25 inches at 125 percent of the design flow rate. At this same flow rate, head in the bypass pipe would be 1.62 inches. This 0.37-inch difference will create a minimal increase in treated flow rate at bypass with the piped bypass configuration. Though small, this higher-than-typical flow rate will result in a conservative estimate of treatment during bypass in the test system.

Physical Components

The Kraken™ 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 Kraken™ 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 2.5-foot by 4-foot cast structure to a 10-foot by 16-foot vault (Table 1) or larger. An external bypass is available, but the Kraken™ Filter can also be provided for use with an internal bypass structure. Total unit height varies base on site-specific conditions. Fall between the inlet and outlet pipes also varies; the required driving head is only a few inches due the internal cartridge riser tube.

Table 1. Specifications of Standard Kraken™ Filter Models.

Kraken™ Model No.	Inside Width (feet)	Inside Length (feet)	Sedimentation Area (sq ft)	Design Flow Rate (cfs)	Effective Media Surface Area (sq ft)	Drainage Basin (acres)[a]	Number of Cartridges
KF-2.5-4	**2.5**	**4**	**7.1**	**0.152**	**1,360**	**1.85**	**8**
KF-4-4	**4**	**4**	**11.7**	**0.303**	**2,720**	3.7	**16**
KF-4-6	4	6	17.8	0.455	4,080	5.55	24
KF-4-8	4	8	23.7	0.606	5,440	7.45	32
KF-8-8	8	8	42.5	0.909	8,160	11.15	48
KF-8-10	8	10	58.0	1.250	11,220	15.3	66
KF-8-12	8	12	68.4	1.477	13,260	18.1	78
KF-8-14	8	14	85.7	1.818	16,320	22.3	96
KF-8-16	8	16	100.5	2.159	19,380	26.5	114
KF-10-16	10	16	127.6	2.879	25,840	35.2	152

Bold values indicate the system models tested as part of this TAPE study

[a] Drainage basin determined using WWHM2012, assuming Seattle climate region, 100 percent impervious, 1 percent slope, 91 percent treatment, and modeled as flow split (offline).

Inlet and Pretreatment

Flow first enters the system into a baffled pretreatment chamber where floatables are skimmed and settleable solids deposited in a primary and secondary sedimentation chamber (Figure 1). The circuitous path encourages sedimentation while removing floatables prior to the water entering the treatment chambers. The pretreatment chamber can be easily accessed from above for maintenance purposes.

Filter Cartridges

The filter cartridges consist of a pleated membrane which is set into a hollow cylindrical cartridge. The membrane pleats enable a very large surface area within a small footprint. Water enters radially from the outside to the inside of the cartridge passing through the membrane filter. Water must then travel upward and over the invert of the internal riser tube (Figure 2) before it is allowed to exit through the manifold beneath the cartridges. The cartridge has a rubber gasket on the bottom and is friction fit over the internal riser tube. Drain down hole are drilled in the base of the internal riser tube on two of the cartridges to allow for water to completely drain from the system between events (Figure 2). Filter cartridges are available in various heights including low profile versions.

Bypass

The Kraken™ Filter has an internal bypass weir (optional for internal bypass configurations) positioned downstream of the pre-treatment chamber (Figure 1). The bypass weir invert elevation is 3 feet above the invert of the outlet pipe. This bypass weir was replaced with a bypass pipe for the duration of testing at the SCTF to prevent the mixing of treated and bypassed flows at the downstream sampling location.

Discharge Chamber

After filter water passes through the filter cartridges, it is collected in the manifold beneath the cartridges and discharged into the discharge chamber (Figure 3). When bypass is occurring, pretreated water spills over a bypass weir directly into the discharge chamber (Figure 4). Water then flows from the discharge chamber into the outflow pipe, exiting the system. During the testing described herein, the bypass was reconfigured to prevent the mixing of treated and bypass waters in the discharge chamber to provide a representative location for collecting treated effluent samples.

System Sizing

Table 1 provides design flow rates to achieve the basic and phosphorus treatment goal from the TAPE. These flow rates should be used in conjunction with the Western Washington Hydrology

Model, Version 2012 (WWHM2012) or another continuous hydrologic model approved by Ecology to determine the drainage area which would result in treatment of 91 percent of the annual runoff volume. For sizing in eastern Washington, HydroCAD, StormSHED, or another approved single-event model should be used to size for the 6-month design storm.

Maintenance Requirements

Appendix B provides Bio Clean's Operations and Maintenance Manual for the Kraken™ Filter. The Kraken™ Filter is designed for easy maintenance. Handles are provided on each filter cartridge to facilitate their installation and removal. The pressure fitting at the bottom of the filter has been designed so the cartridge can be quickly removed and reattached without any tools. Large access hatches allow for cleaning the pretreatment and filtration chambers without entry into the system. The filter cartridges can be removed, held over a standard trash can, and sprayed clean. Completing all maintenance activities for a typical manhole Kraken™ Filter takes less than 1 hour.

Annual maintenance includes using a Vactor truck for oil removal and removal of sediment from the floor of the filter. Filter cartridges must be washed at least once a year depending on solids loading from the drainage basin. Replacement times vary from a few to many years. The minimum required frequency for removing accumulated sediment from the unit is dependent on sediment depth. Maintenance is recommended when the sediment level reaches 1.5 feet in the primary separation chamber (100 percent capacity) and/or 3 inches in the treatment chamber(s). In addition, when the exterior of the filter cartridges appears coated with leaves and other gross solids, the filters may require maintenance. Finally, operators can visually inspect the treated outflow during rain events. If water is not flowing out of the underdrain manifold, then the filter is clogged and the cartridges should be replaced.

Estimated Design Life

The non-consumable structural components of the Kraken™ Filter are designed to last 50 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 may 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 Kraken™ Filter. Based upon this first year of observation, a site-specific maintenance frequency can be established.

Reliability

The Kraken™ Filter is a robust water quality system designed to withstand a variety of conditions in the field. Bio Clean 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 filtration membrane consists of a robust woven polymer which will not degrade under saturated conditions. If left unmaintained, the cartridges would become coated with sediment until water could no longer pass through at which point all flow would be pretreated and then bypass the filtration chamber and exit through the internal bypass. Consequently, there should be no concern over the cartridges degrading and impacting water quality if the system is left unmaintained.

Other Benefits and Challenges

The cartridges are washable and replaceable. In this way, maintenance costs and the environmental footprint of maintaining the system are reduced. Bio Clean recommends washing and replacing the cartridges as needed to maintain treatment flow rate capacity. Eventually, the filters will need to be replaced after several cleanings.

Site Installation Requirements

The Kraken™ 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 Kraken™ Filter shall conform to ASTM specification C891 *Standard Practice for Installation of Underground Precast Utility Structures*, unless directed otherwise in contract documents.

Necessary Soil Characteristics

Specific underlying soil characteristics are not required for the Kraken™ Filter, since it is a self-contained, watertight system and is fully enclosed. However, the manufacturer 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 Kraken™ Filter is manufactured with three types of cartridges; standard (30 inches tall), low profile (20 inches tall), and super low profile (10 inches tall). If standard cartridges are used the hydraulic grade requirement is 2.86 feet. If the low profile cartridges are used, then this value is reduced to 1.92 feet. The actual hydraulic driving head is approximately 3 inches based on the internal riser tube of the cartridges.

Depth to Groundwater Limitations

The Kraken™ Filter concrete vaults are sealed so that they are watertight; therefore, they do not have depth to groundwater limitations.

Utility Requirements

The Kraken™ Filter is a passive system that requires no power, and has a free-draining outfall to an appropriate water conveyance or storage system (i.e., wet pond, storm sewer, or underground infiltration).

Treatment Processes

The Kraken™ Filter provides water quality treatment of captured flows through physical unit processes. Runoff treatment is achieved through separation, sedimentation, and filtration.

Separation

The dual sedimentation chambers and floatable/oil baffle intercept the majority of floatable gross solids, trash, litter, and oil before water enters the filtration chamber.

Sedimentation

The Kraken™ Filter contains a series of baffles and weir walls that promote gravity settling of entrained particles. The amount of sedimentation is a function of particle density, size, water density, turbulence, and residence time. Deposited sediment is collected on the floor of the two sedimentation chambers and on the floor of the cartridge chamber(s).

Filtration

Particulates are physically removed from suspension as they come into contact with the Kraken™ Filter's membrane. The filter uses FDA approved materials and has NSF 61 listing making them safe for public drinking water. The pleated paper membrane material has nominal opening sizes that ensure consistent performance and removal down to a specific micron size. As the membrane filter ripens with use, its ability to capture smaller particulates and even colloidal sizes materials increases. Pollutant removal rates achieved through the filter are a function of the stormwater composition, flow, and pretreatment effectiveness.

Expected Treatment Capability

This section presents methods and results from previous laboratory testing at the Good Harbour Laboratories in Mississauga, Ontario. A series of laboratory tests were conducted by Good Harbour Laboratories to assess the pollutant removal performance of the Kraken™ Filter (Good Harbour 2016). The tests were conducted using synthetic TSS in accordance with the New Jersey Department of Environmental Protection (NJDEP) laboratory protocol (NJDEP 2013) for assessing TSS removal by a manufactured filtration treatment device. TSS removal results from these tests were presented as part of the PULD application for the Kraken™ Filter (Appendix C) and are reproduced in Table 2. As is apparent from these results, the Kraken Filter achieved greater than 80 percent removal of synthetic TSS in a laboratory setting.

Table 2. TSS Mass Removal Results from Laboratory Testing.

Run No.	Average Influent mg/L	Average Effluent mg/L	Average Sediment Removal Efficiency Percent
1	203.5	39	80.5
2	199.3	34	82.5
3	207.0	42	79.1
4	203.6	38	81.1
5	204.9	38	81.2
6	196.8	40	79.4
7	199.0	49	75.3
8	197.1	33	83.0
9	202.3	33	83.5
10	204.2	38	81.5
11	200.4	30	84.8
12	197.4	31	84.1
13	201.5	28	86.2
14	195.5	26	86.9
15	203.5	22	89.4
16	200.8	18	91.1
LCL95 Mean	199.74	30.5	81.5

mg/L: milligrams per liter

The testing at Good Harbour Laboratories also assessed the amount of sediment the Kraken™ Filter could retain prior to filter occlusion (Good Harbour 2016). The filter never clogged after 37 test runs; hence, the experiment was terminated. During those test runs, a total of 603 pounds of synthetic TSS was retained in the system (Table 3). For comparison, the mass of sediment removed by the Kraken™ Filter was flow normalized and then compared with a selection of other already approved devices that have gone through the same NJDEP protocol (Table 3). As it apparent in Table 3, the Kraken™ Filter is comparable to many already approved devices and thus would likely have similar maintenance requirements.

Table 3. Sediment Loading Capacity for NJDEP Approved Filters.

Technology	Testing Protocol	Basic GULD?	Flow Rate Tested (gpm)	Total Tested Sediment Load Retained (lbs)[a]	Sediment Load Capacity (gpm treatment flow rate)
BayFilter	NJDEP	yes	45	262	5.8
Kraken™[b]	**NJDEP**	**no**	**136**	**600**	**4.4**
StormFilter	NJDEP	yes	15	54.5	3.6
UpFlo Filter	NJDEP	yes	10	14.7	1.5
AquaFilter with AquaSwirl	NJDEP	no	95.2	126	1.3
PerkFilter	NJDEP	yes	60	85.8	1.4
StormKleener	NJDEP	no	30	13.9	0.5

a Based on official NJDEP testing results. Sediment load retained until flow capacity reduced by 10 percent or performance dropped to less than 80 percent TSS removal.

b KrakenTM filter did not drop below 90 percent flow capacity or 80 percent TSS performance. Testing was stopped as deemed enough to show sufficient loading capacity.

