CAPITOL HILL WATER QUALITY PROJECT

WATER YEAR 2020 MONITORING

Prepared for
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Herrera Environmental Consultants, Inc.

HERRERA

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INTRODUCTION

Field crews collecting water and vegetation samples from the CHWQP

The Capitol Hill Water Quality Project (CHWQP), commonly referred to as Swale on Yale, is designed to treat stormwater 60 percent of the flows from the 435-acre Minor Avenue sub-basin of Seattle's Capitol Hill which drains to South Lake Union via the Minor Avenue storm outfall (Figure 1). The CHWQP is an offline stormwater treatment facility that operates by treating flows diverted from an existing 48-inch storm drain. The CHWQP consists of a Vortechs 16000 swirl concentrator (Vortechs) by a followed by treatment in one of four biofiltration swales (swales). The facility is designed to be highly flexible, with weirs controlling the diversion rate to the pretreatment structure and flow splitters controlling flows to each of the four independent swales. The swales are lined, flow-through swales with underdrains, vegetated with species of Carex and Juncus. The swales have two treatment pathways: 1) surface pathway (biofiltration); and 2) underdrain pathway (bioretention pathway).

Herrera Environmental Consultants (Herrera) was contracted by Seattle Public Utilities (SPU) to monitor influent and effluent flow and water quality for one of the four swales (CH2, Figure 2) from October 2015 through July 2016 (2016 Campaign). Subsequently, Herrera monitored three of the four swales (CH2, CH3, and CH4, Figure 2) from December 2019 through December 2020 (2020 Campaign). CH1 was never monitored but was constructed at the same time and with a similar design to CH3. Each of the monitored swales was unique in terms of either its hydroperiod or the bioretention soil media (BSM) used in construction. This provided a unique configuration for performance hypothesis testing.

This report provides a description of the facility and then summarizes results from the testing in the context of design improvements and BSM optimization.

STUDY SITE

The CHWQP is located in the Cascade neighborhood of Seattle, Washington (Figure 1). The first two of the four project swales (CH2 and CH4, Figure 2) were constructed in 2015 and the second two swales (CH1 and CH3) were constructed in 2018. The swales were constructed to receive an equivalent amount of hydraulic loading per swale surface area. Due to its slightly higher inlet elevation, CH2 does not receive base flow between storms, but the other swales receive relatively constant base flow during the wet season – meaning these swales consistently have several inches of surface flow and the BSM is saturated for long periods of time.

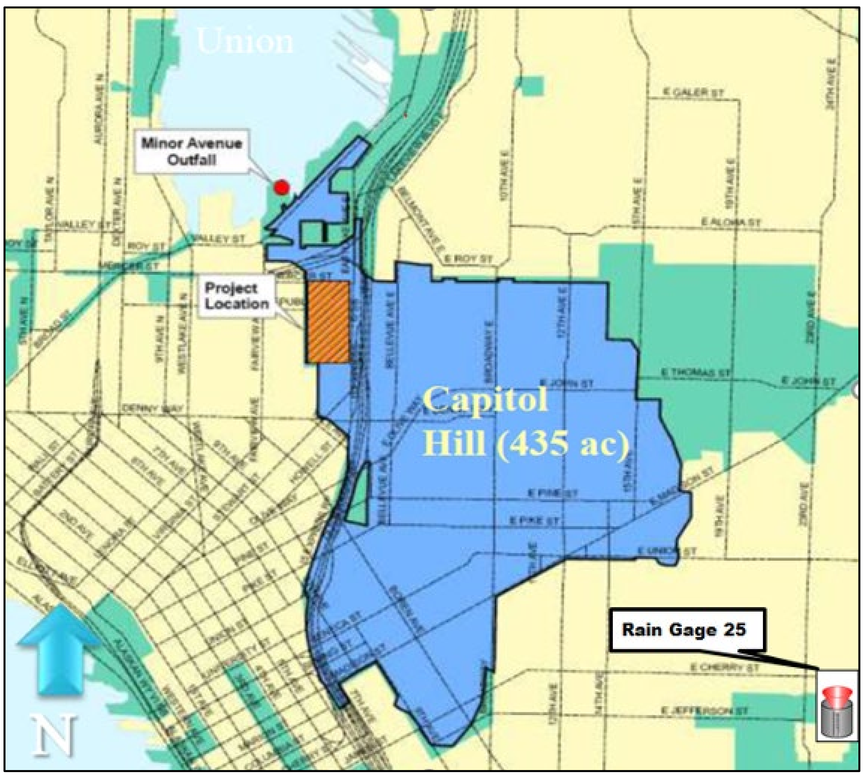


Figure 1. Vicinity Map Showing the Location of the Project Drainage Area, Project Location, Rain Gauge Location, and Outfall Location.

Although the CHWQP is physically located in the Cascade neighborhood, it treats flows from the Minor Avenue sub-basin which flows from the Capitol Hill neighborhood. The Minor Avenue sub-basin is the largest drainage basin that discharges to Lake Union. The sub-basin is 435 acres of dense, highly developed land with a higher-than-average stormwater pollutant load.

The Minor Avenue sub-basin was prioritized as a top candidate for stormwater treatment due to its significant volume of discharge into Lake Union. The basin's high pollutant load and the unique opportunity to meet the retrofit requirements at a lower cost due to a partnership with a private developer also contributed to this prioritization.

Approximately 79 percent of the Minor Avenue sub-basin drains to a dedicated public storm drain, while the remaining 21 percent drains to combined sewers. The system of storm drains in this sub-basin eventually flows to the storm drain that passes through the project site and discharges to Lake Union through the Minor Avenue Outfall at Ward Street and Fairview Avenue North. This storm drain, installed in 1961, is a 48-inch pipe from Stewart Street to John Street and a 72-inch pipe from John Street to the outfall.

A flow splitter located just upstream from each swale is designed to divert the baseflow and stormwater flow from the storm drain up to a predetermined flow rate ranging from 525 to 1000 gallons per minute (gpm) into each swale. Flows exceeding the predetermined inflow rates are diverted back into the existing 72-inch storm drain. Because of the large size of the drainage basin and flow splitters, a small amount of rain falling on Capitol Hill will quickly produce runoff that exceeds the swale's maximum flow limit and result in an "on/off" flow signature.

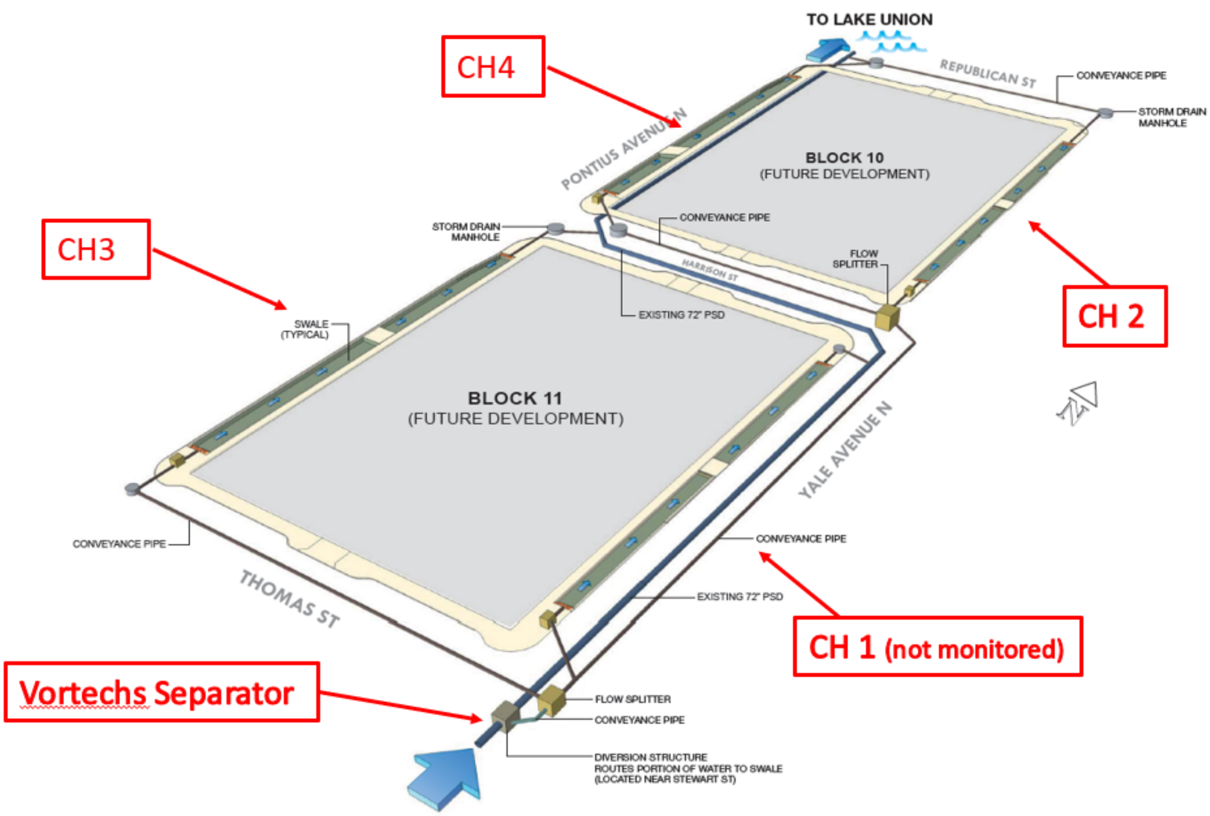


Figure 2. Location of Each Swale Within the Project Boundaries.

At the inlet end of each swale, hydraulic head forces flow in a 12-inch diameter ductile iron pipe (DIP) to rise from a trench drain across the width of the swale and begin to flow down the swale. Approximately every 50 feet down the length of each swale, a broad-crested concrete weir re-disperses the flow across the width of the swale. The four swales have an average bottom width of 10.5 feet and average 264 feet in length.

The BSM layer in each swale is approximately 18-inches thick (Figures 3 and 4) and is densely planted with Carex and Juncus vegetation (Figure 5) that provides contact surfaces and roughness to lower flow velocity and allow suspended solids to settle. The BSM in the two older swales (CH2 and CH4) is composed of approximately 60 percent aggregate and 40 percent compost (60/40) that is produced by Cedar Grove. The mix for the newer swales (CH1 and CH3) was modified to 70 percent aggregate and 30 percent compost (70/30) with the goal of reducing the amount of phosphorus available for export from the compost component. In addition, an 8-inch "polishing layer" is also installed in the newer swales to capture phosphorus that is exported from the compost component of the BSM. This polishing layer is located below the BSM and consists of 90–92 percent ICON-1 (State Sand), 6–7 percent activated alumina, and 2-3 percent iron aggregate by volume (Figures 3 and 4).

Below the BSM (CH2 and CH4) and polishing layer (CH1 and CH3) is a 12-inch thick layer of Type 26 gravel surrounding a 6-inch diameter, slotted, polyvinyl chloride (PVC) underdrain that conveys water passing through the BSM back to the storm drain (Figures 3 and 4). Each swale also has an impermeable liner that prevents water from infiltrating into the native soil through the bottom of vertical walled swale.

Water quality sampling vaults were installed upstream of the inlet and downstream of the outlet at CH2, CH3, and CH4, and conduits were installed to facilitate monitoring. All the monitoring vaults are served with 120 volt (V) electrical power.