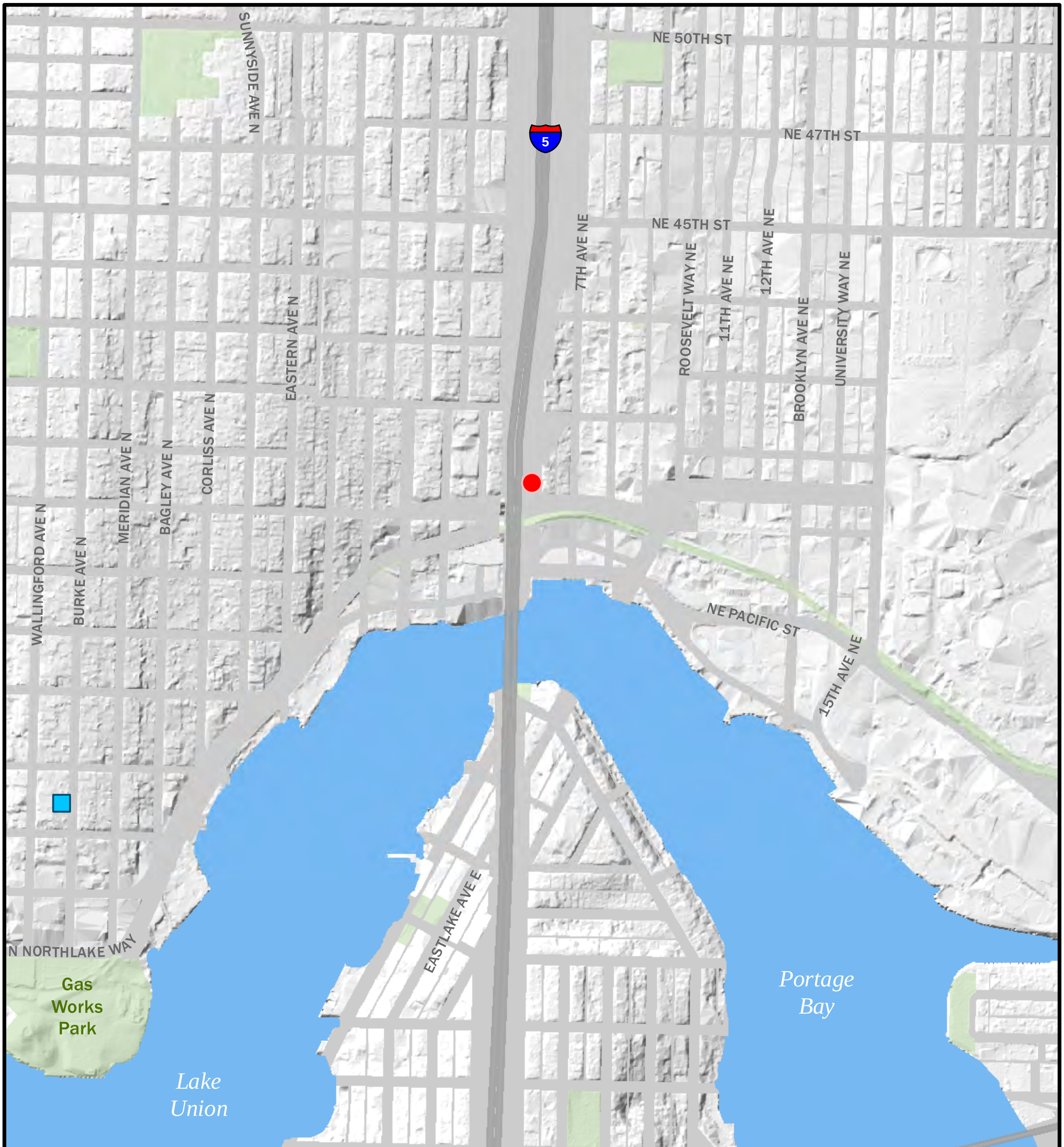
SAMPLING PROCEDURES

This section describes the sampling process design for the field evaluation of a Kraken™ Filter at the SCTF; refer to Appendix D for a detailed description of monitoring procedures at the Tacoma Dome site. This section begins with a description of the SCTF and the Kraken™ Filter installed at that location for testing. Separate sections then describe the field data collection procedures, laboratory analytical methods, quality assurance/quality control (QA/QC) measures, data management procedures, and data analysis procedures that are being implemented for the field evaluation.

WSDOT Ship Canal Test Facility Description

The SCTF is located in Seattle, Washington, below the I-5 right-of-way on the north side of the Lake Union Ship Canal Bridge (Figure 5). The drainage basin to the facility is approximately 31.6 acres, with 22.7 acres of pavement and 8.9 acres of roadside landscaping. The WSDOT stormwater collection system for this drainage basin is separate from the City of Seattle's system; and collects runoff from the I-5 northbound, southbound, express lanes, and the on- and off-ramps. All runoff in the drainage basin passes through 15 Type 1 and 53 Type 2 catch basins and is then consolidated in a 30-inch pipe that is routed to the facility.

WSDOT constructed the SCTF to allow the simultaneous testing of up to four stormwater treatment technologies. This is accomplished by diverting stormwater flow from the 30-inch pipe to the site using a "draw-bridge" half-pipe structure and a series of flow splitters. First, flow from the draw bridge enters an adjustable flow splitter that diverts water toward test bays 1 and 2 on one side, and toward test bays 3 and 4 on the other side (Figure 6). 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 each the test bay even further, a bypass valve is installed immediately upstream of the influent pipe to each system being tested. This bypass valve can divert water around the individual systems without changing the flow rate into the neighboring systems (Appendix A).



Legend

Project area

Project rain gauge

Figure 5.
Location of the Ship Canal Test Facility in Seattle, Washington.

N

0 500 1,000 2,000 Feet

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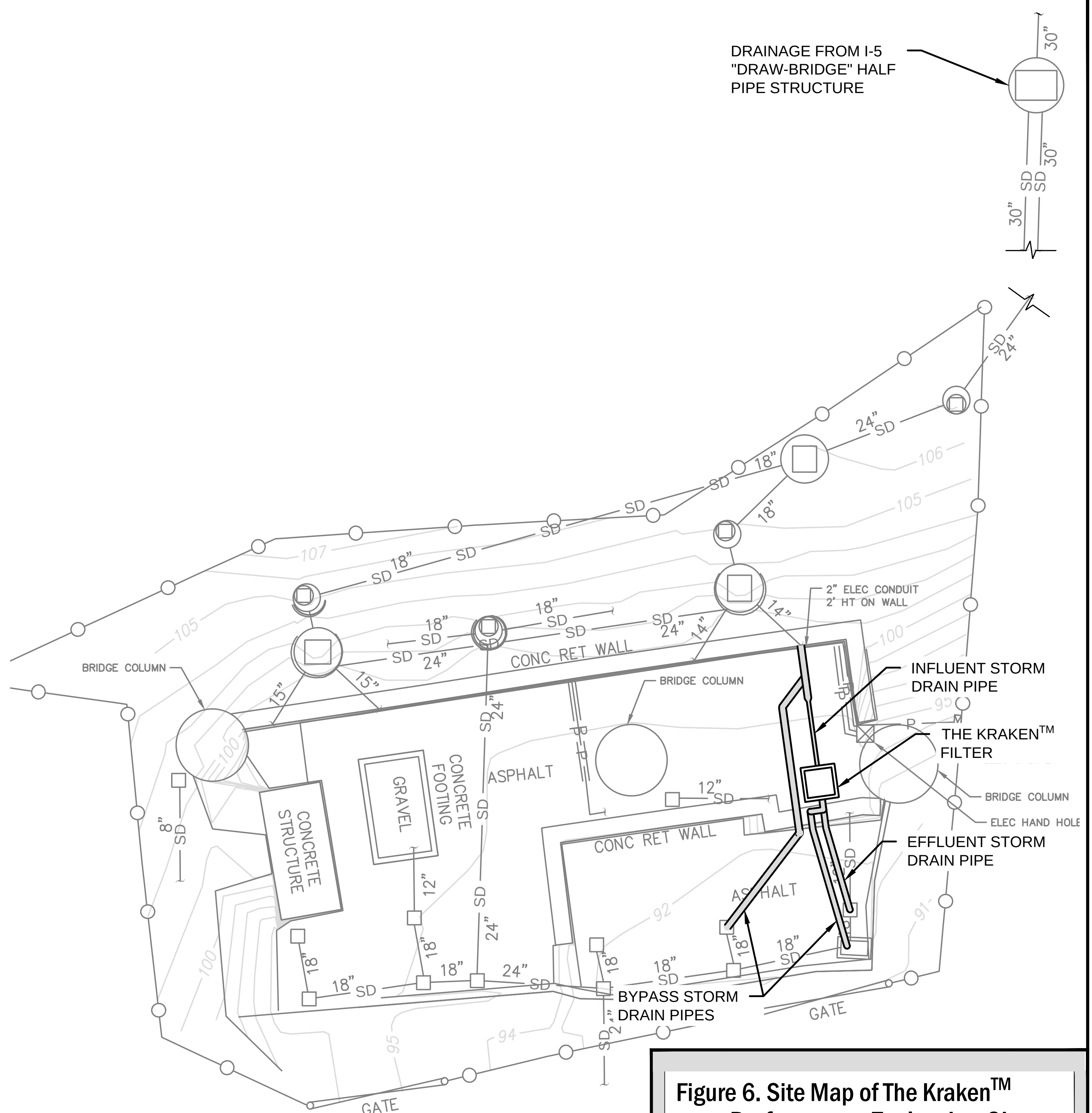
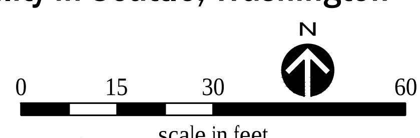


Figure 6. Site Map of The Kraken™ Filter Performance Evaluation Site at the Washington State Department of Transportation Ship Canal Test Facility in Seattle, Washington



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Kraken™ Filter Test System Installation

To facilitate performance monitoring pursuant to the TAPE, a 4- by 4-foot (ID) Kraken™ Filter (WK Test System) was installed for testing purposes at the SCTF. Automated equipment was also installed in conjunction with this system to facilitate continuous monitoring of treated effluent and bypass flow volumes (see Figures 7, 8, and 9 and more detailed description below). In association with this hydrologic monitoring, automated samplers were installed to collect flow-weighted composite samples of the system's influent and effluent during discrete storm events for subsequent water quality analyses.

Figure 7. Photo of the WK Test System at the SCTF.

Monitoring Schedule

Hydrologic and water quality monitoring was conducted at the WK Test System over a 7-month period from October 1, 2016, through April 10, 2017. During this monitoring period, 14 separate storm events were successfully sampled. In addition, water quality (grab samples) monitoring of the second Kraken™ Filter installation at the Tacoma Dome site was conducted over a 16-month period from January 23, 2018, through May 25, 2019, with flow testing occurring from November 6, 2018, to May 6, 2019.

Hydrologic Data Collection Procedures

Hydrologic field data collection procedures for the Kraken™ Filter at the SCTF are described in the following subsections.

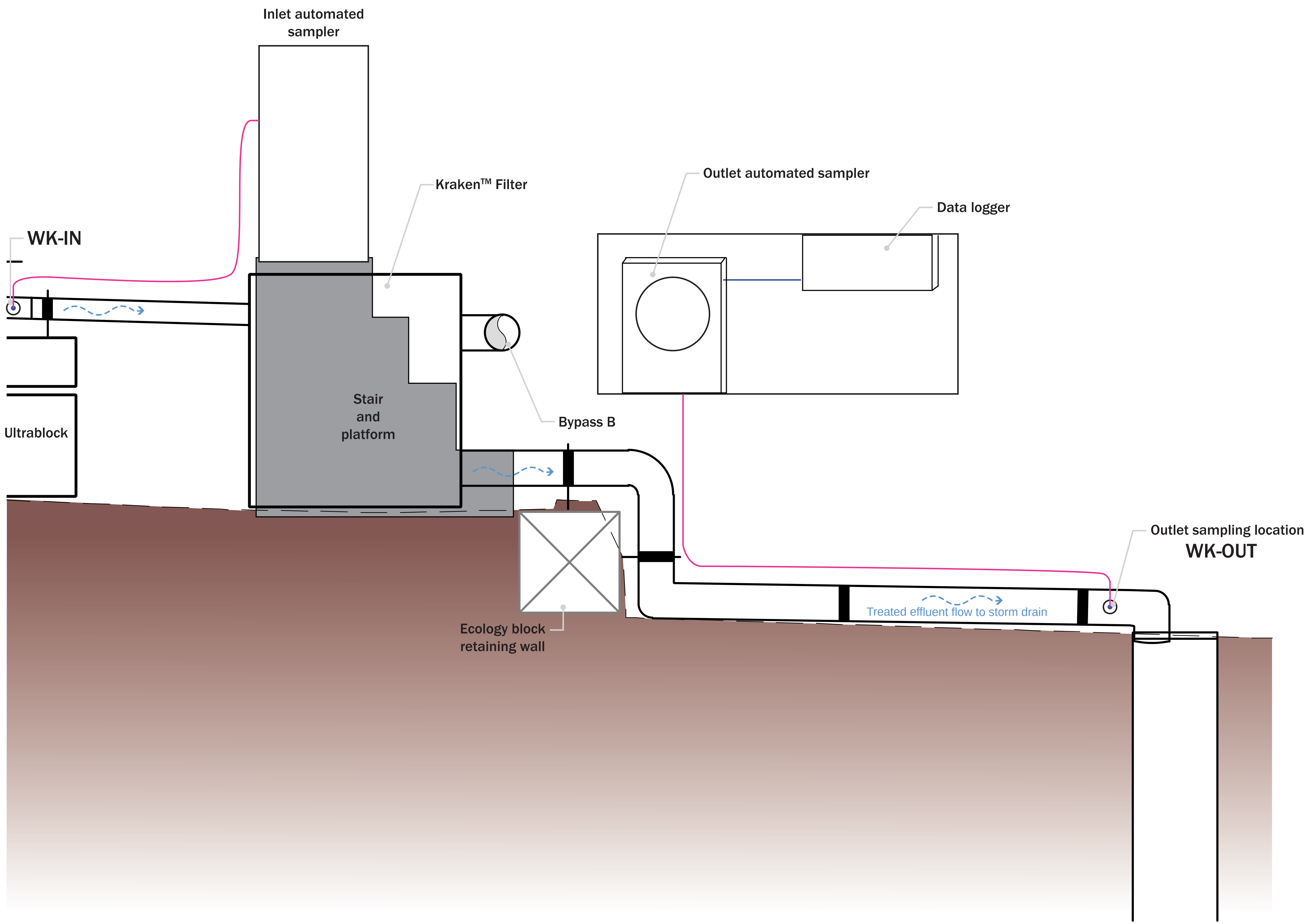

Figure 9.
Cross Section Diagram of the Kraken™ Filter Installation at the Washington State Department of Transportation Ship Canal Test Facility in Seattle, Washington.

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

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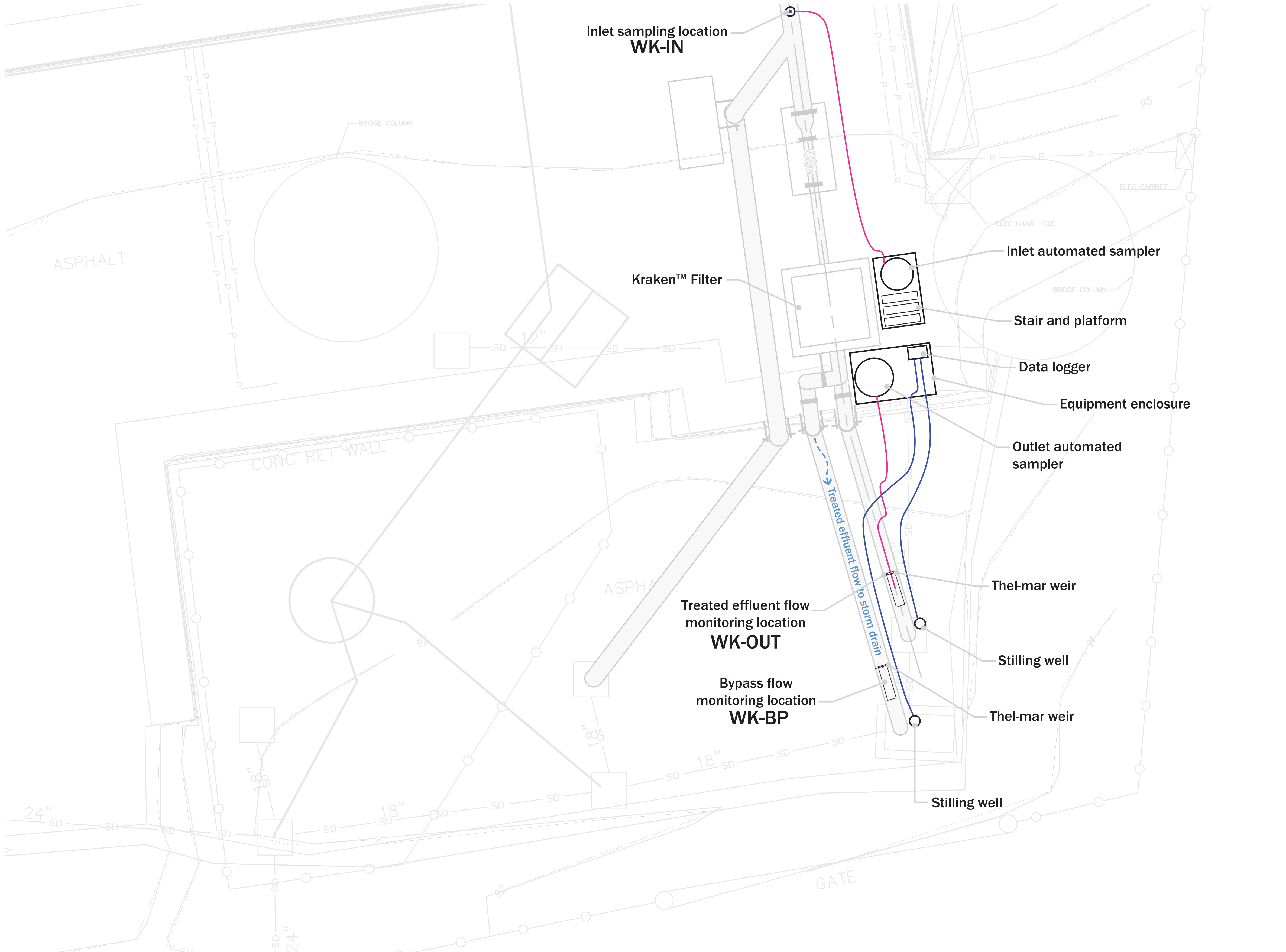

Figure 8.
Plan View Diagram of the Kraken™ Filter Installation at the Washington State Department of Transportation Ship Canal Test Facility in Seattle, Washington.

Legend

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

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Flow Monitoring Stations (WK-IN, WK-OUT, WK-BP)

Continuous monitoring of effluent flow rates for the WK Test System at the SCTF was conducted at a monitoring station, designated WK-OUT, that was established in the outlet pipe for the system (Figures 7, 8, and 9). Continuous monitoring of bypass flow rates was conducted at a second monitoring station, designated WK-BP, that was established at the terminus of the bypass pipe. Thel-Mar weirs were installed in connection with both stations to facilitate the collection of these data. Influent flow (WK-IN) was estimated by combining the flow from WK-OUT and WK-BP. The influent flow rate for WK-IN was considered accurate enough for pacing the influent automated sampler (see description below) because the residence time in the filter at the design flow rate is ~1 minute. This minimal amount of residence time will not significantly alter the effluent hydrograph relative to the influent. This method has been used for numerous previous TAPE certifications on similar filters.

Stilling wells equipped with a pressure transducers (INW PS-9805) were installed in association with the Thel-Mar weirs described above to facilitate the accurate measurement of water levels above the weir crests. The pressure transducers were interfaced with a Campbell Scientific CR1000 datalogger programmed to scan every 10 seconds and record average water levels behind the Thel-Mar weirs on a 5-minute time step. The datalogger then converts these water level readings to estimates of discharge based on standard hydraulic equations (Walkowiak 2006). The datalogger was interfaced with a Raven XTV digital cellular modem. This communication system was configured to automatically download data and send text message alarms to field technicians and project managers. The monitoring equipment was housed in a Knaack box model 69 enclosure. Conduit was installed to convey pressure transducer cabling and automated sampler suction lines from the base of the enclosure to each station. Power to the monitoring equipment was supplied using onsite AC power.

Precipitation Monitoring Station (Wall-RG)

In addition to stations WK-OUT and WK-BP, a third hydrologic station, designated Wall-RG, was installed approximately 4,000 feet west of the SCTF in a residential yard (Figure 5) to facilitate continuous monitoring of precipitation depths. Recording precipitation at the SCTF is not feasible because the facility is located beneath the I-5 Ship Canal Bridge. Precipitation depths were measured 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 is programmed to scan every 10 seconds and record precipitation depth on a 5-minute time step. The datalogger is equipped with an Airlink Raven XTV digital cellular modem to allow communication with the Wall-RG station via remote access.

All flow and precipitation depth data stored on the dataloggers were remotely downloaded on a 5-minute basis via the digital cellular modems described above. These data were processed and validated in accordance with procedures described below.

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 E. On July 25, 2016, a dynamic flow test was conducted using known flow rates from a nearby fire hydrant. The hydrant flows were used to calibrate the Thel-Mar weir equations at WK-OUT and WK-BP. Results from the dynamic flow testing are presented in Appendix E. The adjusted weir equations which resulted from this testing were applied to the entire dataset prior to final analysis.

WATER QUALITY DATA COLLECTION PROCEDURES

To evaluate the water quality treatment performance of the WK Test System installed at the SCTF, water quality sampling was conducted at the WK-IN and WK-OUT stations (Figures 7, 8, and 9) during discrete storm events. A general description of the procedures used for this monitoring is provided herein. Figure 10 provides photos taken during the course of monitoring at the SCTF. A more detailed description of these procedures can also be obtained from the QAPP that was prepared for this project (Herrera 2016).

To facilitate water quality sampling for this project, Isco 6712 portable automated samplers were installed in association with the WK-IN and WK-OUT stations. The intake strainer for the automated sampler at the WK-IN station was installed in the pipe upstream of the filter (Figures 7 and 8); the intake strainer for the automated sampler at the WK-OUT station was installed behind the station's associated Thel-Mar weir. 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.

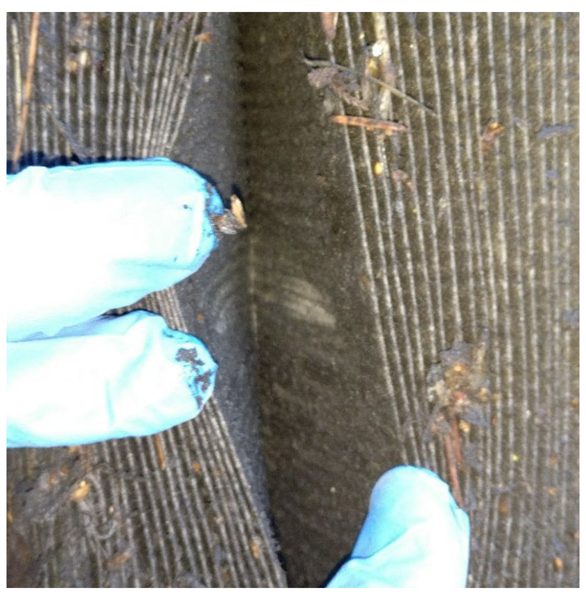
The following conditions serve as guidelines for defining the acceptability of specific storm events for sampling:

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

Bypass and outlet pipes

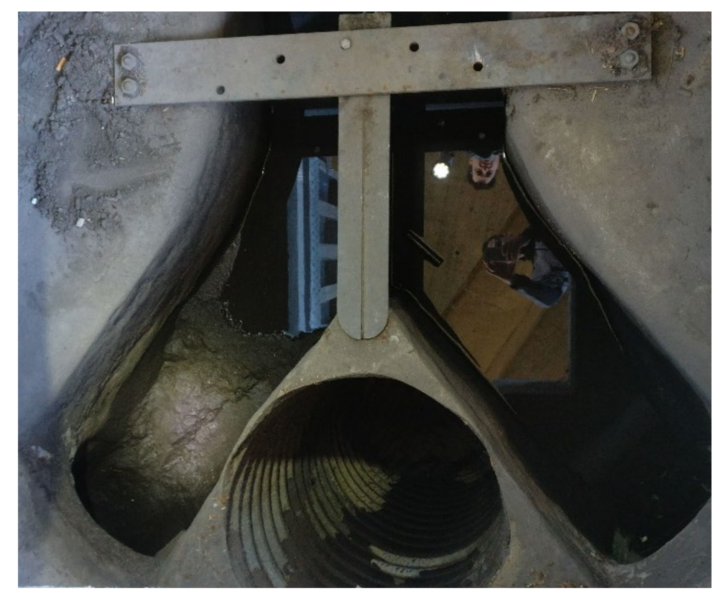
System prior to maintenance

Cartridge cleaning



Sediment penetration into pleats

New cartridges installed in WK



Upstream Flowsplitter

Bypass and Outlet flow monitoring

Figure 10. Photos of Monitoring at the WK Test System.