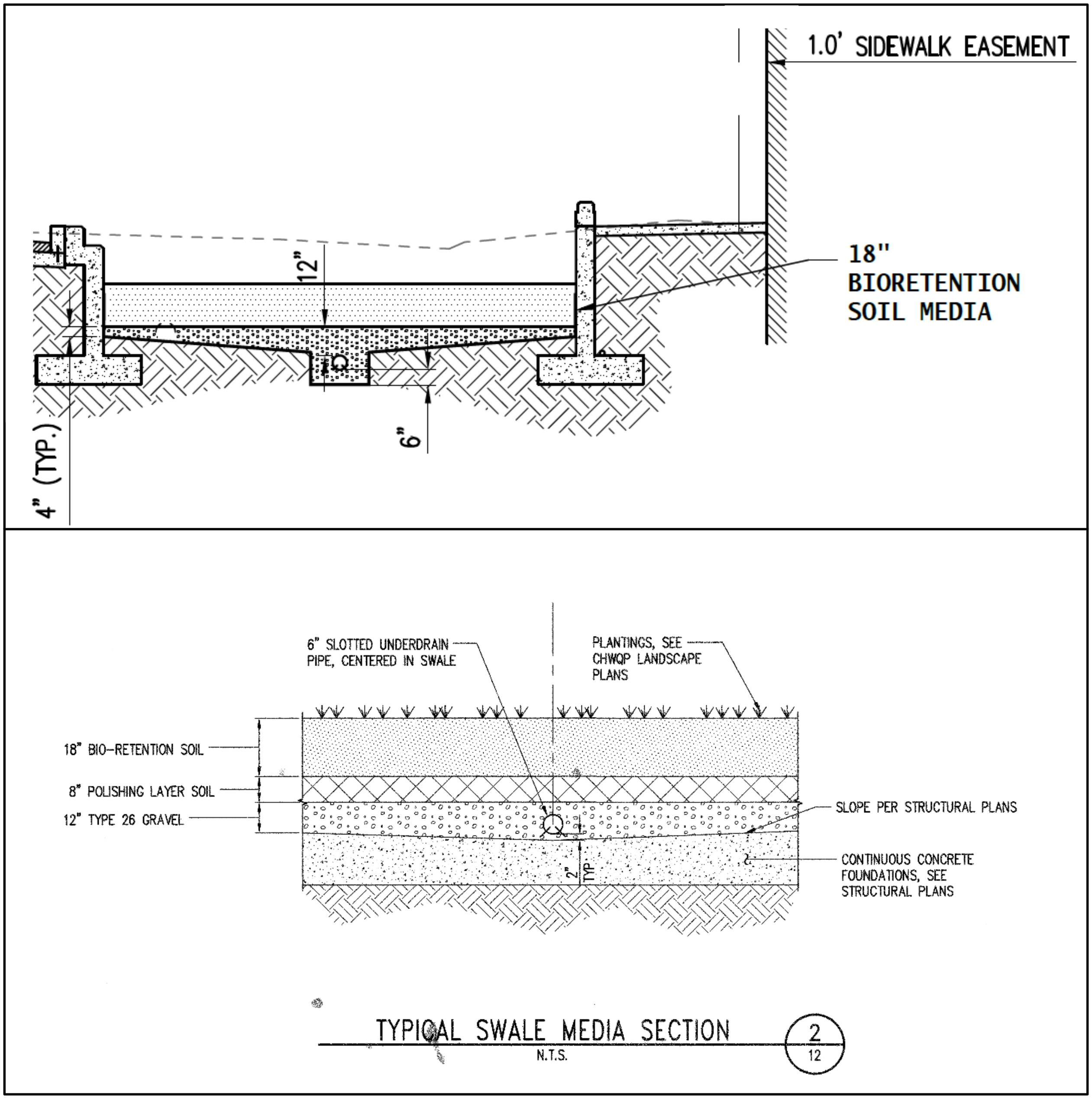
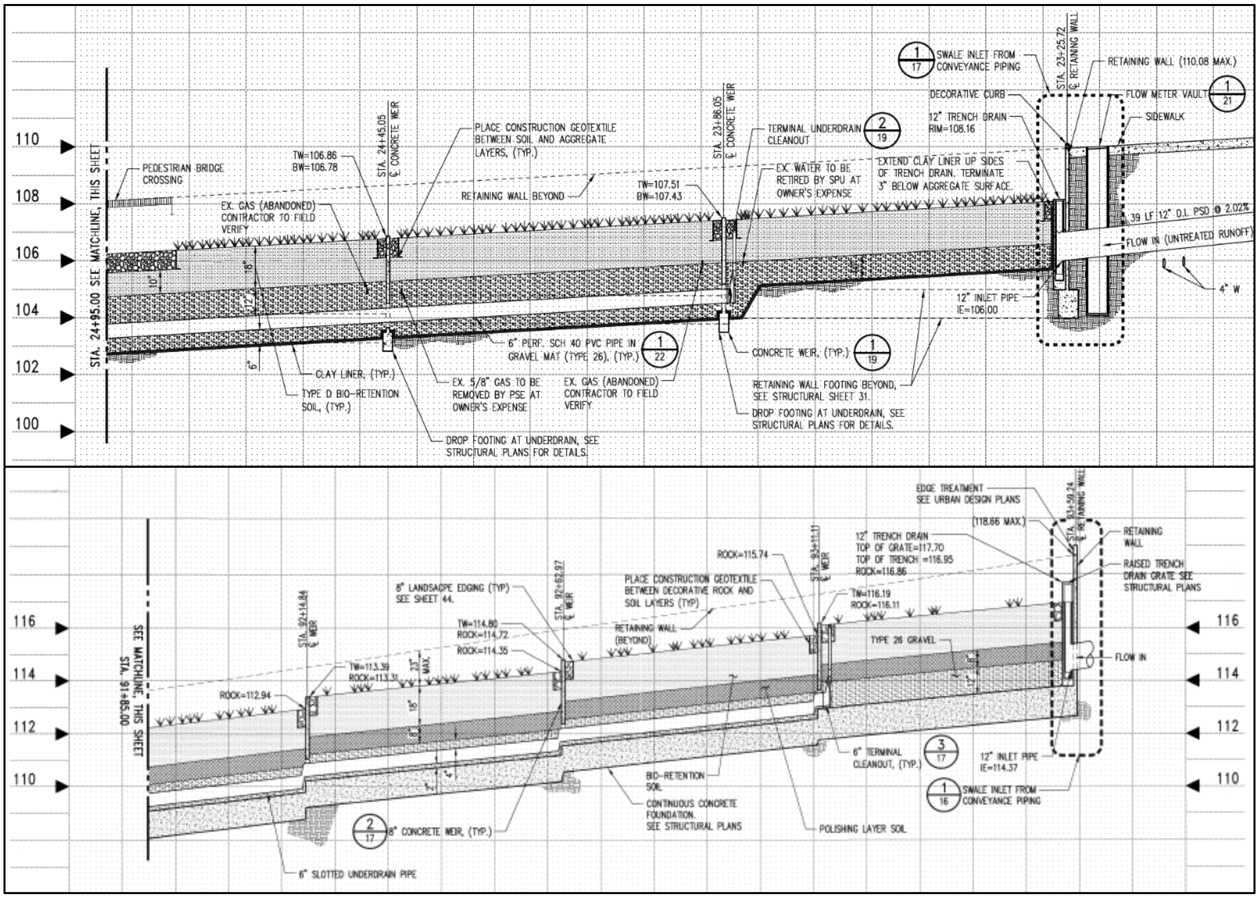


Figure 3. Typical Media Cross Sections CH2 and CH4 (top) and CH3 (bottom).



The CH2 profile is typical of the CH4 profile, so CH4 is not shown here.

Figure 4. CH2 (top) and CH3 (bottom) Profile.

Figure 5. Image of CH2 Looking Downstream (North) from the Top of the Swale.

EXPERIMENTAL DESIGN

Monitoring of the CHWQP was performed to meet the following study objectives:

1. Determine the long-term water quality treatment performance of CH2 (60/40 BSM).

2. Assess the performance of two swales of the same age (CH2 and CH4), with one receiving only storm flow (CH2) and one receiving storm and winter baseflow (CH4).

3. Compare the performance of a swale with a polishing layer (CH3) to swales without polishing layers (CH2 and CH4).

The project Sampling and Analysis plan (SAP) (Appendix A) provides a detailed explanation of the monitoring procedures that were used to meet these study objectives; these procedures are briefly summarized in Table 1 and described herein.

Table 1. CHWQP Swale Monitoring Information.

Swale	Year Built	Baseflow?	BSM	Period Monitored	Monitoring Explanation
CH1	2018	yes	70/30+ polish	NA	NA
CH2	2015	no	60/40	10/1/15–7/8/16 and 12/14/19–12/14/20	WY2016 monitoring was to assess initial performance of system. WY2020 monitoring was for comparison with the other swales
CH3	2018	yes	70/30+ polish	12/14/19–12/14/20	Assess performance of polishing layer
CH4	2015	yes	60/40	12/14/19–12/14/20	Assess performance of saturated system

NA = not applicable, swale was not monitored.

Each swale had one influent monitoring station and two effluent monitoring stations, one station for surface flow and one station for underdrain flow. Flow rate was measured at the influent stations in a 12-inch ductile iron pipe which was designed to conduct pressurized flows. A MACE Doppler ultrasonic insert sensor was tapped into the top of the pipe and connected to a MACE FloSeries3 FloPro XCi data logger. Data from this data logger were transferred to a Campbell Scientific Inc. (CSI) CR1000 datalogger which stored and transmitted the flow data wirelessly via a CSI CELL210 modem.

The CSI CR1000 datalogger was also programmed to control an Isco 6712 automated sampler. Flow paced sampling was used during this study and storm selection and sampling criteria were identical to those used in the Washington State Technology Assessment Protocol – Ecology

(TAPE) program for certifying the performance of emerging stormwater treatment devices (Ecology 2011).

The effluent stations for CH2 and CH3 were configured in the same manner. Swale surface flow was routed into a 12-inch diameter pipe in which a Thel-mar volumetric pipe weir was installed. A CSI CS-451L pressure transducer connected to a CR1000 datalogger was used to measure water level behind the weir. The datalogger was programmed to convert water level to flow using a weir equation. Underdrain flow was discharged from a 6-inch pipe which would surcharge during the peaks of events. This made using a pipe weir for flow measurement infeasible, instead a custom built 90-degree v-notch weir box, with internal baffles for calming flows, was constructed and attached to the end of the 6-inch underdrain pipe. A second CSI CS-451L pressure transducer was placed in the weir box to measure water level behind the weir. The CR1000 datalogger described above was also programmed to convert these water level measurements to flow using a weir equation. This datalogger also controls two Isco 6712 automated samplers, one for the underdrain flow and one for the surface flow.

The effluent station for CH4 was configured differently. Due to the site layout, it was only feasible to measure underdrain flows and total flows; surface flows could not be independently measured. Here a Hach FL901 datalogger with two Flo-Tote 3 electromagnetic velocity sensors was installed. One sensor was placed in the underdrain pipe to measure underdrain flow, the second was placed in the outflow pipe capturing total flows. Surface flow was calculated as the difference of underdrain and total flows. The sensors were interfaced with a CSI CR1000 datalogger which was also programed to control two Isco 6712 automated samplers.