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 would visit each station to verify that the equipment was operational and to start the sampling program. A clean 20-liter polyethylene carboy and ice were also placed in the automated samplers at this time. The speed and intensity of incoming storm events was tracked using Internet-accessible Doppler radar images. Actual rainfall totals during sampled storm events were quantified based on data from the rain gauge at Wall-RG.

During the storm event sampling, the datalogger described above was programmed to enable the sampling routine in response to a predefined increase in water level (stage) at WK-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 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 aliquots that constitute an acceptable composite sample is 10. If the sample is determined to be acceptable, the carboy containing the flow-weighted composite sample was immediately capped, removed from the automated sampler, and kept below 6ºC 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)
- Total and dissolved copper
- Total and dissolved zinc
- Orthophosphorus
- Hardness

To augment data collected using the flow-weighted composite samples, discrete samples were also collected during select storm events by opening the upstream valve conveying stormwater to the SCTF until the treated flow rate was equivalent to the design flow rate for the WK Test System; at this point the automated samplers at WK-IN and WK-OUT were manually activated until an adequate volume of stormwater was collected for sample analysis at both stations. This method was used to collect water quality 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).

In addition, pH was measured on three occasions using a YSI 556 field meter. Additional parameters were also measured (Appendix F); however, this report only addresses those parameters that are pertinent to the issuance of a GULD for basic and phosphorus treatment.

Sediment Monitoring Procedures

Sediment sampling for the Kraken™ 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 one sample).

Sediment depth was measured at three different locations within the pretreatment chamber. The average of the three depths was used to calculate the amount of sediment captured in the sump. The sediment sample was collected from three separate areas of the pretreatment chamber 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.

Laboratory Analytical Methods

Laboratory analytical methods for this project are summarized in Table 4. Analytical Resources, Inc. (ARI) in Tukwila, Washington, was the laboratory used for this project for all parameters except PSD. ARI is certified by Ecology, and participates in audits and inter-laboratory studies by Ecology and EPA. These performance and system audits have verified the adequacy of the laboratory's standard operating procedures, which include preventive maintenance and data reduction procedures. Environmental Technical Services (ETS) in Petaluma, California was used for PSD analysis.

Quality Assurance/Quality Control Measures

Field and laboratory QA/QC procedures used for the Kraken™ Filter field evaluation are discussed in the following sections.

Table 4. Methods and Detection Limits for Water Quality Analyses.

Parameter	Analytical Method	Method Number[a]	Field Sample Container	Pre-Filtration Holding Time	Total Holding Time[b]	Field Preservation	Laboratory Preservation	Reporting Limit/ Resolution	Units
Total suspended solids	Gravimetric[c]	SM 2540D	20-liter HDPE bottle	7 days	7 days	Maintain ≤6 C□	Maintain ≤4 C	1.0	mg/L
Total phosphorus	Automated ascorbic acid	SM 4500P-F		NA	28 days		Maintain ≤4 C, H_2SO_4 to pH <2	0.008	mg/L
Orthophosphorus	Automated ascorbic acid	SM 4500P E		12 hours[d]	48 hours		Maintain ≤4 C, H_2SO_4 to pH <2	0.004	mg P/L
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
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
Zinc, total				NA			Maintain ≤6 C, HNO_3 to pH <2	0.004	0.005
Hardness	Titration	SM 2340B		28 days	28 days		Maintain ≤4 C, HNO_3 to pH <2	0.05	mg/L as $CaCO_3$
pH	Potentiometric	SM 4500-H^+		24 hours[d]	24 hours		Maintain ≤4 C	0.01	std. units
Particle Size Distribution	Sieve and filter	ASTM D422		7 days	7 days		Maintain ≤4 C	NA	microns

[a] SM method numbers are from APHA et al. (1998); EPA method numbers are from US EPA (1983; 1984). 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; US EPA 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 orthophosphorus and dissolved metals and measurement of pH 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 for this study is 12 hours.

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

C = Celsius
HDPE = High-Density Polyethylene
mg/L = milligrams per liter
NA = not applicable.

Field Quality Assurance/Quality Control

This section summarizes the QA/QC procedures that were implemented by field personnel to evaluate sample contamination and sampling precision. The results from QA/QC procedures that were performed for the collection of water quality samples are reported in Appendix G.

Field Blanks

Automated sampler tubing was cleaned 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 also collected on June 1, 2016, prior to the first sampled storm event at both monitoring stations. A second set of field blanks was collected on April 17, 2017, after the last sample was collected, to determine if the tubing was a source of contamination for monitoring conducted up to this date. 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 influent station was chosen for the field duplicates in order to ensure a high enough concentration for comparison between the replicate samples. The resultant data from these samples was used to assess variation in the analytical results that is attributable to environmental (natural) and analytical variability.

Laboratory Quality Control

The 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. ARI and ETS 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 accompany the analytical results.

Data were also reviewed and validated by Herrera within 7 days of receiving the results from the laboratory. This review was performed to ensure that all data are 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. In this report, estimated values were used for evaluation purposes, but rejected values were not used.

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.

ARI and ETS 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 were subsequently entered into a Microsoft Access database for all subsequent data management and archiving tasks.

An independent review was performed to ensure that the data are 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 for the hydrologic and water quality data summarized in this report are described 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 period covered by this report:

- 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 guidelines from the TAPE for valid storm events.

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 were compared for paired influent and effluent across all storm events using a 1-tailed Wilcoxon signed-rank test (Helsel and Hirsch 2002). The test was specifically used to evaluate the hypothesis that effluent pollutant concentrations were significantly lower than influent concentrations. In all cases, statistical significance was evaluated at an alpha level ( ) 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:

$$\Delta C = 100 \times \frac{C_{in} - C_{eff}}{C_{in}}$$

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 values and 95 percent confidence interval about the mean were estimated using a bootstrapping approach (Davison and Hinkley 1997). The lower confidence interval was used to determine if the mean percent removal was significantly higher than the percent removal targets presented in TAPE (e.g., 80 percent removal for TSS).

Calculation of Pollutant Removal Efficiency as a Function of Flow

Analyses were conducted to evaluate whether pollutant removal efficiency varied as a function of influent flow rate. As a first step in these analyses, the influent flow rate when each sample was collected was calculated. Specifically, for composite samples the instantaneous flow rates associated with each aliquot were averaged over the sampled event to generate an average sampled flow rate. This value was then compared with the percent pollutant removal for the event. This process was repeated for each sampled event; the results were subsequently plotted to visually assess potential relationships between percent removal and sampled flow rate. Regression analyses were then conducted to determine if any observed relationships were statistically significant. In order to obtain a sampled flow rate near or at the design flow rate, a discrete sampling approach was also employed where the samplers were programmed to collect aliquots only when flow rates were at the design flow rate. The result is a sample which does not represent an EMC but instead the instantaneous performance of the filter when it is at its design flow rate. The EMC and discrete sample dataset were combined for this analysis.

DATA SUMMARIES AND ANALYSIS

This section summarizes data collected at the SCTF during the October 2016 through April 2017 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 E, while Appendix G 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 WK 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 (October 1, 2016, through April 31, 2017) were anomalous. The NWS rain gauge is located at Sand Point, approximately 4.25 miles northeast of the Wall-RG rain gauge. The analysis specifically involved a comparison of rainfall totals measured at the Sand Point rain gauge over the monitoring period to averaged totals for the same gauge from the past 30 years. These data are summarized in Table 5 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), located 1.1 miles to the east of Wall-RG.

Results from this analysis (Table 6) showed the average October through April rainfall total at the Sand Point rain gauge from 1986 through 2016 was 28.52 inches. In comparison, the rainfall total at the same rain gauge over the monitoring period was 44.12 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 WK Test System), this factor did not affect the representativeness of the results.

Table 6 also indicates a discrepancy among the rain gauges during this period. Wall-RG, the furthest west of the three gauges, recorded 47.60 inches of rain during the monitoring period. The furthest east gauge, Sand Point, measured 44.12 inches. RG-03, located between the other two gauges at the University of Washington, measured 45.26 inches. Historically, these three gauges have been in closer agreement, but that was not the case for this monitoring period.

Table 5. Summary Statistics for Sampled Storms at the SCTF Test System from October 6, 2016, through April 10, 2017.								
Storm Start Date and Time	**Storm Depth (inches)**	**Peak Storm Intensity (in/hr)**	**Total Volume (gallons)**	**Bypass Volume (gallons)**	**Percent of Total Volume Bypassed**	**Peak Treated Flow Rate (gpm)[a]**	**Average Sampled Flow Rate (gpm)[a]**	**Percent Water Year Treated**
New Filters Installed 9/12/2016 (10 Micron Filters)								
10/6/2016 21:00	0.27	0.36	13,838	4,452	32	118	60	0.2
Filters Cleaned and Reinstalled 11/14/2016 (10 Micron Filters)								**0.9**
11/14/2016 23:40	0.87	1.20	21,405	0	0	54	41	0.9
12/2/2016 6:25	0.15	0.24	7,342	1,906	26	61	32	2.0
12/9/2016 7:30	0.81	0.24	58,583	33,622	57	23	15	2.5
New Filters Installed 1/17/2017 (20 Micron Filters)								**3.6**
1/17/2017 11:50	2.91	0.48	125,325	78,063	62	145	52	3.6
2/3/2017 1:55	1.55	0.24	14,088	1,985	14	25	12	5.3
2/8/2017 8:45	2.59	0.36	40,408	24,468	61	26	11	5.8
2/14/2017 21:40	2.45	0.60	36,845	20,578	56	13	7	6.6
Filters Cleaned and Reinstalled 3/16/2017 (20 Micron Filters)								**11.9**
3/17/2017 13:15	1.38	0.24	2,750	0	0	139	133	11.9
3/23/2017 21:25	0.68	0.24	46,744	23,338	50	136.9	49.9	12.1
Filters Cleaned and Reinstalled 3/28/2017 (10 Micron Filters)								**12.9**
3/29/2017 0:15	0.53	0.24	19,124	0	0	63.7	57.1	13.0
4/4/2017 21:25	0.62	0.12	8,857	352	4	147.0	170[b]	13.6
4/6/2017 5:25	0.19	0.12	4,463	1,592	36	23.6	12.7	13.9
4/10/2017 1:25	0.24	0.24	9,831	7,754	79	15.8	9.9	14.2
minimum	0.15	0.12	2,750	0	0	13	7	
median	0.75	0.24	16,606	3,219	34	57.5	32	
maximum	2.91	1.20	125,325	78,063	79	147	133	

[a] Design flow rate is 136 gallons per minute (gpm)

[b] Sampled flow rate is greater than peak treated flow rate because the samples were discrete samples collected at the peak of the storm when instantaneous discharges were recorded by field staff. Peak treated flow rate data are 5-minute averages, thus the true peak flow was not recorded in the continuous dataset.

Table 6. Monthly Precipitation Totals at the Ship Canal Test Facility Compared to Historical Totals at Sand Point.				
	Monthly Averages from Monitoring Period: October 1, 2016, Through April 31, 2017			Monthly Averages from Historical Data: 1986–2016
Month	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)
October 2016	10.86	10.23	10.3	3.18
November 2016	8.36	7.70	7.71	5.59
December 2016	4.11	3.85	3.71	5.33
January 2017	4.12	4.72	3.70	4.99
February 2017	8.96	8.18	8.16	2.88
March 2017	7.07	6.59	6.49	3.74
April 2017	4.12	3.99	4.05	2.81
Total	47.60	45.26	44.12	28.52

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.