Table 2 presents the station ID's and sample collection goals for each station. Due to the Covid-19 pandemic in 2020, sampling was interrupted and only six of the nine events were sampled (sample dates are presented in the results section). In addition, the final rinsate blank was not collected. Further discussion of the data quality is presented in the *Results* section. Samples were analyzed for the parameters listed in Table 3. Total Petroleum hydrocarbons (TPH) and fecal coliform bacteria were analyzed by grab sample, the remaining parameters were analyzed from the automated volume-weighted composite samples.

Table 2. Stormwater Sample Collection Goal Per One Year of Monitoring.

Station ID	Station Location	Stormwater Composite Samples per Station	Stormwater Grab Samples per Station	Number of Field QC Samples	
				Tubing Blank (FBS)	Duplicate (FSS)
CH2-In	Inlet Trench Drain	9	≤9	2	1
CH2-SurOut	Surface Outflow–12″ DIP	9	≤9	2	1
CH2-UndOut	Underdrain Outflow–6″ PVC	9	≤9	2	1
CH3-In	Inlet Trench Drain	9	≤9	2	1
CH3-SurOut	Surface Outflow–12″ DIP	9	≤9	2	1
CH3-UndOut	Underdrain Outflow–6″ PVC	9	≤9	2	1
CH4-In	Inlet Trench Drain	9	≤9	2	1
CH4-SurOut	Surface Outflow–12″ DIP	9	≤9	2	1
CH4-UndOut	Underdrain Outflow–6″ PVC	9	≤9	2	1

Table 3. Stormwater Analytes, Methods, and Reporting Limits (RL).

Analyte Group	Analyte	RL	Units	Lab Method
Conventionals	Hardness	1.0	mg/L CaCO3	SM2540-D
	Dissolved Organic Carbon	1.0	mg/L	SM5310-B
	Total Suspended Solids (TSS)	1.0	mg/L	SM2540-D
Metals	Copper–Dissolved	0.5	ug/L	EPA200.8
	Copper–Total	5.0	ug/L	EPA200.8
	Zinc–Dissolved	4.0	ug/L	EPA200.8
	Zinc–Total	4.0	ug/L	EPA200.8
	Lead–Total	1.0	ug/L	EPA200.8
	Lead–Dissolved	0.01	ug/L	EPA200.8
Nutrients	Ortho-Phosphate	0.004	mg-P/L	SM4500-PE
	Phosphorus, Total (TP)	0.016	mg-P/L	SM4500-P
	Nitrate-Nitrite (N03-N02)	0.01	mg-P/L	EPA 353.2
Petroleum Hydrocarbons	Semivolatiles (NWTPH-Dx)	0.01	mg/L	NWTPH-Dx
Bacteria	Fecal Coliform	1	cfu/100mL	SM9222-D

RESULTS

This section presents the results from the hydrologic and water quality monitoring of CH2, CH3, and CH4 at the CHWQP. The first section presents a quality assessment of the hydrologic data followed by the associated results. Subsequently, the results from the water quality monitoring are reported. Supporting information is provided in the following appendices to this document:

- Appendix B: laboratory reports
- Appendix C: Individual Storm Reports (ISRs) that document sampled events
- Appendix D: field forms
- Appendix E: hydrologic and sampling summary statistics for sampled events

Because total suspended solids (TSS), total phosphorus (TP), dissolved copper, dissolved zinc, and nitrate+nitrite performance are of the most interest to the region, the results presented in this section only focus on this subset of parameters.

HYDROLOGIC DATA QUALITY

As mentioned in the Methods section, nine separate flow measurement devices were used in this study, one device at each inlet and both outlets of the three monitored swales. Prior to deployment all level sensors (stand-alone transducers [CH2 and CH3 outlets] and transducers integrated in the Flo-Tote 3 velocity sensor [CH4 outlets]) were checked for precision and bias in the lab by submersing the sensors in a graduated cylinder and raising the water level by known increments to assess accuracy (bias) and leaving the sensors submerged in covered graduated cylinders overnight to assess drift (precision). The results from this testing are presented in Table 4. As is apparent, all the level sensors met the method quality objectives (MQOs) identified in the project SAP (Appendix A).

Table 4. CHWQP CH2, CH3, and CH4 OUT Pre-Deployment Transducer QA Check.

Station	Sensor Type	Serial #	Date	Precision (%)	Bias (%)
CH2-SurOUT	Campbell CS451-L	20010648	8/17/2015	0.30	0.80
CH2-UndOUT	Campbell CS451-L	20010650	8/17/2015	0.47	-0.08
CH3-SurOUT	Campbell CS451-L	20011691	8/27/2019	0.07	-0.70
CH3-UndOUT	Campbell CS451-L	20011724	8/27/2019	0.72	-0.70
CH4-TotOUT	Hach Flo-Tote 3	213M00428	11/21/2018	0.32	0.27
CH4-UndOUT	Hach Flo-Tote 3	211J00747	11/21/2018	0.17	0.69
MQO (%)	–	–	–	**<5.0**	**<5.0**

MQO = method quality objective from project SAP (Appendix A).

The SAP indicates that the sensors should again be checked in the lab after project completion. However, as of the writing of this report it is unknown if monitoring will continue at the CHWQP; hence, the sensors have not been removed to recheck their precision and bias.

To confirm that the level sensors held calibration in the field, calibration checks were conducted periodically. The CH4-SurOUT and CH4-TotOUT transducers (integrated in the Flo-Tote 3 velocity sensors) could not be field checked because the Flo-Tote sensors were installed approximately 2.5 feet into their respective pipes in a structure that was too small for a person to safely enter. The quality of the data from these sensors was checked qualitatively by comparing flows to the other outlet stations and to CH4-IN (see discussion below).

Table 5 summarizes the results of the field calibrations of the level sensors at CH2-OUT and CH3-OUT. As is apparent, drift in the sensors is very minor and well below the MQO of 5 percent. CH3-SurOUT had the greatest amount of drift between the December 3, 2019 and the January 9, 2020 calibration dates, but all drift was corrected in an Aquarius Continuous Data Management System (Aquarius) during post processing; hence, the error introduced by the drift did not propagate to the final flow data.

Table 5. CHWQP CH2 and CH3 OUT Transducer Field Calibration.

Date	Campaign	CH2–SurOUT	CH2–UndOUT	CH3–SurOUT	CH3–UndOUT
10/16/2016	2017	1.212	0.505	–	–
3/16/2017	2017	1.212	0.495	–	–
3/16/2017	2017	1.187	0.495	–	–
5/13/2017	2017	1.178	0.495	–	–
7/26/2017	2017	1.178	0.491	–	–
12/3/2019	2020	1.187	0.493	1.363	0.491
1/9/2020	2020	1.177	0.493	1.332	0.491
9/17/2020	2020	1.172	0.481	1.329	0.487
Average Error (ft)	**–**	**0.006**	**0.003**	**0.017**	**0.002**
Average RPD (%)	**–**	**0.5**	**0.7**	**1.3**	**0.4**
MQO (%)	**–**	**<5**	**<5**	**<5**	**<5**

RPD = relative percent difference, MQO = method quality objective from project SAP (Appendix A).

The inlet stations did not have pressure transducers because the inlet pipes were pressurized and always flowed full. Instead, the Mace FloPro XCi velocity sensors recorded velocity alone. The calibration of these sensors could only be checked by confirming they were reading zero when there was no flow. At no point were the sensors recording flow when none was present in the swales. However, it should be noted that the inlet sensors at CH3-IN and CH4-IN would frequently become clogged with floating debris near the top of the pipe and stop recording velocity. This resulted in frequent data loss during and between rain events. This phenomenon did not occur at CH2-IN presumably because this station did not receive baseflow and thus leaves and other debris could fall off the sensor head when velocity slowed on the falling limb. Due to the sensor occlusion issue the inlet flow data were only used for targeted sampling event pacing, in assessing load reductions (discussed in the *Water Quality Results* section), and for QA purposes (relative comparisons among stations when all sensors were working properly). When sensor occlusion was not occurring, the data appeared to be of a high quality, tracking with the other inlet station's hydrograph timing, form, and intensity (Figure 6).

Similar to the inlet velocity sensors, flow data from the CH4-OUT velocity sensors were assessed by comparing the hydrographs qualitatively in Aquarius. Figure 7 provides the same example hydrograph as Figure 6 (January 31, 2020), but this time for the swale effluent stations instead of the influent. As is apparent, when comparing the stations to one another, the CH4-OUT flows are consistent with what would be expected given the relationship to inflow and outflow from the other stations. This relationship held true for the entire 2020 Campaign.

Overall, the flow data from all of the outlet stations and the CH2-IN station are graded as 'Good' whereas the flow data from the CH3-IN and CH4-IN stations are graded as 'Poor' and only suitable for evaluating specific portions of the hydrograph.

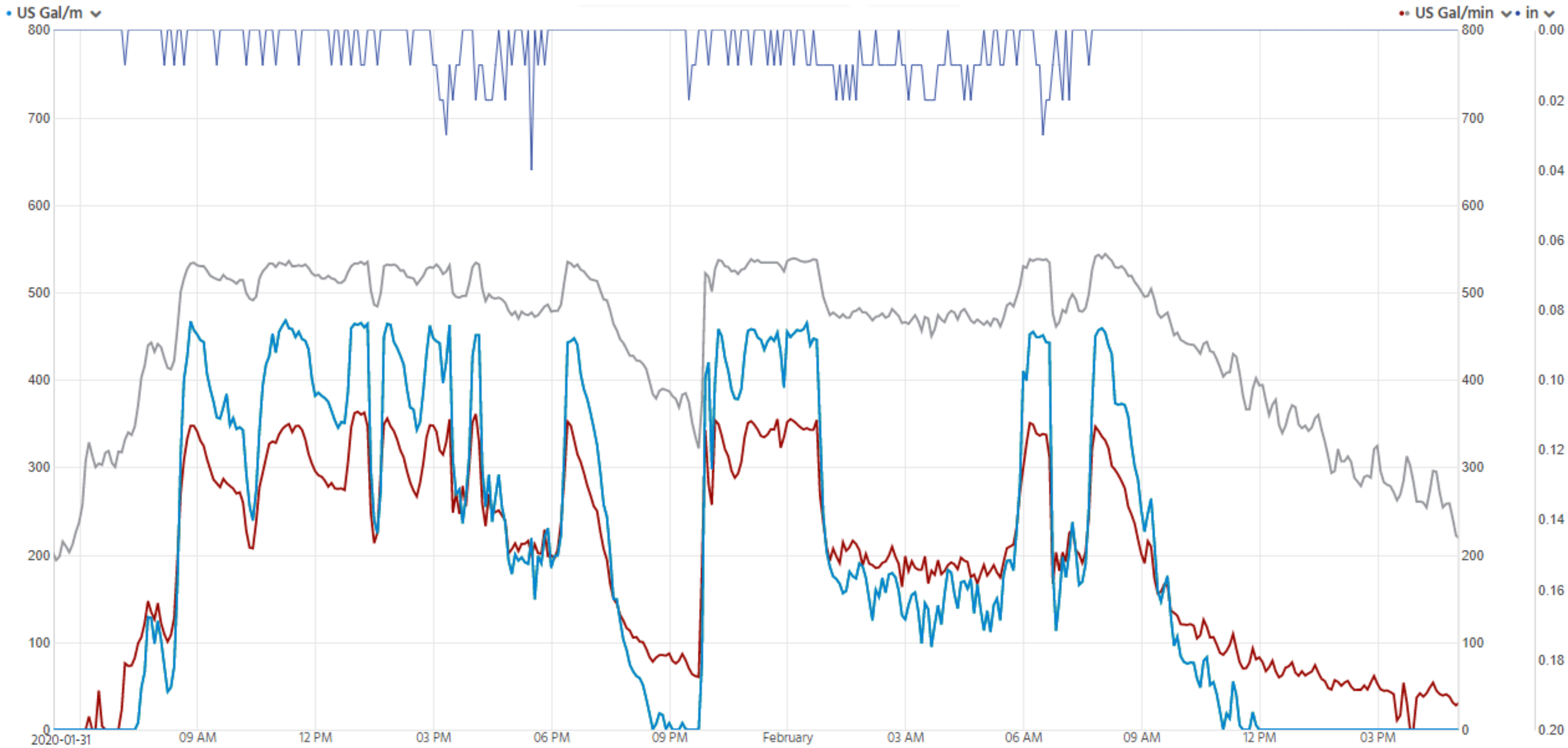


Figure 6. Example Event (January 31, 2020) Showing Influent Hydrographs for CH2-IN (blue), CH3-IN (red), and CH4-IN (grey).

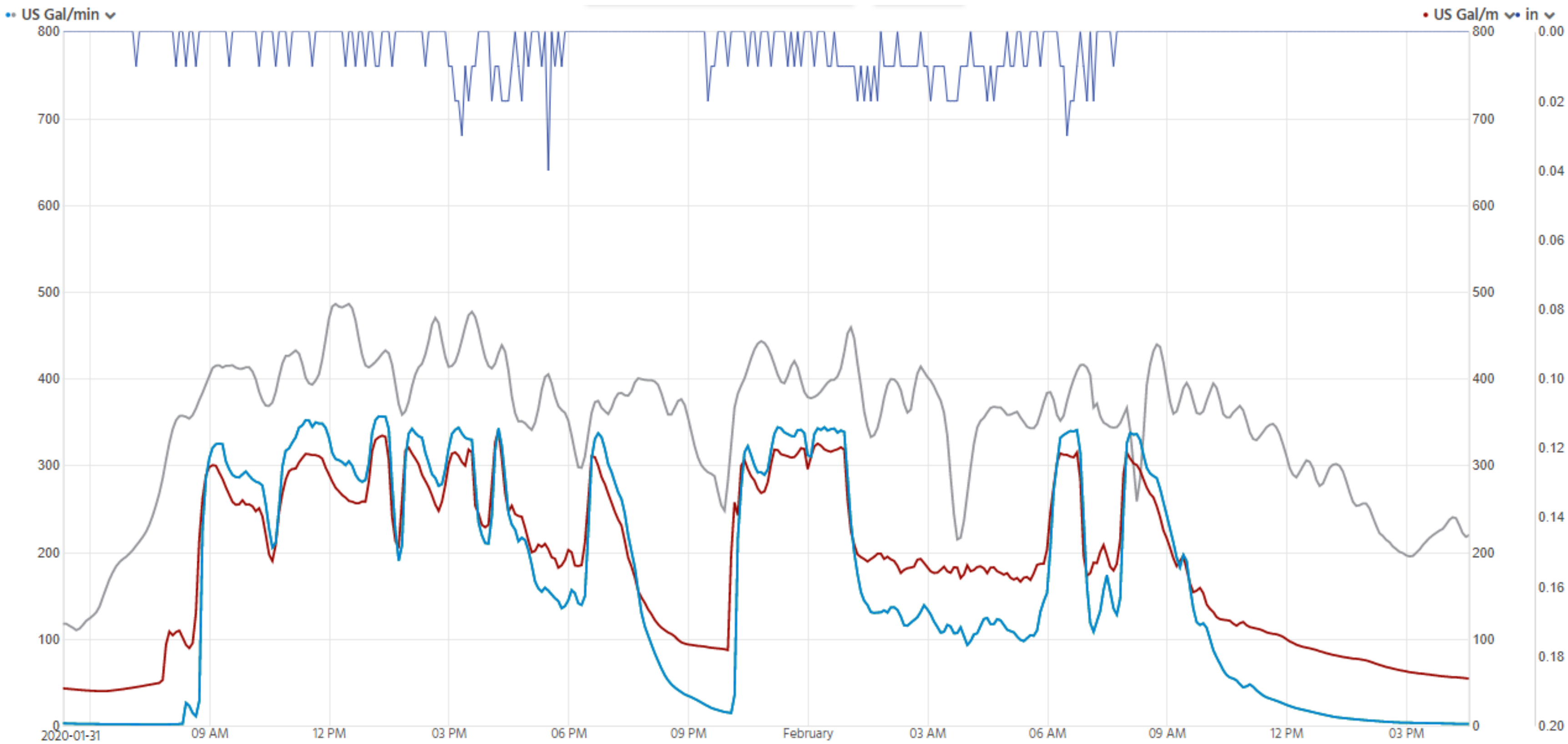


Figure 7. Example Event (January 31, 2020) Showing Total Outflow (sum of surface and underdrain flow) Hydrographs for CH2-IN (blue), CH3-IN (red), and CH4-IN (grey).

HYDROLOGIC MONITORING RESULTS

Annual Treated Volume

Flow rates were monitored at each of the three swales (9 stations) from December 14, 2019 to December 14, 2020 (2020 Campaign). A previous monitoring effort at CH2 was conducted from October 1, 2015 to July 8, 2016 (2016 Campaign). Table 4 presents the treated volume results (as measured at the outlet stations) from the 2020 Campaign when all three swales were being monitored simultaneously. The performance of CH1, the one unmonitored swale, was assumed to be equivalent to CH3, as they had similar designs, hydrology, and were constructed at the same time.

In total, the CHWQP was estimated to treat 91.2 million gallons (Mgal) per year during the 2020 Campaign (Table 6). The facility was initially designed to treat 153 Mgal per year and consequently appears to be receiving 40 percent less water relative to this target. Of the 91.2 Mgal treated, 49.0 was treated via media filtration (underdrain flow) and 42.2 Mgal was treated via swale flow (surface flow) (Table 6). This roughly even split between surface flow (46 percent) and underdrain flow (54 percent) was not uniform across the swales. CH3, the newest of the monitored swales, had only 18 percent surface flow an 82 percent underdrain flow (Table 6). During the one year it was monitored (2020 Campaign) CH4 received 39.2 Mgal more than CH2 and CH3 combined. Because it went online at the same time as CH2 (October 12, 2015), and has been receiving most of the flow, it has clogged more rapidly than the other swales. As these systems clog more water is routed to the surface pathway. During the 2020 Campaign 77 percent of the flow treated by CH4 was via the surface pathway and only 23 percent via the underdrain pathway (Table 6). More evidence of clogging of the surface pathway with time can be seen in Table 7. After CH2 was put online on October 12, 2015, monitoring indicated 39 percent of the flow was treated via the surface pathway and 61 percent via the underdrain pathway (Table 7). During the 2020 Campaign treatment via the surface flow path increased by 10 percent to 49 percent, while treatment via the underdrain pathway decreased 10 percent to 51 percent (Table 7). The ramifications of the these changing treatment pathway with time are discussed in the *Water Quality Data Results* section.

Table 6. CHWQP Monitored Swale Treated Volumes During 2020 Campaign.							
Swale	**Monitoring Period**	**RG25 Rain Total (in)[b]**	**Under-drain Vol (MGal)**	**Percent Underdrain Flow (of Total Treated Flow)**	**Surface Flow Vol (MGal)**	**Percent Surface Flow (of Total Treated Flow)**	**Total Treated Flow Vol (MGal)**
CH1 (estimated)[a]	Not monitored	41.62	17.8	82%	3.8	18%	21.6
CH2	12/14/19–12/14/20	41.62	4.5	51%	4.3	49%	8.8
CH3	12/14/19–12/14/20	41.62	17.8	82%	3.8	18%	21.6
CH4	12/14/19–12/14/20	41.62	8.9	23%	30.3	77%	39.2
Sum	–	–	49.0	54%	42.2	46%	91.2

[a] CH1 was not monitored but was designed to have similar hydraulics to CH3. CH3 results are extrapolated to CH1 here.

[b] Mean annual Seattle rainfall = 35.93 (Western Regional Climate Center: <https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa7488>.

Table 7. CHWQP CH2 Treated Volumes Over Time.							
Swale	**Monitoring Period**	**RG25 Rain total (in)[a]**	**Under-drain Vol (MGal)**	**Percent Underdrain Flow (of Total Treated Flow)**	**Surface Flow Vol (MGal)**	**Percent Surface Flow (of Total Treated Flow)**	**Total Treated Flow Vol (MGal)**
CH2	10/1/16–7/1/17	43.4	4.1	61%	2.6	39%	6.7
CH2	12/14/19–12/14/20	41.62	4.5	51%	4.3	49%	8.8

[a] Mean annual Seattle rainfall = 35.93 (Western Regional Climate Center: <https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa7488>.

Infiltration Rates

To assess the infiltration rate for each swale during the 2020 Campaign, first the maximum measured underdrain flow for the year was converted to an infiltration rate using the media surface area of the swales (Table 8). Using this method, maximum infiltration rates ranged from 9 inches per hour (in/hr) at CH4 to 14.7 in/hr at CH3. The infiltration rate for a new BSM using 60/40 or 70/30 is approximately 24 in/hr and is estimated to have a long-term infiltration rate of 6 in/hr (accounting for anticipated clogging) (SvR 2013). Hence, based on the maximum achieved infiltration rate for the year, it appears that all the swales are infiltrating at an acceptable rate. However, this method only tells us the *maximum achieved* infiltration rate for the entire monitoring year. To get a better understanding of the *average* infiltration performance across the entire year the data were first disaggregated into individual storm events using storm definition criteria from the TAPE program (Ecology 2011). The events with no surface flow were then removed from the dataset because the objective was to only include data characteristic of saturated conditions when there was standing water across the entire swale.

The peak underdrain flows for each of these events were then averaged to estimate the average infiltration rate for the year (Table 8). Based on this analysis, it appears that both CH2 and CH3 are averaging approximately 6 in/hr, while CH4 is averaging only 2 in/hr. This finding is consistent with the fact that CH4 receives more water and thus sediment load compared with CH2 and CH3.

Table 8. CHWQP Estimated Media Infiltration Rates during 2020 Campaign.

Swale	Media Surface Area (ft^2)	Maximum Underdrain Flow (GPM)[a]	Maximum Infiltration Rate (in/hr)[b]	Average Storm Peak Underdrain Flow (GPM)[c]	Average Infiltration Rate (in/hr)[d]
CH2	2772	373	13	173	6.0
CH3	2772	422	14.7	170	5.9
CH4	2772	258	9	58	2.0

[a] Highest underdrain flow rate recorded during the 2020 Campaign.

[b] Maximum infiltration rate recorded during the 2020 Campaign.

[c] Average of the peak underdrain flows for events with surface flow.

[d] Average peak infiltration rate for events with surface flow.

Treated Flow Rates and Hydrograph Relationships

Figure 8 presents the total outflow hydrographs (sum of underdrain and surface flow pathways) from the 2020 Campaign for each of the three monitored swales. It can clearly be seen that CH2 (blue line) only treats storm events, whereas CH3 and CH4 also receive and treat baseflow for about half of the year. Numerous aspects of the hydrograph form indicate the ongoing alterations by operators during the year. For instance, in Figure 8 it is apparent that the amount of baseflow entering CH3 (red line) and CH4 (grey line) steadily increases from February to June, at which point it abruptly decreases to zero only to return at an even higher level during the month of August. On August 26, the baseflow again disappears and then returns to a lesser degree (and intermittently) in October. Such patterns do not happen in natural systems and are the results of operators adjusting upstream weirs. These adjustments affect the total volume treated by the swales, once the final weir settings are optimized the CHWQP will likely treat a total volume closer to the intended design target of 153 Mgal per year.