The calibration record for Wall-RG, presented in Appendix E, indicates a bias of 2 percent or less for calibrations conducted before and after the test period. The other rain gauges are calibrated by Seattle Public Utilities (RG-03) and the National Oceanographic and Atmospheric Administration (Sand Point) and are thus assumed to be accurate as well. Consequently, it is assumed that the discrepancy among the gauges is due to isopluvial variation across the region during the monitoring period.

System Hydraulic Performance

The water budget for the WK 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

SCTF Hydrologic Monitoring Results

While the WK Test System was being monitored at the SCTF, three separate stormwater treatment devices were also being monitored at this location. Rapid clogging of all four systems

(WK Test System included) was observed after between one and four storm events with treated flow rates falling below 80 percent of the design flow rate in each case. This clogging was most likely due to the high oil and automobile pollutant loading from the basin which is dominated by runoff from I-5. This stretch of highway has an Annual Average Daily Traffic count of 173,000 and consequently produces runoff with relatively high levels of pollution compared with typical basins (e.g., commercial parking lots, residential arterials) in which manufactured stormwater treatment devices would be installed.

Table 5 presents the hydrologic monitoring results from the 14 sampled storm events at the SCTF for the WK Test System while Appendix H presents the hydrologic results for all the sampled and unsampled events (n = 29). The 6-inch valve controlling flow into the Kraken™ Filter was regularly (but not always) shut off between targeted sampling events. This approach was employed to allow the collection of water quality samples to continue for as long as possible. The objective was to generate a water quality data set which could be used to support TAPE approval with the assumption that an additional site would be selected to verify the maintenance interval using stormwater that is more representative of urban runoff (i.e., not highway runoff). The parking lot west of the Tacoma Dome, in Tacoma, Washington was chosen as the second monitoring site. The details of this monitoring are provided in Appendix D, and results from this monitoring are also presented below in the *Tacoma Dome Hydrologic Monitoring Results* section.

As shown in Table 5, the SCTF system was maintained four times during the 7 months of testing from October 2016 to April 2017. Initially, 10 micron filters were used in the Kraken™ Filter for treatment. When it was found that these filters were rapidly clogging, 20 micron filters were deployed on January 17, 2017. The washed 10 micron filter was reinstalled on March 28, 2017. A comparison between the TSS and TP removal results for each of the filters (10 and 20 micron) is provided in the next section with the objective of pooling the data from both filters based on evidence that there is no significant difference in treatment performance. The design flow rate of the test system with either filter was 136 gallons per minute (gpm). The maximum treated flow rate exceeded this threshold during 4 of the 14 events (Table 5). The average sampled treated flow rate ranged from a low of 7 gpm to a maximum of 170 gpm. These data are presented again in the next section with the results from the water quality monitoring to evaluate relationships between sampled flow rate and treatment performance.

The water quality treatment goal for the WK Test System was to capture and treat 91 percent of the average annual runoff volume. Table 5 indicates that flows equivalent to 0.9 percent of a water year in Seattle 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 8.3 percent of a water year passing through the system between maintenance events (Table 5). Maintenance entailed removing sediment from the sump with a shop vac and replacing the cartridges with either new or previously washed cartridges. By the end of the study on April 10, 2017, flows equivalent to 14.2 percent of a water year had passed through the system, this value is below the goal of 91 percent treatment. However, as mentioned above, the testing at the

Tacoma Dome was completed to augment this dataset and provide additional information on the system's required maintenance interval.

Hydrograph Form and Sample Distribution

Due to progressive clogging of the 6-inch valve conveying stormwater to the WK Test System, the hydrograph form was not always correlated with the hyetograph form (see the individual storm report—Appendix I—for the February 8, 2017, event as an example). This resulted in a sample distribution across the hydrograph that 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.

Tacoma Dome Site Hydrologic Monitoring Results

In order to determine how the Kraken^{TM} Filter would perform under more typical commercial applications, a second test system was installed at the Tacoma Dome site; hydraulic monitoring of this system was conducted over a 7-month period from November 6, 2018, through May 6, 2019. A more detailed presentation of the testing conducted at the Tacoma Dome is presented in Appendix D. This section summarizes the results of the hydraulic testing at this site.

The system at the Tacoma Dome site consisted of a KF-2.5-4 model Kraken^{TM} Filter configured with four cartridges. To assess the hydraulic performance of this system, a water truck was brought to the site and the design flow rate of 34 gpm (8.5 gpm per cartridge) was discharged into the pretreatment chamber (Figure 11). Once the water level stabilized in the system, the distance between the water surface elevation and the bypass was measured and recorded. This test was repeated quarterly until the system went into bypass at the design flow rate (an indication of clogging). Specifically, flow tests were conducted on November 6, 2018, February 6, 2019, and May 6, 2019, at which point the system went into bypass and was only able to treat flows up to 20 gpm (Table 7); this flow rate is 41 percent lower than the design flow rate.

To determine the maintenance threshold for the Kraken^{TM} Filter, the percent of a typical water year in Tacoma that was treated by the test system prior to each flow test was estimated by comparing the measured rainfall during the study period at Pierce County Rain Gauge CL_RIB_WS located 6 miles to the east of the site to the typical annual rainfall for Tacoma (48.95 inches). This analysis showed the test system had treated an equivalent volume of 36 percent of a typical water year prior to the second test and 56 percent of the water year prior to the third test (when the system was flowing at 41 percent below the design flow rate). These data indicate that at some point during the ensuing 3 months between the second and third flow tests the system was no longer able to treat the design flow rate without bypassing. Thus, the system clogged at between 36 and 56 percent of a water year.

Figure 11. Water Being Discharged into the Tacoma Dome Test System at 34 gpm, the Design Flow Rate.

Table 7. Flow Testing Results from the Kraken™ Filter Tacoma Dome Site.						
Date	**Days Online**	**Percent Clogged (percent)[a]**	**Rain to Date (in)[b]**	**Percent Rain of Typical WY (percent)[c]**	**Water Level Below Bypass Elevation (in)**	**Treated Flow Rate (gpm)**
11/6/2018	0	0	0	0	6	34
2/6/2019	92	0	13.98	36	5.5	34
5/6/2019	181	41	21.92	56	-1[d]	20

[a] Percent clogged determined by discharging 34 gpm (design flow rate) into the filter and comparing bypass flow to design flow

[b] Rain data obtained from Pierce County rain gauge CL_RIB_WS located 6 miles to the east

[c] Average annual rainfall for Tacoma area 38.95 inches

[d] Estimated as measuring water depth over the weir crest was difficult due to turbulence

in = inches

gpm = gallons per minute

WY = water year

WATER QUALITY DATA

Results from the 7 months of water quality sampling at the SCTF that occurred over the period from October 2016 to April 2017 are presented in this section. The section begins with a summary of results from quality assurance reviews of the data that were collected over this period. Storm event characteristics and sample collection procedures are then compared to criteria identified in the TAPE for assessing the representativeness of collected samples for use in quantifying system performance. Finally, water quality data are compared to the specific performance goals from the TAPE. A database with all flow, precipitation, and water quality results from the sampled events is provided in Appendix F. In addition, the field forms for each sampled event are provided in Appendix J while Appendix I provides individual storm reports (ISR) for each sampled event. ISRs are one page summaries consisting of a hydrologic and sampling statistics summary table, a hydrograph and hyetograph showing sample collection times, and a water quality data summary table. Finally, laboratory reports for each sampled event, including chain of custody forms, are provided in Appendix K.

This section also summarizes water quality data from grab samples collected from the test system at the Tacoma Dome site. A more detailed explanation of these results is provided in Appendix D.

Quality Assurance Review Results

The water quality data were assessed against method quality objectives in the QAPP that was prepared for the project (Herrera 2016). The results of this assessment are reported in Appendix G. Based on this assessment, some of the collected data were qualified as estimates; however, no data were rejected and all individual values were carried forward into the analyses presented below.

Comparison to Criteria for Assessing Sample Representativeness

The TAPE identifies criteria for assessing the representativeness of collected samples based on the characteristics of sampled storm events and sample collection procedures. The data collected through this monitoring effort are evaluated relative to these criteria in the following subsections.

Storm Event Criteria

During the October 6, 2016, through April 10, 2017, monitoring period, 14 storm events were sampled to characterize the water quality treatment performance of the WK Test System. Precipitation data from the sampled storm events in this period were compared to the following criteria from the TAPE for determining sample acceptability:

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

Summary data related to these criteria are presented in Table 8 for each of the 14 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 these events were 0.15, 0.75, and 2.91 inches, respectively. The criterion for minimum antecedent dry period (6 hours) was also met for every event. Antecedent dry periods during the sampled storm events ranged from 10 to 278 hours, with a median value of 52 hours. Finally, the storm duration criterion (1 hour) was met for all events. Storm durations ranged 2.0 to 47.2 hours, with a median value of 23.7 hours (Table 8).

Table 8. Sampled Events Versus TAPE Storm and Sampling Criteria.									
Storm Start Date and Time	Rainfall Depth (inches) Goal ≥0.15	Rainfall Duration (hours) Goal ≥1	Antecedent Dry Period (hours) Goal ≥6 hours	Number of Aliquots IN Goal ≥10	Number of Aliquots OUT Goal ≥10	Percent Storm Volume Sampled IN Goal ≥75	Percent Storm Volume Sampled OUT Goal ≥75	Sampling Duration IN Goal <36	Sampling Duration OUT Goal <36
New Filters Installed 9/12/2016 (10 Micron Filters)									
10/6/2016 21:00	0.27	6.0	65	28	20	96	89	5	4
Filters Cleaned and Reinstalled 11/14/2016 (10 Micron Filters)									
11/14/2016 23:40	0.87	6.8	19	100	100	93	88	9	8
12/2/2016 6:25	0.15	3.4	53	25	18	95	95	5	5
12/9/2016 7:30	0.81	30.7	87	92	77	98	98	28	28
New Filters Installed 1/17/2017 (20 Micron Filters)									
1/17/2017 11:50	2.91	36.6	176	100	68	91	92	23	23
2/3/2017 1:55	1.55	46.5	278	29	40	98	96	23	22
2/8/2017 8:45	2.59	47.2	40	55	25	93	89	23	23
2/14/2017 21:40	2.45	31.7	111	51	33	94	90	34	34
Filters Cleaned and Reinstalled 3/16/2017 (20 Micron Filters)									
3/17/2017 13:15[a]	1.38	22.5	50	**8**	**8**	**22**	**22**	0.1	0.1
3/23/2017 21:25	0.68	26.7	50	100	63	**74**	91	10	14
Filters Cleaned and Reinstalled 3/28/2017 (10 Micron Filters)									
3/29/2017 0:15	0.53	10.0	51	100	100	90	90	5	5
4/4/2017 21:25a	0.62	24.8	67	**1**	**1**	**0**	**0**	0	0
4/6/2017 5:25	0.19	4.8	10	16	13	91	86	6	4
4/10/2017 1:25	0.24	2.0	51	50	17	97	88	4	4
minimum	0.15	2.0	10	1	1	0	0	0	0
median	0.75	23.7	52	51	29	93	89.5	7.5	6.5
maximum	2.91	47.2	278	100	100	98	98	34	34

Bold values indicate results which did not meet the criteria

[a] The 3/17/2017 and 4/4/17 events did not meet the sampling goals because they were high flow rate discrete sample events.

Sample Collection Criteria

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 14 sampled events (March 17, 2017, and April 4, 2017) involved the collection of discrete samples during peak flows; flow-weighted composite samples 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. None of the sample collection criteria described above are applicable to the discrete samples.

The criterion for minimum number of sample aliquots (10) was met for all of the flow-weighted composite samples (Table 8). The criterion for minimum portion of storm volume covered by sampling (75 percent) was also met for all flow-weighted composite samples except the influent sample from the March 23, 2017, event. The storm volume covered by this sample was only 1 percent shy of the goal; therefore, the data from this sample were deemed valid for subsequent use in analyses. Finally, the sampling duration did not exceed 36 hours for all of the flow-weighted composite samples.