Table 9 provides maximum treated flow rates for each of the treatment pathways and the sum of both pathways. CH4 treated the highest peak flows (741 GPM) followed by CH2 (530 GPM) and CH3 (468 GPM). Flow rates for CH1 were assumed equivalent to CH3 so that the flow rates could be summed to estimate the maximum treated flow rate for the whole facility during the 2020 Campaign. The result was 2,391 GPM (5.3 CFS) which occurred during a storm event on December 19, 2019. The design flow for the system is 7.2 CFS, this is further evidence that the system is receiving less flow than designed.

Table 9. CHWQP Monitored Swale Treated Flow Rates During 2020 Campaign.

Swale	Monitoring Period	RG25 Max Rainfall Intensity (in/hr)[b]	Underdrain Max Flow (GPM)	Surface Max Flow (GPM)	Total Treated Max Flow (GPM)
CH1 (estimated)[a]	Not monitored	1.2	422	309	468
CH2	12/14/19–12/14/20	1.2	373	397	530
CH3	12/14/19–12/14/20	1.2	422	309	468
CH4	12/14/19–12/14/20	1.2	258	695	741
Average	–	–	369	428	552
Total	–	–	1205[c]	1440[c]	2,391[c]

[a] CH1 was not monitored but was designed to have similar hydraulics to CH3. CH3 results are extrapolated to CH1 here.

[b] Maximum intensity calculated on 5-minute tipping bucket data. This is here for reference only and does not necessarily correspond with when the maximum flows were recorded.

[c] To calculate this value, first all treated flow rates for each time step were summed. This was done first for all measured underdrain flows, then surface flows, then the sum of underdrain and surface flows. The maximum value was then found (December 19, 2019 event) and an estimate of the CH1 flow (assumed equivalent to CH3 flows) was added to the total.

Water Balance

There were only a few periods during the 2020 Campaign when the inlet flow sensors at CH3-IN and CH4-IN were operating correctly, with no dropouts and no issues with sensor occlusion. An example hydrograph for one of these periods (May 7, 2020 to May 20, 2020) is provided in Figure 9 with a comparison of CH4-IN flow along with CH4 total outflow. As is apparent, the flow signals track very closely. During this period, 9.6 percent more water exited the swale than entered. This is generally considered within the range of error for such water balance calculations; hence, it can be assumed that total inflow was equivalent to total outflow for CH4. Similarly, Figure 10 shows another example hydrograph comparing CH3-IN flow and CH3 total outflow from a period when the sensors were operating correctly (May 22, 2020 to June 10, 2020). During this period, it was estimated that the swale exported 6 percent more water than entered, again within the range of error. There were many other brief periods when both the inlet and outlet flow sensors were working correctly at CH3 and CH4, but the hydrograph relationships were similar to what is seen in Figures 9 and 10, so no additional analyses were completed on those data.

The water balance for CH2 was different because this swale did not receive baseflow. Consequently, the BSM in the system tended to act more like a sponge, soaking up flows and then losing water to evapotranspiration between events. An example section of hydrograph for this swale is provided in Figure 11. For the 2016 Campaign, water loss in CH2 was estimated at 28 percent. For the 2020 Campaign, the loss was estimated to be 17 percent. This loss is accounted for in the load reduction calculations in the *Water Quality Results* section.

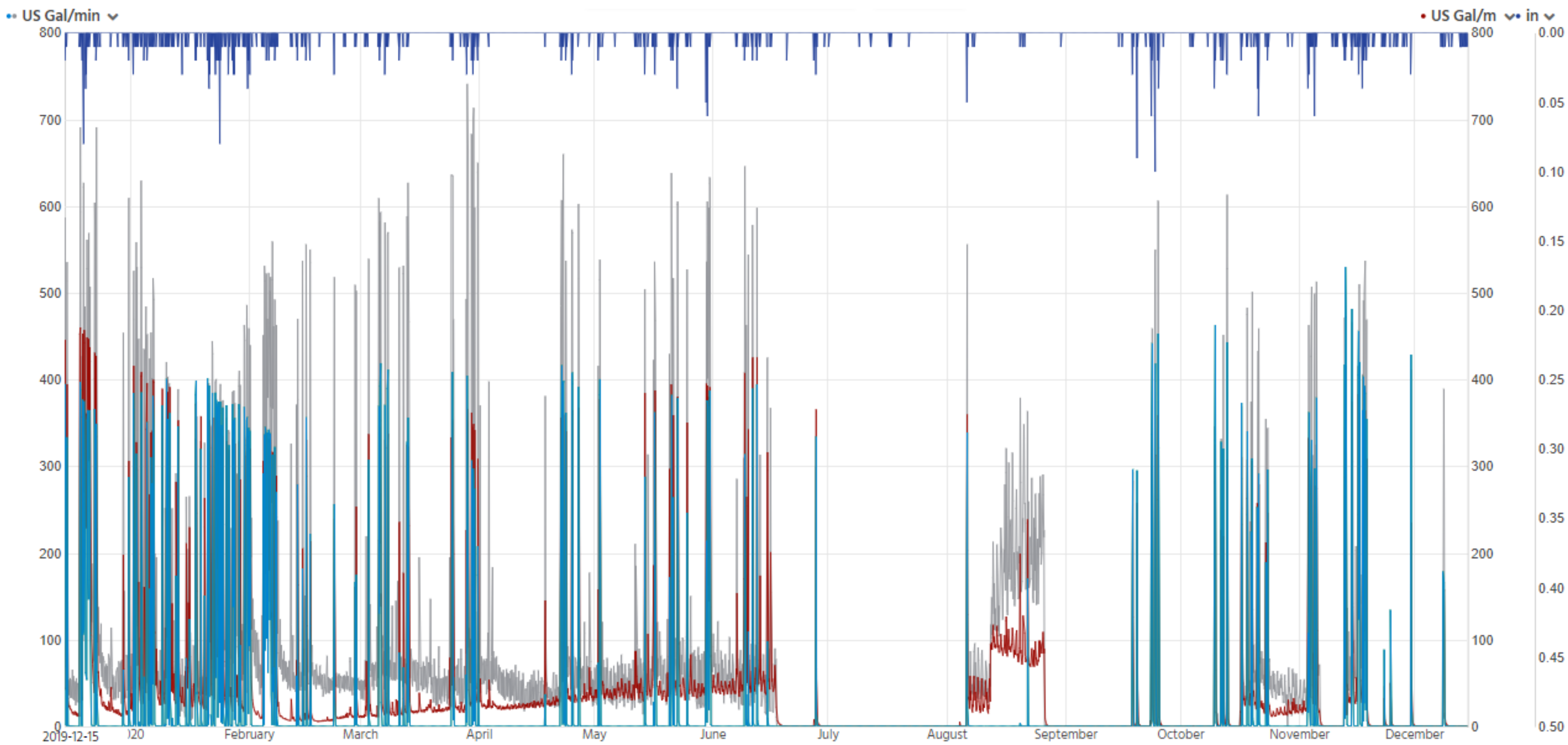


Figure 8. Total Treated Outflow from CH2 (blue), CH3 (red), and CH4 (grey)–2020 Monitoring Period.

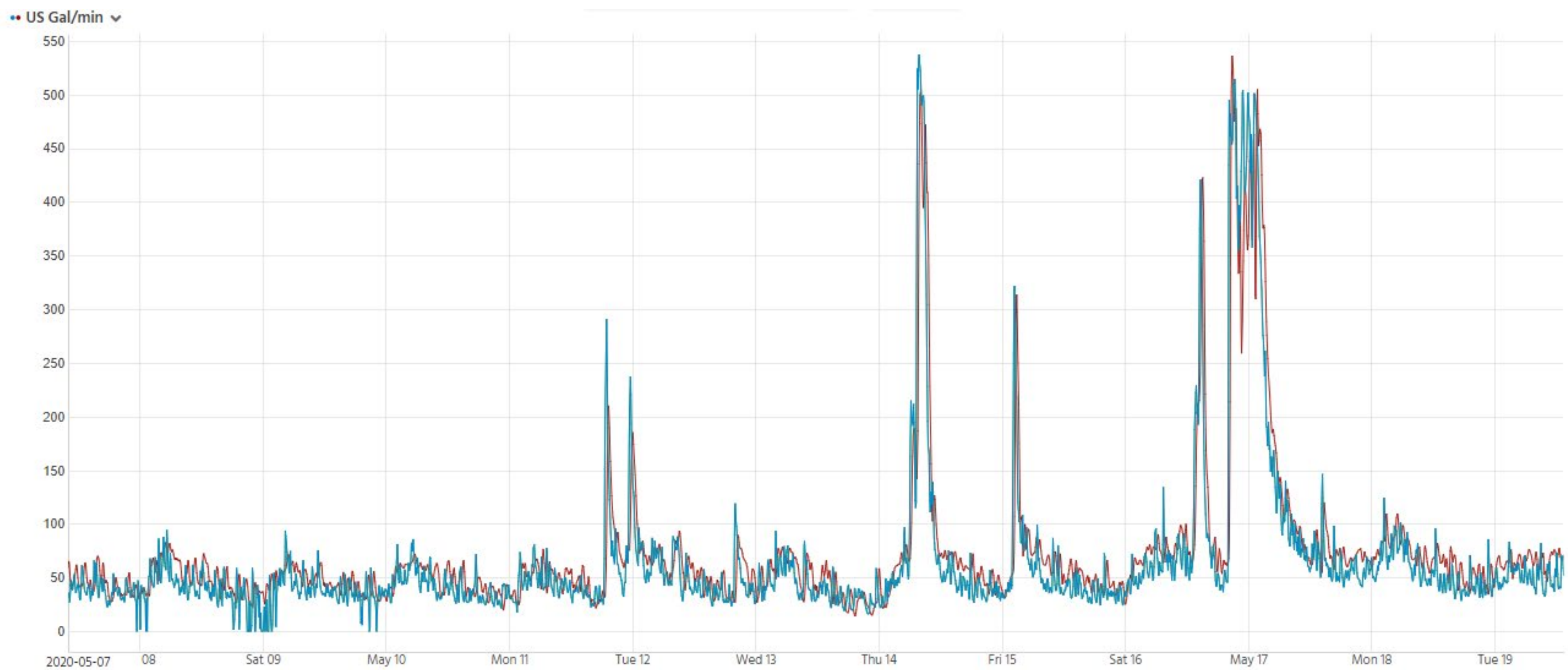


Figure 9. Example CH4 Hydrograph (May 7, 2020–May 19, 2020) for CH4-IN (blue), and CH4 Total Outflow (red).