Performance Evaluation

This section evaluates water quality data relative to treatment goals identified in the TAPE. Over the monitoring period from October 6, 2016, to April 10, 2017, a total of 14 storm events were successfully sampled. Of the 14 sampled events, 12 involved the collection of flow-weighted composite samples and 2 involved the collection of discrete samples during peak flows (see Table 8). Results from these sampling are specifically compared to goals identified in the TAPE for basic and phosphorus treatment in the following subsection along with results from additional screening parameters.

Basic Treatment

The basic treatment goal identified in the TAPE indicates that the bootstrapped 95 percent lower confidence interval (LCL95) for 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) for 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), cannot be used for assessing TSS removal performance. Additionally, it must be shown that a statistically significant difference between influent and effluent concentrations exists. Finally, pollutant removal meeting the TAPE goals must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate.

TSS data obtained from samples collected during all 14 sampled storm events are summarized in Table 9. Through not specifically a TAPE parameter, SSC values are also presented in the table for reference. The average influent TSS concentration from these samples was 73 mg/L while the average effluent concentration was 7 mg/L. Table 10 presents data from a subset of these samples that have been screened by influent concentrations to only include samples meeting requirements from the TAPE for use in assessing treatment performance. Out of the 13 samples in this subset, four had influent TSS concentrations that exceeded 100 mg/L and the remaining nine had influent concentrations between 20 and 100 mg/L.

The TAPE requires a minimum n-value of 12 for use in comparing to treatment goals. Because only four samples had influent concentrations greater than 100 mg/L, the LCL95 for the mean percent reduction could not be calculated for comparison to the 80 percent reduction goal (as a rule of thumb a minimum of 10 samples are required to conduct the bootstrap calculation for determining the LCL95). However, it should be noted that the mean TSS percent reduction from these four samples was 96.4 percent.

To evaluate the effluent concentration treatment goal, TSS data from all thirteen samples in Table 10 were pooled; inclusion of the samples with influent concentrations exceeding 100 mg/L provides a conservative estimate of performance relative to this treatment goal. The calculated UCL95 around the mean effluent concentration was 10.1 mg/L (Table 10); this value meets the effluent goal specified above for basic treatment.

Results from a Wilcoxon Signed Rank test (Helsel and Hirsch 2002) that was applied to the TSS data from Table 10 also indicated effluent concentrations were significantly lower than influent concentrations ($p = 0.007$).

Finally, the effluent TSS concentrations from Table 10 were plotted versus the average sampled treated flow rate (Figure 12); this comparison was not performed using percent removal due to the low n-value for this measure of performance. As shown in Figure 12, the fitted linear regression line through these data is statistically significant ($p = 0.002$) and indicates the system can meet the effluent goal from TAPE up to the design flow rate of 136 gpm (8.5 gpm per cartridge).

Based on these analyses, it can be concluded that the Kraken™ Filter meets the basic treatment goal from the TAPE with a 136 gpm (or 8.5 gpm per cartridge) design flow rate.

Table 9. Summary of Water Quality Results from the WK Test System at the SCTF.

Date	TSS (mg/L)			Total SSC (mg/L)			Total Phosphorus (mg/L)			Ortho-Phosphorus (mg/L)		
	In	Out	%	In	Out	%	In	Out	%	In	Out	%
10/6/2016	46	4.4	90	74	11	85	0.140	0.056	60	0.011	0.009	18
11/14/2016	31	4	87	53.8	3.5	93	0.062	0.024	61	0.06	0.006	90
12/2/2016	52	4	92	72.4	9.9	86	0.156	0.052	67	0.018	0.012	33
12/9/2016	116	2	98	129.3	4.2	97	0.290	0.024	92	0.019	0.004	79
1/17/2017	56	9	84	117.4	6.4	95	0.166	0.028	83	0.01	0.011	-10
2/3/2017	44	5	89	57.4	4.1	93	0.136	0.024	82	0.017	0.01	41
2/8/2017	103	4	96	147.5	2.2	99	0.166	0.018	89	0.016	0.006	63
2/14/2017	162	4	98	541.8	4.3	99	0.216	0.014	94	0.009	0.004	56
3/17/2017	97	9	91	81.9	16.1	80	0.144	0.074	49	0.021	0.022	-5
3/23/2017	50	18	64	42.8	4.4	90	0.078	0.030	62	0.007	0.006	14
3/29/2017	10	5	50	13.9	6.9	50	0.066	0.034	49	0.008	0.009	-13
4/4/2017[a]	54	23	57	135.4	17.6	87	0.120	0.070	42	0.012	0.011	8
4/6/2017	44	4	91	251	3.3	99	0.110	0.018	84	0.011	0.004	64
4/10/2017	158	2	99	400.3	2	100	0.264	0.012	96	0.008	0.004	50
Mean	73	7	85	151.4	6.9	89	0.151	0.034	72	0.016	0.008	35
Median	53	4	91	99.7	4.4	93	0.142	0.026	75	0.012	0.008	37
Min	10	2	50	13.9	2.0	50	0.062	0.012	42	0.007	0.004	-13
Max	162	23	99	541.8	17.6	100	0.290	0.074	96	0.06	0.022	90

[a] Sample collected at 170 gpm, above the design flow rate of 136 gpm

mg/L = milligrams per liter

Table 10. Screened Water Quality Results and Comparison to TAPE Criteria.							
	TSS (mg/L)			Total Phosphorus (mg/L)			Average Sampled Treated Flow Rate (gpm)
Date	**In**	**Out**	**%**	**In**	**Out**	**%**	**Out**
10/6/2016	46	**4**	90	0.140	0.056	**60**	59.7
11/14/2016	31	**4**	87	0.062	0.024	**61**	40.8
12/2/2016	52	**4**	92	0.156	0.052	**67**	31.8
12/9/2016	116	**2**	98	0.290	0.024	**92**	14.8
1/17/2017	56	**9**	84	0.166	0.028	**83**	52.2
2/3/2017	44	**5**	89	0.136	0.024	**82**	12.0
2/8/2017	103	**4**	96	0.166	0.018	**89**	11.1
2/14/2017	162	**4**	98	0.216	0.014	**94**	7.4
3/17/2017	97	**9**	91	0.144	0.074	**49**	133.3
3/23/2017	50	**18**	64	0.078	0.030	**62**	49.9
3/29/2017	–[b]	–	–	0.066	0.034	**49**	57.1
4/4/2017[b]	54	**23**	57	0.120	0.070	**42**	170.0
4/6/2017	44	**4**	91	0.110	0.018	**84**	12.7
4/10/2017	158	**2**	99	0.264	0.012	**96**	9.9
n-value for TAPE assessment		13				14	
LCL95 Mean % Reduction			NC[a]			<u>64.2</u>[d]	
UCL95 Mean Effluent Conc.		<u>10.1</u>					

[a] Not calculable, only four values had influent above 100 mg/L.

[b] Data excluded because influent TSS below 20 mg/L

Bold indicates values used in calculations for comparison to TAPE criteria

Underlined indicates value meet TAPE criteria (<20 mg/L effluent TSS concentration; >50 percent total phosphorus removal)

mg/L: milligrams per liter

Phosphorus Treatment

The phosphorus treatment goal identified in the TAPE indicates that the bootstrapped 95 percent lower confidence interval (LCL95) for the mean TP removal must be greater than or equal to 50 percent for influent concentrations ranging from 0.1 to 0.5 mg/L. Additionally, it must be shown that a statistically significant difference between influent and effluent concentrations exists. Finally, pollutant removal meeting the TAPE goals must be shown for sample pairs across a range of treated flow rates up to and including the design flow rate.

TP data obtained from samples collected during all 14 sampled storm events are summarized in Table 9. The average influent TP concentration from these samples was 0.151 mg/L while the average effluent concentration was 0.034 mg/L. Data for three influent samples had concentrations below 0.1 mg/L and outside the acceptable range identified above for evaluating treatment performance. Normally, the associated sample pairs would be excluded from the calculations performed to assess performance. However, to obtain the requisite sample size, data from all samples were included in these calculations; inclusion of the samples with influent concentrations below 0.1 mg/L provides a conservative estimate of performance relative to the treatment goal. The calculated LCL95 around the mean percent reduction was 62.4 percent (Table 10); this value meets the percent reduction goal specified above for phosphorus treatment.

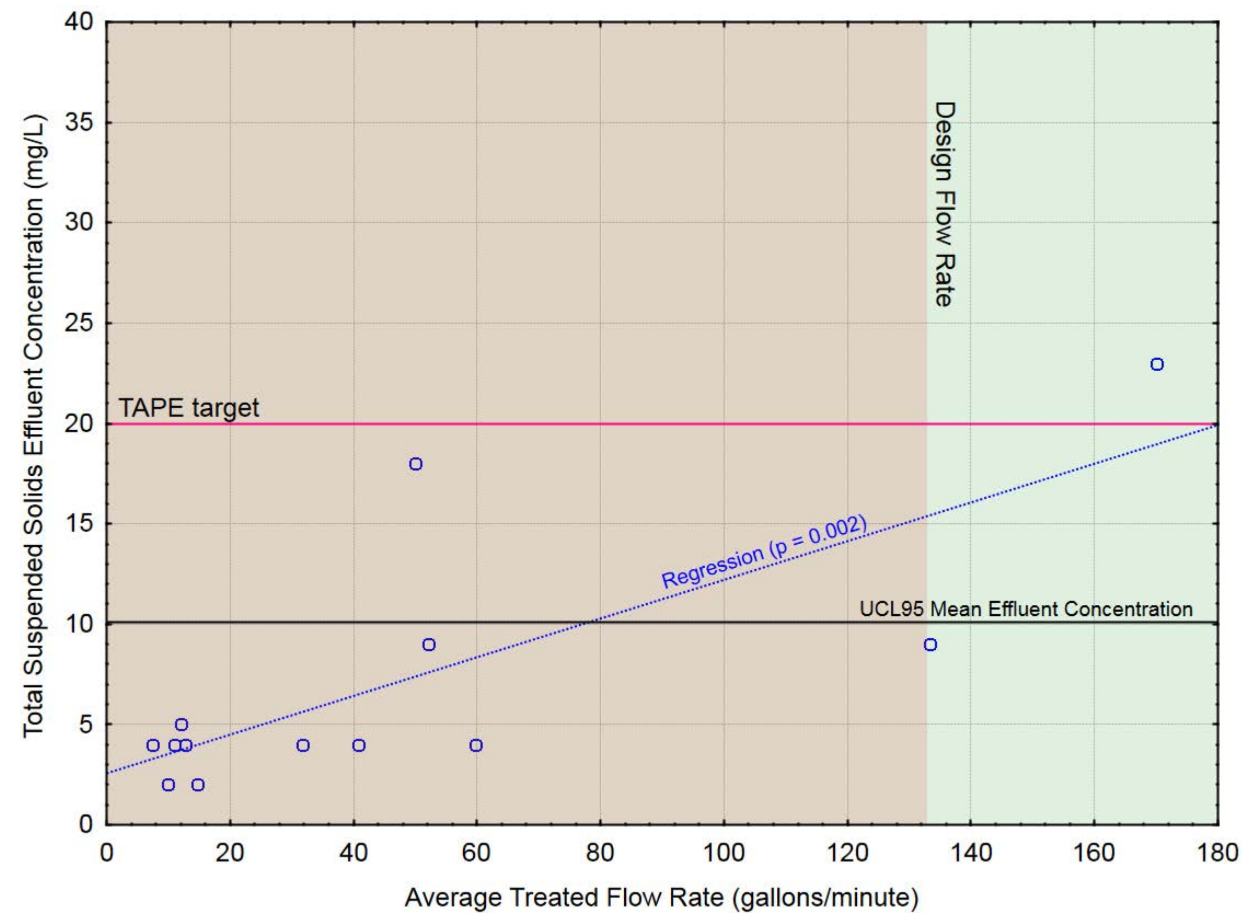


Figure 12. Total Suspended Solids Effluent Concentrations Versus Average Sampled Treated Flow Rate

Results from a Wilcoxon Signed Rank test (Helsel and Hirsch 2002) that was applied to the TP data from Table 10 also indicated effluent concentrations were significantly lower than influent concentrations ($p < 0.001$).