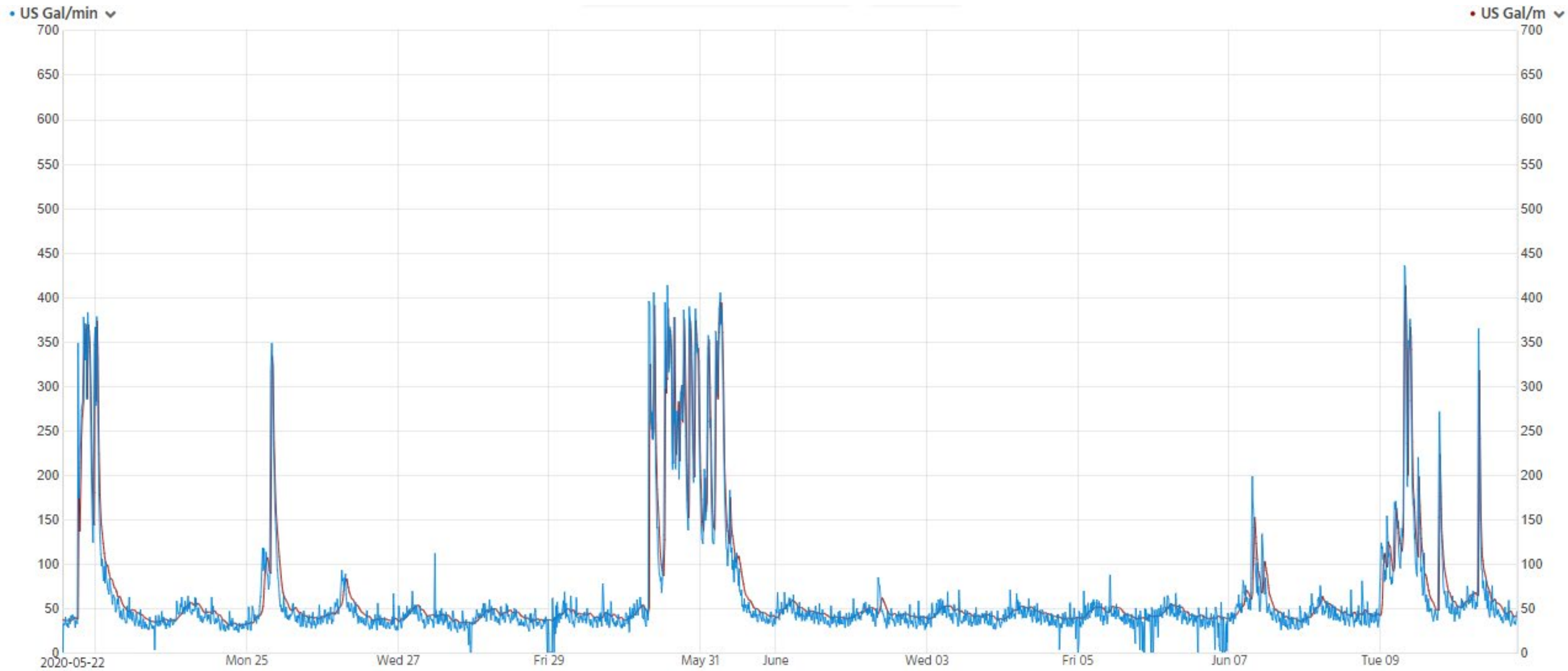


Figure 10. Example CH3 Hydrograph (May 22, 2020–June 10, 2020) for CH3-IN (blue), and CH3 Total Outflow (red).

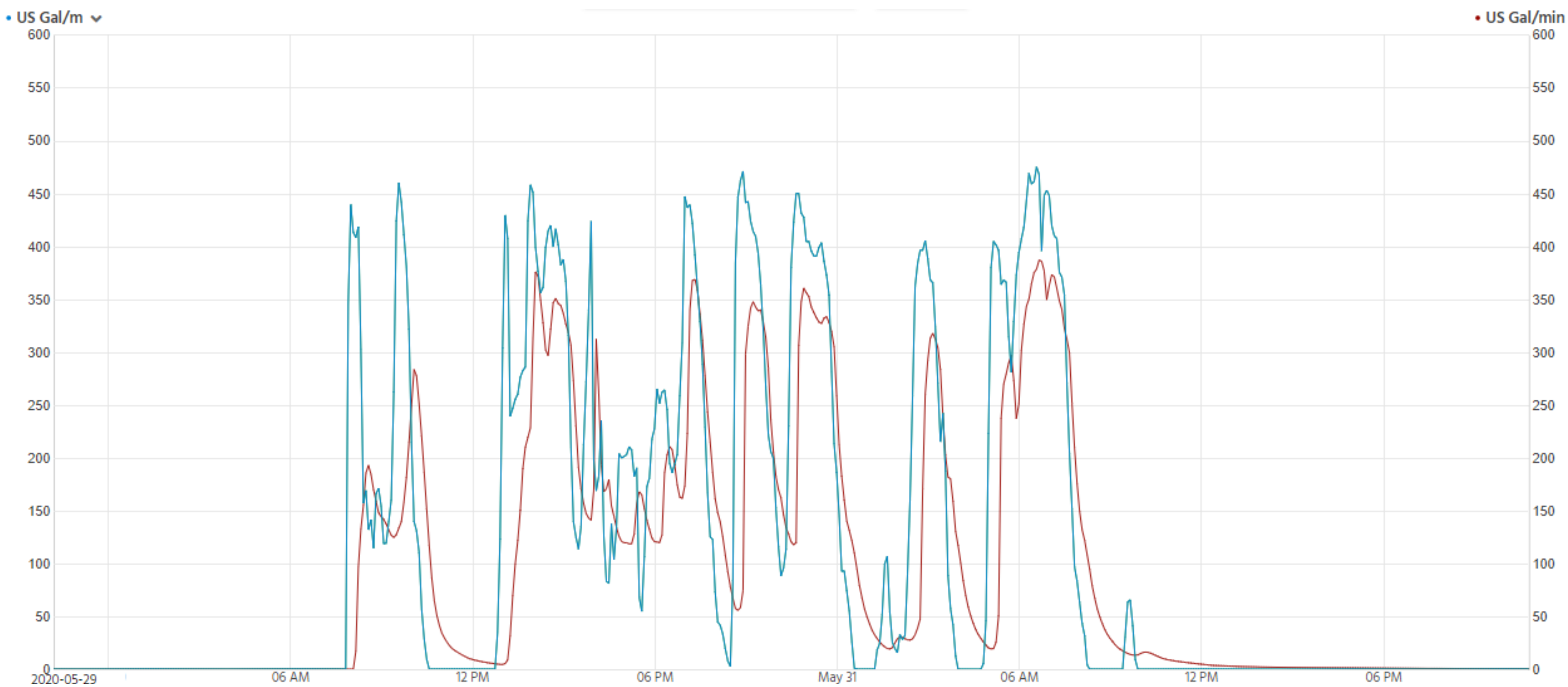


Figure 11. Example CH2 Hydrograph (May 29, 2020 event) for CH2-IN (blue), and CH2 Total Outflow (red).

WATER QUALITY DATA QUALITY

This section presents a data quality review for the 1,058 water quality analytical results from the 2020 Campaign. It specifically summarizes all relevant data concerns and qualifications identified in laboratory reports from the monitoring (Appendix B). In addition, field duplicate and rinsate blanks samples were reviewed against MQOs from the SAP by Herrera; results from this review are also summarized below. A data quality review of water quality analytical results from the 2016 Campaign was conducted separately by SPU.

Custody, Preservation, Holding Times, and Completeness—Acceptable

The samples were properly preserved, and sample custody was maintained from sample collection to receipt at the laboratory. Samples were analyzed within the required method holding times. The laboratory reports were complete and contained results for all samples and tests requested on the chain-of-custody (COC) forms.

Laboratory Quality Assurance—Acceptable with Qualification

The following samples were flagged by the laboratory as estimates because the results were below laboratory reporting limits.

Table 10. Flagged Estimates.

Date Collected	Lab SDG	Sample Location	Parameter	Reason for Qualification	Flag
1/10/20	20A0143	CH4-UNDOUT CH3-UNDOUT	Dissolved Lead	Results below RL	J
1/28/20	20A0362	CH3-UNDOUT	Dissolved Lead	Results below RL	J

Rinsate Blanks—Acceptable with Qualification

Rinsate blanks samples were analyzed for all parameters. Parameter concentrations exceeding the reporting limit were detected in a total of 14 rinsate blanks. However, no data were qualified for a specific parameter if the concentration in the rinsate blank was detected at less than the reporting limit. Concentrations of total copper, zinc, phosphorus, and nitrate +nitrite were detected above this threshold in rinsate blanks from the following stations: CH2-IN, CH2-SUROUT, CH2-UNDOUT, CH4-UNDOUT, CH3-IN and CH3-SUROUT. As a consequence, all corresponding data from these station exceedances were qualified as estimates (assigned a “J” flag) if the detected concentration were less than 10 times the concentration detected in the rinsate blank, as shown in the table below.

Table 11. Rinsate Blank Samples from CH4-UNDOUT and CH2-SUROUT.					
Date Collected	**Lab SDG**	**Parameter**	**Sample Location**	**Reason for Qualification**	**Flag**
1/10/20	20A0143	Total Copper	CH2-UNDOUT	Rinsate detected above RL	J
1/24/2020	20A0324	Total Copper	CH2-SUROUT	Rinsate detected above RL	J
1/26/20	20A0355				
1/28/20	20A0362				
3/30/20	20C353				
9/23/20	20I0372				
9/23/20	20I0372	Nitrate+Nitrite			
1/10/20	20A0143	Total Copper	CH4-UNDOUT	Rinsate detected above RL	J
1/26/20	20A0355				
1/28/20	20A0362				
3/30/20	20C353				
9/23/20	20I0372				
1/26/20	20A0355	Total Phosphorus			
3/30/20	20C353				

Field Duplicates—Acceptable with Qualification

Field duplicate samples were analyzed for all parameters. The relative percent difference (RPD) was calculated for each parameter where both duplicate values were greater than five times the reporting limit (RL). The difference between duplicate values was calculated if the detected parameter concentration was less than five times the RL in either the sample or the duplicate. With the exceptions noted below, the RPD values or difference values met the control limits established by the laboratory or specified method.

Two results had field duplicate RPD values for specific parameters (total lead and TSS) that exceeded 20 percent and were qualified as estimates, as shown in the table below.

Table 12. Field Duplicate RPD Values that Exceeded 20 Percent.					
Date Collected	**Lab SDG**	**Sample Location**	**Parameter**	**Reason for Qualification**	**Flag**
1/23/20	20A0324	CH2-IN	Total Lead	Exceeded RPD	J
1/23/20	20A0324	CH4-IN	Total Suspended Solids	Exceeded RPD	J

Water Quality Data Results

This section presents the results from the water quality monitoring at the CHWQP for CH2, CH3, and CH4. CH2 was monitored during the 2016 Campaign and then again during the 2020

Campaign; CH3 and CH4 were only monitored during the 2020 Campaign. This section first presents a comparison of pollutant concentration reductions at CH2 during both the 2016 and 2020 Campaigns. Next, a comparison of performance across the swales (both concentration and pollutant load reduction) is provided using only data from the 2020 Campaign. Though results for all the monitored parameters are provided in tabular summaries within this section, the discussion is only focused on the following priority parameters: TSS, TP, dissolve copper, dissolved zinc, and nitrate+nitrite.

2016 vs 2020 CH2 Water Quality Results

Table 13 presents the average influent, surface outlet, and underdrain outlet concentrations for CH2 for all monitored parameters. The purpose of this comparison is to determine if performance at CH2 is changing over time. There are very few studies on the performance of regional treatment facilities and none, that we are aware of, which have addressed long-term performance. CH2 was put online on October 12, 2015 and the first samples were collected on October 25, 2015; hence, data from the 2016 Campaign represent performance of a newly installed system. For the 2020 Campaign, the first samples were collected on January 10, 2020, or 4.3 years after the system went online. A comparison of the two datasets provides insight into how such systems may perform over multiple years of service.

As is apparent in Table 13, dissolved copper removal in the CH2 underdrain appears to decrease over time; despite this decrease, data collected during the 2020 Campaign show the swale can still generally meet the performance target from the TAPE program for this parameter of ≥30 percent removal.

The underdrain also exported total phosphorus and that export appears to increase over the four years of operation. The system is now increasing TP concentrations by 58.4 percent relative to concentrations measured during the 2016 Campaign. This export was the primary motivation for including a polishing layer in CH1 and CH3.

Finally, zinc was also exported from the underdrain of CH2 (Table 13); the source of this zinc was traced to galvanized materials placed near the sample collection points. This was remedied for the CH2-UndOUT station on February 18, 2020 and the subsequent two events did not show a similar export of zinc. CH2 was constructed with the 60/40 BSM which has shown to provide excellent zinc removal in other regional studies of similar BSMs (WSU 2014, Herrera 2015, Herrera 2016); hence, the high values measured at the CH2-UndOUT station are considered erroneous and directly related to the presence of the galvanized materials.

TSS removal in 2016 averaged 68.0 and 94.7 percent for the surface and underdrain flow path, respectively. These values were essentially the same during the 2020 Campaign (62.8 and 96.2 percent, respectively) (Table 13).

Table 13. Average CH2 Influent and Effluent Concentrations and Average Percent Reduction by Parameter from the 2016 and 2020 Campaigns.

Parameter[a]	2016 Campaign			2020 Campaign			2016 Campaign		2020 Campaign	
	CH2-IN Conc.	CH2-SurOUT Conc.	CH2-UndOUT Conc.	CH2-IN Conc.	CH2-SurOUT Conc.	CH2-UndOUT Conc.	CH2-SurOUT % Red[b]	CH2-UndOUT % Red[b]	CH2-SurOUT % Red[b]	CH2-UndOUT % Red[b]
Copper, Total	30.9	19.2	4.5	31.7	18.5	8.7	34.8	84.2	34.8	64.8
Copper, Dissolved	12.2	12	4.5	13.1	10.1	8.4	**-12.1**	**63.5**	**18.4**	**31.5**
Dissolved Organic Carbon	8.3	6.0	4.2	4.7	3.8	5.4	10.2	27.6	18.3	-16.6
Fecal Coliform	9150	8900	1200	7380	4950	1475	2.1	77.8	-4	89
Hardness	36	29	27	29.7	28.1	14.8	13.6	16.7	3.1	4.5
Lead, Total	8.4	3.9	0.4	9.7	4.5	0.5	58.7	95.2	40.6	94.3
Lead, Dissolved	0.6	0.7	0.2	0.5	0.4	0.3	2.5	63.4	19.7	46.5
Nitrate + Nitrite	0.577	0.393	0.700	0.592	0.537	1.867	17.7	-43.2	12.8	-246
Ortho-Phosphate	0.11	0.086	0.284	0.089	0.066	0.353	18.1	-237.2	15.9	-364
TPH-Diesel	0.38	0.18	0.1	0.17	0.13	0.10	25.6	83.5	16	34
TPH-Motor Oil	1.1	0.37	0.2	0.60	0.38	0.20	30.8	84	29	54
Phosphorus, Total	0.288	0.152	0.290	0.254	0.163	0.379	**42.7**	**-10**	**33.2**	**-58.4**
Total Suspended Solids	37.9	11.8	1.2	51.5	17.5	1.7	**68.0**	**94.7**	**62.8**	**96.2**
Zinc, Total	106	68	39	82.2	130.1	135.7[c]	-2	-203	-61.2	-30.6
Zinc, Dissolved	47	44	30	42.1	87.0	123.5[c]	**-67.7**	**-641**	**-30.6**	**-169.2**

[a] Note all concentration units are in mg/L except for metals which are in ug/L and fecal coliform in CFU/100mL.

[b] Percent reductions are calculated on the paired data for each event, then the average is reported here. This results in an accurate estimate of average percent reduction which does not always equate with the percent reduction calculated by comparing the average influent and average effluent concentrations.

[c] CH2-UndOUT zinc concentrations affected by galvanized metal in the weir box. Intake repositioned on Feb 18, 2020, two sampled events afterward showed improvement with effluent concentrations decreasing by an order of magnitude.

Note: 2016 n-values = 9-11. 2020 All n-values = 6.

Bold black text indicates performance meets TAPE standards (Ecology 2011).

Bold red text indicates performance does not meet TAPE standards (Ecology 2011).

Table 14. CHWQP 2020 Mean Concentrations at Each Station

Parameter	Units	CH2-IN	CH2-SurOUT	CH2-UndOUT	CH3-IN	CH3-SurOUT	CH3-UndOUT	CH4-IN	CH4-SurOUT	CH4-UndOUT
Copper, Total	ug/L	31.7	18.5	8.7	29.3	22.1	8.3	27.8	22.3	12.3
Copper, Dissolved	ug/L	13.1	10.1	8.4	13.0	12.2	7.1	13.8	13.4	9.6
Dissolved Organic Carbon	mg/L	4.7	3.8	5.4	4.7	4.3	4.6	5.0	4.7	4.9
Fecal Coliform	CFU/100mL	7380	4950	1475	7100	4000	750	6620	6000	4076
Hardness	mg/L	29.7	28.1	14.8	31.5	28.3	38.1	33.9	34.9	56.7
Lead, Total	ug/L	9.7	4.5	0.5	8.7	4.9	0.4	7.0	4.3	1.7
Lead, Dissolved	ug/L	0.5	0.4	0.3	0.5	0.5	0.1	0.5	0.5	0.3
Nitrate + Nitrite	mg/L	0.592	0.537	1.867	0.683	0.614	1.496	0.808	0.815	1.677
Ortho-Phosphate	mg/L	0.089	0.066	0.353	0.087	0.077	0.018	0.105	0.116	0.123
TPH-Diesel	mg/L	0.17	0.13	0.10	0.19	0.14	0.10	0.17	0.14	0.10
TPH-Motor Oil	mg/L	0.60	0.38	0.20	0.64	0.39	0.20	0.58	0.46	0.22
Phosphorus, Total	mg/L	0.254	0.163	0.379	0.241	0.163	0.055	0.241	0.205	0.172
Solids, Total Suspended	mg/L	51.5	17.5	1.7	48.0	17.2	4.5	43.2	19.3	6.8
Zinc, Total	ug/L	82.2	130.1	135.7[a]	81.6	57.8	6.0	75.6	62.3	29.7
Zinc, Dissolved	ug/L	42.1	87.0	123.5[a]	40.7	36.8	4.4	42.8	38.5	23.6

[a] CH2-UndOUT zinc concentrations affected by galvanized metal in the weir box. Intake repositioned on Feb 18, 2020, two sampled events afterward showed improvement with effluent concentrations decreasing by an order of magnitude.

All n-values equal 6, except for CH3-SurOUT which was sampled for five of the six events due to not enough flow reaching the end of the swale during one of the events.

2020 Pollutant Concentration Results

A primary objective of this study was to compare the water quality performance of CH2 (online for 5 years, 60/40 BSM, only stormflow), CH3 (first year of operation, 70/30 BSM with polishing layer, receives storm and baseflow), and CH4 (online for 5 years, 60/40 BSM, receives storm and baseflow). Table 14 presents the average influent and effluent parameter concentrations for all nine of the stations in the study (n-value = 6 for all stations except CH3-SurOUT, where n=5 due to not enough flow reaching the end of the swale during one of the targeted events). Figures 13 to 17 present boxplots of these same data for TSS, TP, dissolved copper, dissolved zinc, and nitrate+nitrite, respectively. Finally, Table 15 provides average removal efficiencies for each swale and flow path.

All three swales performed well as TSS filters (Figure 12) particularly along the underdrain flowpath where average reductions were all above the performance target from the TAPE program of ≥80 percent removal (Table 15). Along the surface flow path reductions were 62.8, 65.2, and 48.4 percent for CH2, CH3, and CH4, respectively. With the exceptions noted below, CH4 was the worst performing swale, likely due to the constant saturation and excessive pollutant loading relative to the other swales.

Of all the stations only one, CH3-UndOUT, met the performance target from the TAPE program for TP treatment (≥50 percent) (Table 15). As noted above, this swale was designed with a polishing layer to capture phosphorus that is exported from the compost component of the BSM. CH2-UndOUT exported phosphorus (-58.4 percent) while all other swales and pathways exhibited modest TP reductions ranging from 14.5 to 33.2 percent (Figure 13, Table 15). It is notable that CH2-UndOUT is still exporting TP 5 years after construction. This is one of the few datasets in the region which has documented the long-term export potential of BSMs which contain compost.

CH3-UndOUT was the best performing swale/pathway for dissolved copper reduction (mean = 43.9 percent), meeting the TAPE goal of ≥30 percent (Figure 14, Table 15). This indicates that the polishing layer is also effective at copper capture in addition to TP. CH2-UndOUT also met the performance target from the TAPE program of ≥30 percent criterion with a mean removal of 31.5 percent. This was a surprising result as this is the only study which has shown the 60/40 BSM reducing copper to this extent. Typically, dissolved copper is exported from these BSMs (WSU 2014, Herrera 2015, Herrera 2016, Mullane et al. 2015), not reduced. All other swale/flow paths did not retain as much dissolved copper, with one (CH3-SurOUT) exporting a small amount (Table 15).

As mentioned above, dissolved zinc performance at CH2 was impacted by galvanized materials placed near the outlet sampling stations. This is apparent in Figure 15, Table 14, and Table 15. Consequently, only CH3 and CH4 are compared here. CH3-UndOUT exhibited the lowest dissolved zinc concentrations in the study (mean = 4.4 ug/L, Table 14) and, consequently, the highest percent removals (mean = 89.2 percent, Table 15). This was the only station which met the performance target from the TAPE program for dissolved zinc (≥60 percent). The surface flow pathways only reduced dissolved zinc by around 10 percent at CH3 and CH4 (Table 15).

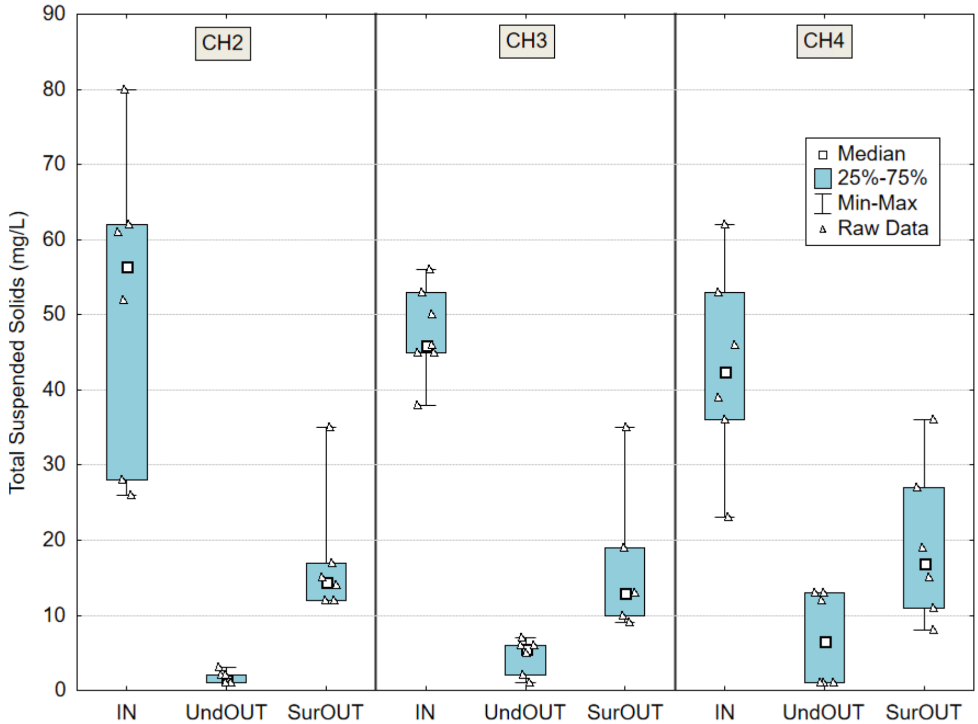


Figure 12. Boxplot of TSS Concentrations from the 2020 Campaign.