Percent reduction values from Table 10 were plotted versus the average sampled treated flow rate (Figure 13); these data suggest treatment performance decreases as flow rate increases. The fitted linear regression line through these data confirmed this relationship was statistically significant with treatment performance approaching 50 percent at a flow rate of 119 gpm.

Based on this analysis, it can be concluded that the Kraken™ Filter meets the phosphorus treatment goal from the TAPE with a 119 gpm (or 7.4 gpm per cartridge) design flow rate.

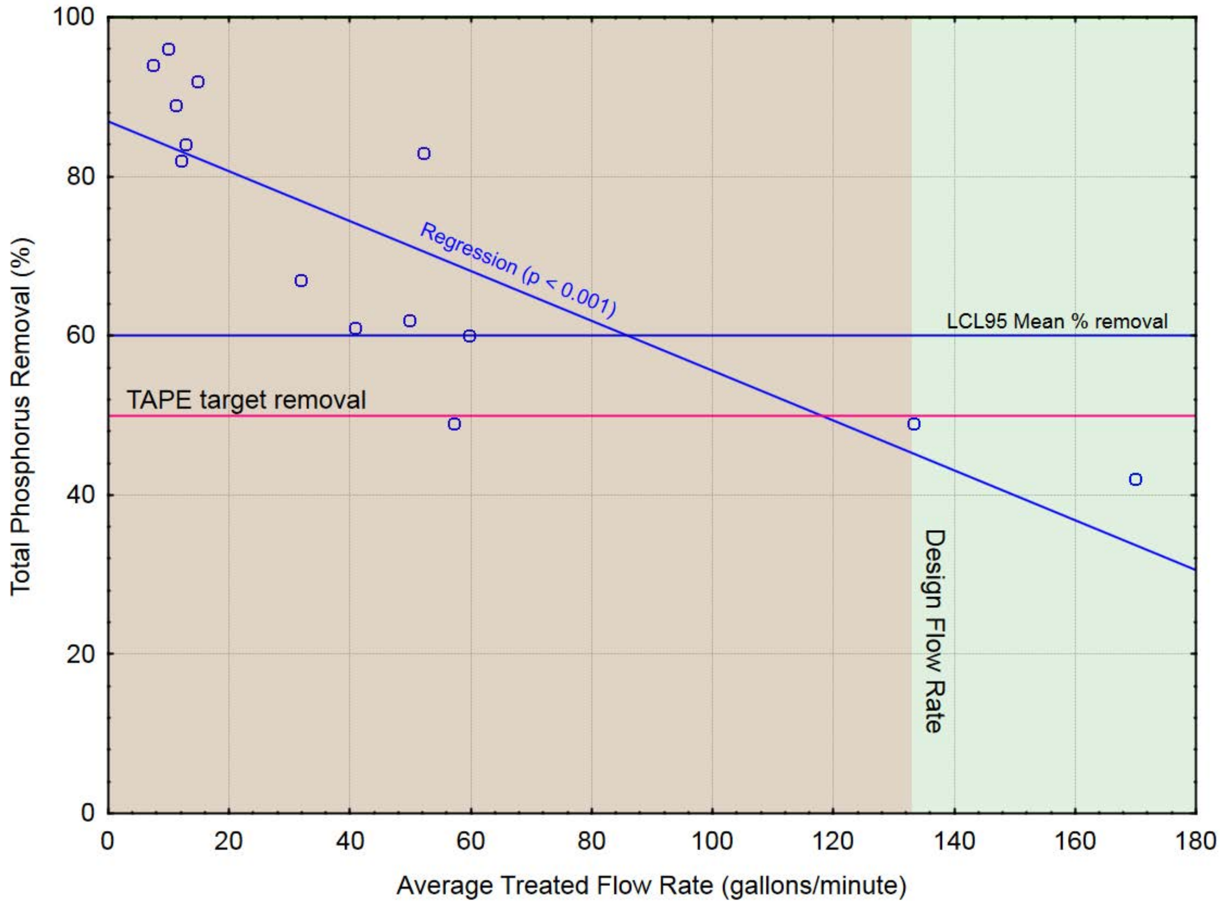
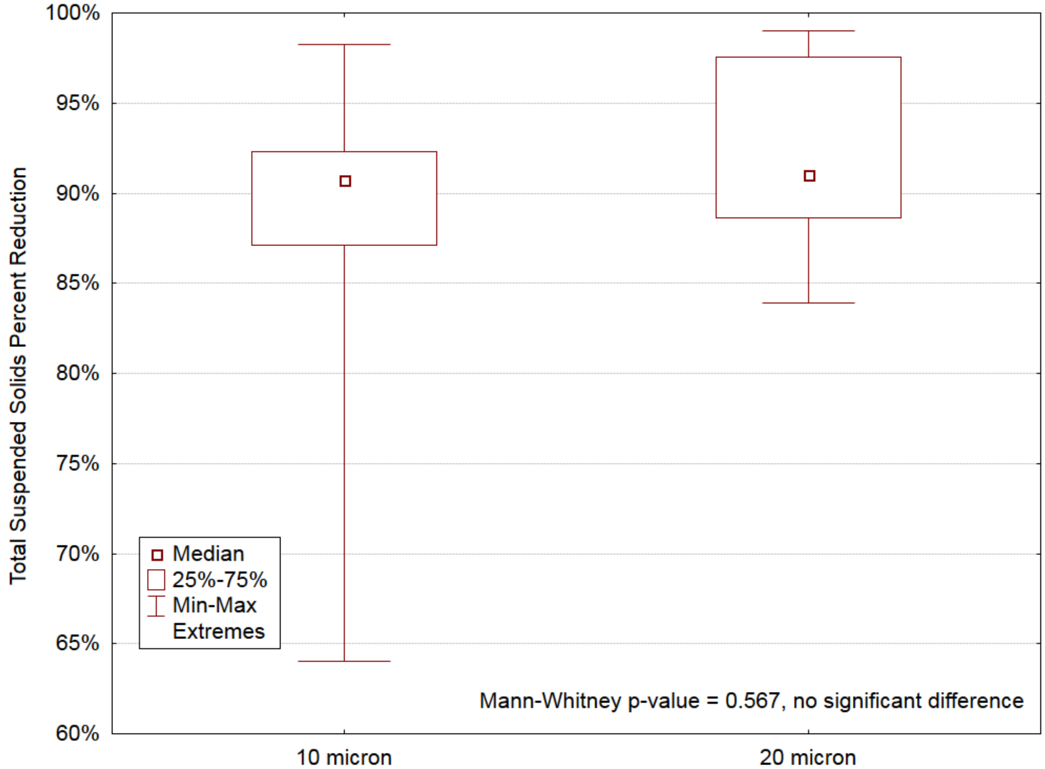


Figure 13. Total Phosphorus Percent Reduction versus Average Sampled Treated Flow Rate

Comparison of Datasets with Different Micron Ratings

The analyses presented above used data from eight events with filters having a 10-micron rating installed in the WK Test System and six events with filters having a 20-micron rating which are almost identical. The micron ratings were switched during monitoring to increase longevity without sacrificing performance described in the section above on System Hydraulic Performance. To demonstrate there is no significant difference in treatment performance between the micron ratings, a Mann-Whitney U Test was used to compare the treatment performance for TSS and TP from both filters. As shown in Figure 14, results from these tests show there is no significant difference in TSS and TP removal performance between the two filters. Based on these results, the standard configuration for the Kraken™ Filter will include the 20-micron rating because it is capable of meeting the TAPE performance goals while likely providing an extended maintenance cycle relative to the 10-micron filter. The 20-micron rated filters actually performed better overall.



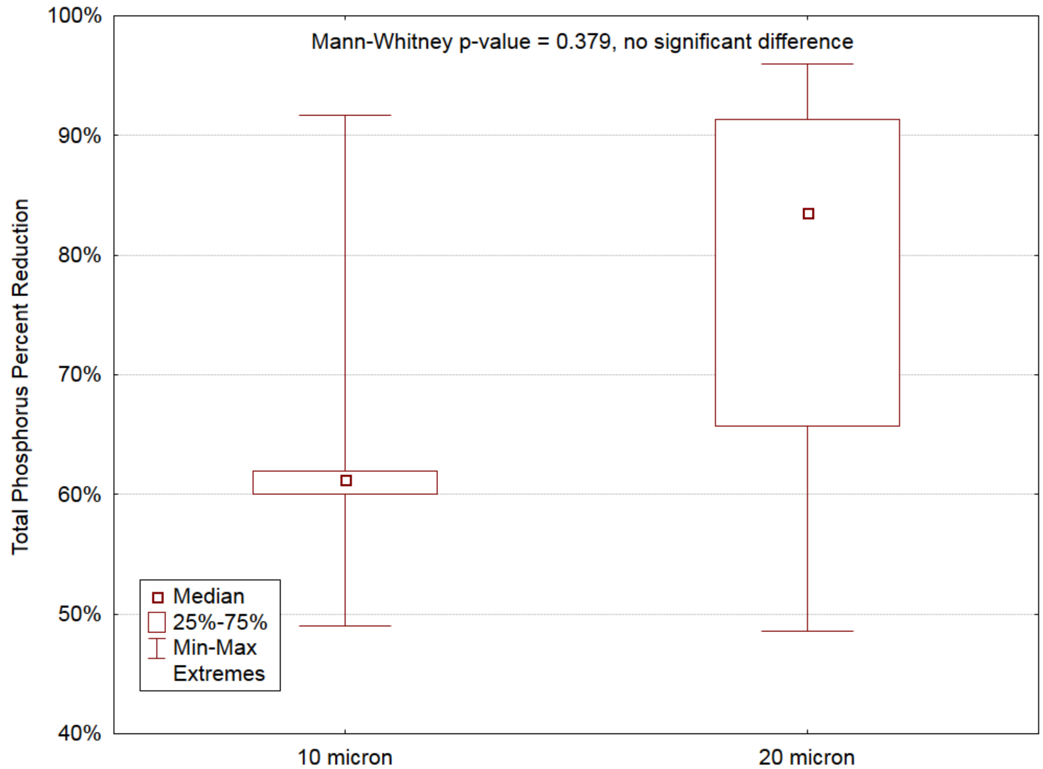


Figure 14. Results of the Comparison in Performance Between the 10 and 20 Micron Filters.

Screening Parameters

For Basic and Phosphorus treatment verification through the TAPE, the following screening parameters must be analyzed during at least three events: PSD, pH, orthophosphorus, hardness, and total and dissolved copper.

Orthophosphorus was analyzed for every sample collected with the results presented along with those for TSS and TP in Table 9. These data show the average orthophosphorus removal was 35 percent.

The TAPE states that Pacific Northwest stormwater typically contains mostly silt-sized particles; thus, PSD results must be provided to indicate whether the stormwater runoff used for testing conforms to this assumption. PSD measured at the influent station (WK IN) during the 14 sampled events are summarized in Figure 15. These results show the median particle diameter (D50) for the influent to the WK Test System was approximately 22 microns (Figure 15). The influent water was highly variable with respect to PSD with the individual sample D50 ranging from 2 microns to 450 microns. Based on this analysis it can be concluded that the influent PSD was majority silt or finer.

Results from the metals and hardness analyses are presented in Table 11 for the 14 sampled events. These results show the Kraken™ Filter was effective at treating total metals with a 57 and 62 percent reduction for total copper and total zinc, respectively. However, the system did not perform well at treating dissolved metals with a -3 and 0.4 percent reduction for dissolved copper and dissolved zinc, respectively (Table 11).

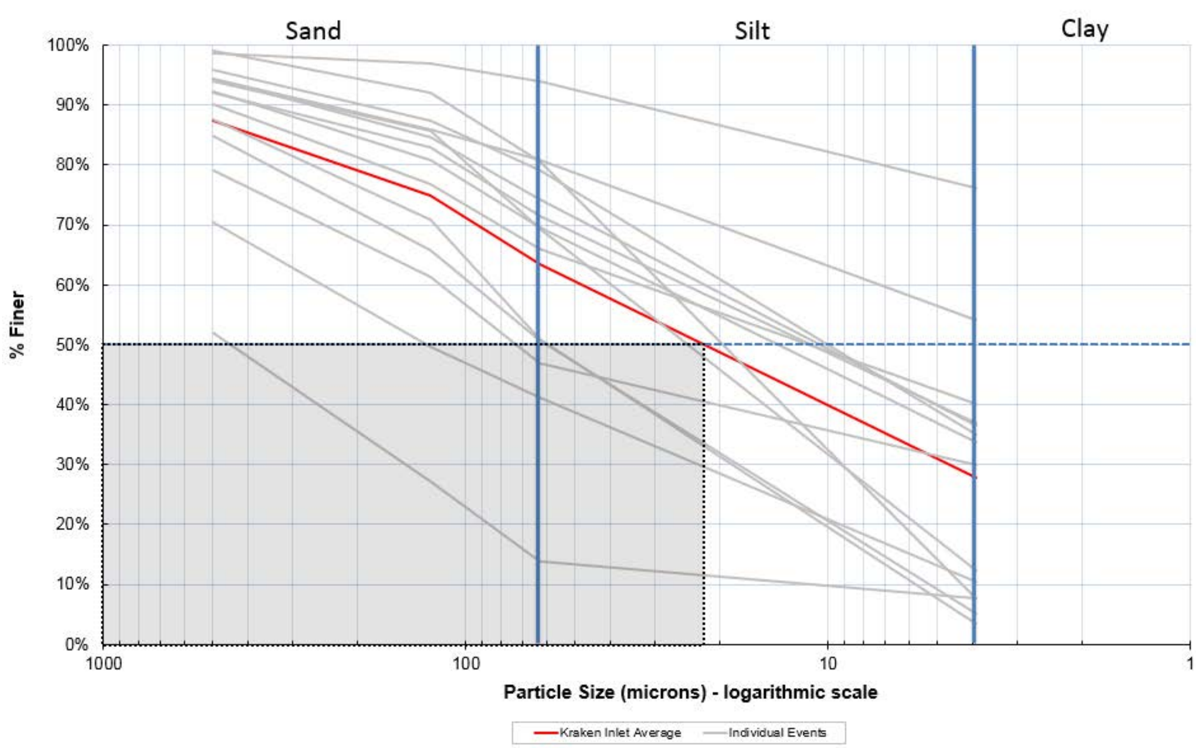


Figure 15. Influent Particle Size Distribution Results.

Table 11. Summary of Screening Parameter Metals and Hardness Results from the WK Test System at the SCTF.

	Total Copper (ug/L)			Dissolved Copper (ug/L)			Total Zinc (ug/L)			Dissolved Zinc (ug/L)			Hardness (mg $CaCO_3$/L)		
Date	**In**	**Out**	**%**	**In**	**Out**	**%**	**In**	**Out**	**%**	**In**	**Out**	**%**	**In**	**Out**	**%**
10/6/2016	54.5	23.5	57%	14.1	15.9	-13%	149	48.5	67%	34.8	33	5%	33.6	32	5%
11/14/2016	29.4	12.1	59%	9.08	8.13	10%	98.4	36.8	63%	26.8	27.6	-3%	32.8	26.9	18%
12/2/2016	53.5	25.1	53%	13.6	17.8	-31%	174	56.1	68%	39.6	35.8	10%	49.6	50.6	-2%
12/9/2016	88.9	18.8	79%	21.1	16.2	23%	444	128	71%	121	110	9%	200	214	-7%
1/17/2017	37.7	16.7	56%	9.79	10.4	-6%	124	61.5	50%	34	35.5	-4%	32.4	27.4	15%
2/3/2017	38.4	13.2	66%	11.9	10.1	15%	131	48.8	63%	38.3	37.1	3%	42.5	43.6	-3%
2/8/2017	62.4	14.7	76%	13	12.2	6%	248	54.1	78%	48.7	42.6	13%	45.1	50.1	-11%
2/14/2017	33.9	19.7	42%	11.3	18.6	-65%	137	50.9	63%	31.6	47.8	-51%	46.7	38.7	17%
3/17/2017	52	25.6	51%	14	14.4	-3%	166	65	61%	35.1	32.8	7%	43.8	41.7	5%
3/23/2017	29	13.5	53%	10.6	10.7	-1%	104	41	61%	41.1	32.3	21%	48	55.9	-16%
3/29/2017	17.3	13.6	21%	7.62	9.06	-19%	55.7	36.1	35%	21.5	22.8	-6%	38.9	39.7	-2%
4/4/2017	44	28.2	36%	15.3	14	8%	131	71.6	45%	38.8	34	12%	50	48.2	4%
4/6/2017	36.4	12.1	67%	13	9.79	25%	104	43.8	58%	36	34.5	4%	45.3	45.7	-1%
4/10/2017	57.2	8.46	85%	8.6	7.78	10%	252	33	87%	27	30.8	-14%	37.2	37.2	0%
Mean	**45.3**	**17.5**	**57%**	**12.4**	**12.5**	**-3%**	**165.6**	**55.4**	**62%**	**41.0**	**39.8**	**0.4%**	**53.3**	**53.7**	**2%**

Finally, Table 12 shows the results from the three events where pH was measured. These results indicate the Kraken™ Filter did not substantially alter pH values, reducing influent pH by between 1 and 3 percent.

Table 12. pH Screening Results.

Date	IN	OUT	Percent Change
4/5/2017	7.36	7.31	1%
4/6/2017	7.64	7.4	3%
6/8/2017	7.69	7.56	2%

Tacoma Dome Water Quality Monitoring Results

Appendix D provides a comprehensive review of the water quality data collected at the Tacoma Dome site. The mean influent TSS concentration from samples collected at the Tacoma Dome site was 57.4 mg/L while the mean effluent concentration was 6.1 mg/L. Two paired samples had influent TSS concentration that exceeded 20 mg/L (May 25, 2019, and July 9, 2019, events) and the corresponding effluent sample concentrations were 5 and 8 mg/L, respectively; hence, the goal for basic treatment per the TAPE was met for these sample pairs. The remainder of the paired samples had influent TSS concentrations below 20 mg/L so could not be used to assess removal efficiency.

It should be noted that TSS export from the Kraken™ Filter at the Tacoma Dome site was evident in samples collected during the December 11, 2018, event. Furthermore, the effluent sample collected during the October 5, 2018, event was also contaminated by bypassed stormwater; hence, the associated data were not included in the analysis. More generally, influent sample TSS concentrations appeared correlated with parking lot activity and first flush dynamics. For example, only one influent sample was collected when a concert was occurring at the site and the parking lot was full (March 26, 2019); the TSS concentration for this sample was 3 times greater than the mean for all samples. Because the remaining influent samples were collected when the parking lot was empty, it is likely that the data obtained from the Tacoma Dome Test Site may underestimate the TSS load delivered to test system given the parking lot is in frequent use on the weekends when sampling did not typically occur. The July 9, 2019, event was collected as water was first entering the trench drain, so very early on the rising limb. This sample was characterized by a TSS concentration of 362 mg/L, greater than 6 times higher than the mean influent concentration. The final dataset seems to indicate that the majority of sediment is entering the system when the parking lot is being used, early on the rising limb, and likely during the most intense peaks of rain events when the sediment deposited on the flat parking lot actually becomes mobilized. With this intermittent and irregular export of TSS it is difficult to characterize the average runoff TSS with a grab sampling program.

SEDIMENT MONITORING RESULTS

As indicated in the Sampling Procedures section, sediment depth and quality were assessed in the WK Test System installed at the SCTF. Sediment depth never exceeded an average of 3.2 inches in the sump (Table 13). Sediment accumulation between maintenance events was evident, particularly in the early winter. The mean sediment depth over the duration of the study was 1.25 inches. One sediment quality sample was collected on June 28, 2017. The results are reported in Table 14 along with Model Toxics Control Act (MTCA) disposal criteria limits for metals. As is apparent these limits were not exceeded.

Table 13. Sediment Depth Measurements in Sump.

Date	Sediment Depth (inches)
New Filters Installed 9/12/2016 (10 Micron Filters)	
September 2016	0
October 2016	3.2
November 2016	3.2
Filters Cleaned and Reinstalled 11/14/2016 (10 Micron Filters)	
December 2016	2.1
New Filters Installed 1/17/2017 (20 Micron Filters)	
January 2017	0
February 2017	0.5
March 2017	1
Filters Cleaned and Reinstalled 3/16/2017 (20 Micron Filters)	
Filters Cleaned and Reinstalled 3/28/2017 (10 Micron Filters)	
April 2017	0
May 2017	1.5
June 2017	1
Mean	1.25

It should be noted that more than half the deposited solids were organic with a percent volatile solids of 54.71 percent dry weight (Table 14). Organic matter is runoff tends to be more buoyant and thus more difficult to settle. This can lead to more solids moving through the pretreatment chamber and reaching the filters, thus requiring more frequent maintenance. There were many elements which lead to the high maintenance frequency at the WK test system, the organic fractionation of the influent suspend solids is just one.

Table 14. Summary of Sediment Quality Results.			
Sample Date	**Units**	**6/28/2017**	***MTCA – Method A (unrestricted) Cleanup Level (mg/kg)***
Total Solids	percent wet weight	15.7	–
Volatile Solids	percent dry weight	54.0	–
Total Phosphorus	mg-P/kg dry	525	–
Pebbles and greater	percent	10.8	–
Very coarse sand	percent	11.0	–
Coarse sand	percent	18.3	–
Medium sand	percent	19.3	–
Fine sand	percent	14.9	–
Very fine sand	percent	11.3	–
Coarse silt	percent	2.4	–
Medium silt	percent	5.2	–
Fine silt	percent	2.9	–
Very fine silt	percent	1.9	–
Clay	percent	1.2	–
Colloidal	percent	0.8	–
Total fines	percent	14.3	–
Copper	mg/kg dry	217	*3,200*[a]
Zinc	mg/kg dry	860	*24,000*[a]

[a] MTCA Method B, non-cancer.

CONCLUSIONS

To obtain performance data to support the issuance of a GULD for the Kraken™ Filter, Herrera oversaw installation of the WK Test System at the WSDOT SCTF in Seattle, Washington. Herrera then conducted hydrologic and water quality monitoring of this system from October 6, 2016, to April 10, 2017. Over this monitoring period, 14 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 14.2 percent of a water year had passed through the system after four required maintenance events, with a maximum of 8.3 percent of a water year treated between individual maintenance events.

Out of the 14 sampled events, paired influent and effluent samples from 13 events met criteria specified in the TAPE for evaluating the basic treatment goal. Analyses performed on the data from these samples indicated the Kraken™ Filter can meet the effluent concentration goal (TSS <20 mg/L) from the TAPE with a 136 gpm (or 8.5 gpm per cartridge) design flow rate. Data from all 14 of the sampled events were used to evaluate the phosphorus treatment goal. Analyses performed on the data from these samples indicated the Kraken™ Filter can meet the 50 percent TP removal goal from the TAPE at flow rates up to 119 gpm (7.4 gpm per cartridge). Based on these results, we recommend the Kraken™ Filter be granted a GULD for basic and phosphorus treatment at 8.5 gpm per cartridge and 7.4 gpm per cartridge, respectively.

The WF Test System rapidly clogged during testing at the SCTF; however, every filter that has been tested at the SCTF since 2016 has also clogged prematurely. This indicates the runoff from this site may be unusually difficult for filters to treat. To support the issuance of a GULD for the Kraken™ Filter, data were collected from a second system installed near the Tacoma Dome in Tacoma, Washington. Flow testing indicated this system was able to filter 36 to 56 percent of a typical water year in Tacoma before reaching the threshold Ecology has established for required maintenance (bypassing at or below the design flow). During this period, grab sampling during 10 events at the inlet and 6 events at the outlet indicated that the overall average influent TSS concentration was 57.4 mg/L while the effluent averaged 6.1 mg/L. Of these events, six had paired influent and effluent samples. Only two of these six events had influent concentration above 20 mg/L, and for each the effluent was less than 20 mg/L.

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