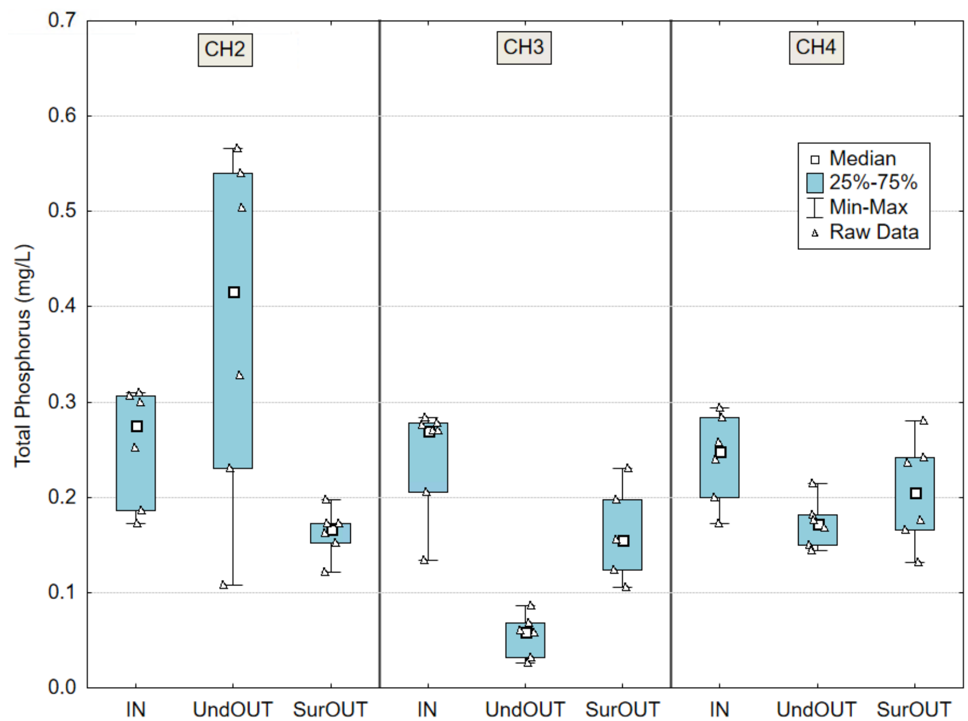


Figure 13. Boxplot of Total Phosphorus Concentrations from the 2020 Campaign.

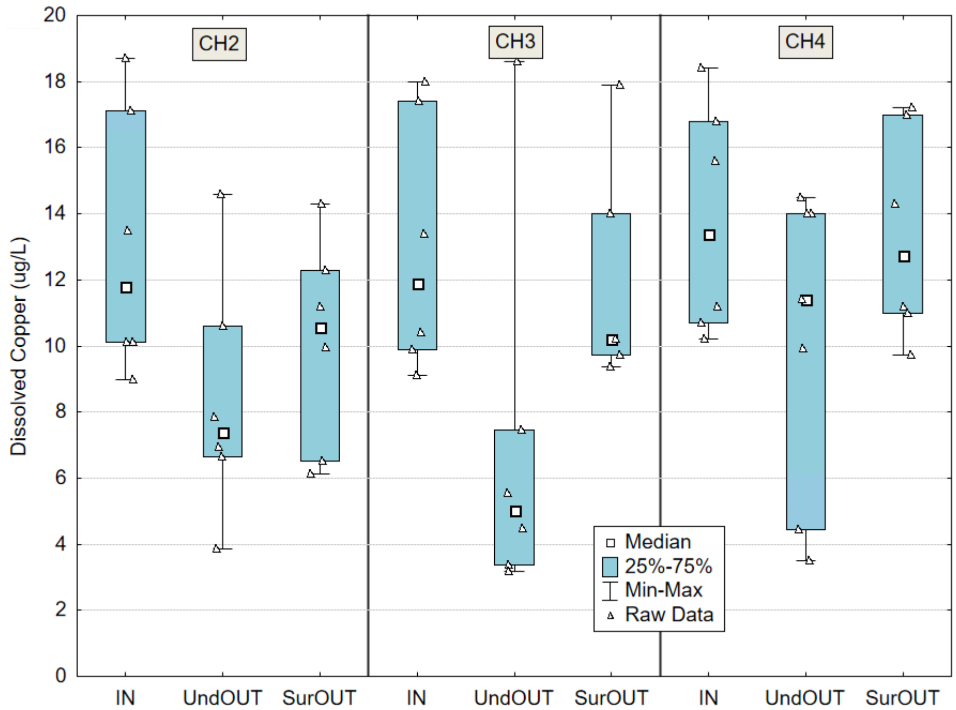


Figure 14. Boxplot of Dissolved Copper Concentrations from the 2020 Campaign.

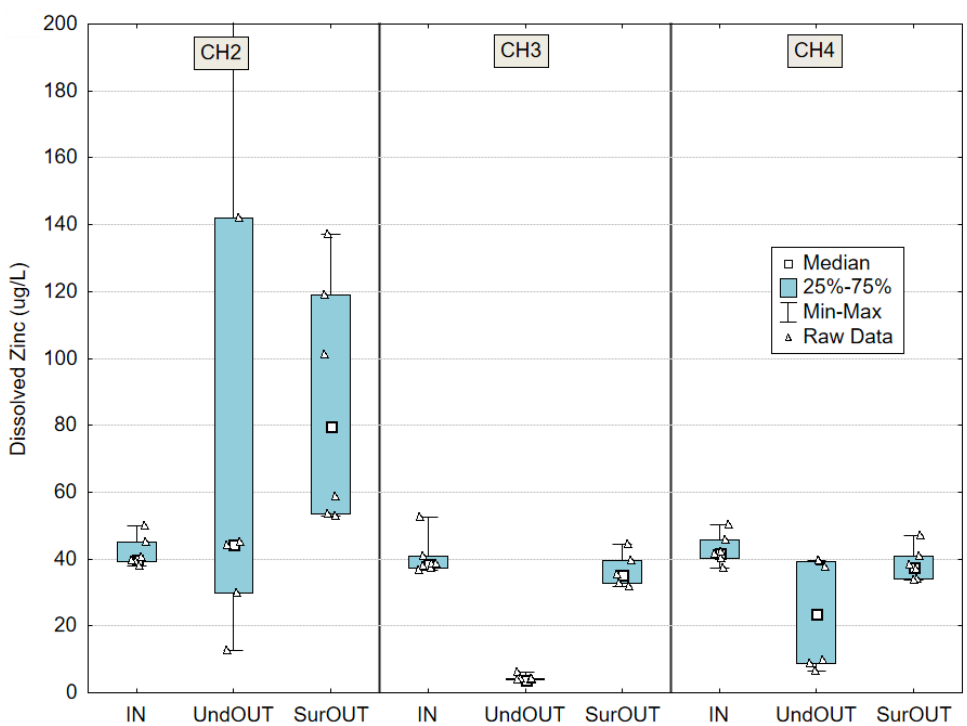


Figure 15. Boxplot of Dissolved Zinc Concentrations from the 2020 Campaign.

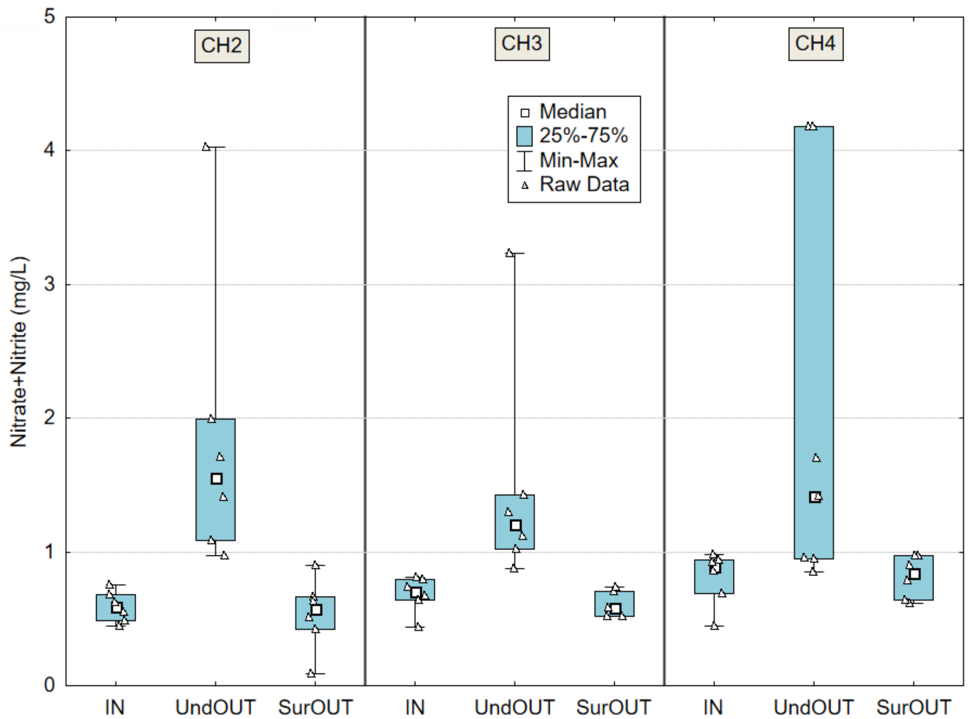


Figure 16. Boxplot of Nitrate+Nitrite Concentrations from the 2020 Campaign.

Nitrate+nitrite was exported in large quantities from all underdrain pathways during the 2020 Campaign (Table 14, Table 15, Figure 16). Note there are no performance targets from the TAPE program for nitrate+nitrite for comparison to these data. When comparing the three swales the surface flow pathways behaved similarly with either a slight retention or export of nitrate+nitrite. The underdrain pathways exported -245.9, -155.9, and -172.3 percent nitrate+nitrite for CH2, CH3, and CH4, respectively. These data indicate that the polishing layer reduces nitrate+nitrite export slightly, however substantial export is still an issue. If nitrate+nitrite reduction is a priority in future projects, designers should consider using an anoxic zone in the underdrain. Such systems have been shown to significantly reduce nitrate+nitrite concentrations in the effluent (Dietz and Claussen 2006, LeFevre et al. 2015).

In summary, from the perspective of concentration reduction, the polishing layer has significantly improved swale performance, with CH3 exhibiting the greatest reductions of TP, dissolved copper, dissolved zinc, and exporting the least amount of nitrate+nitrite. CH4 tended to perform the worst, likely due to prolonged saturation and elevated pollutant mass loading.

Table 15. CHWQP 2020 Pollutant Removal Efficiencies.

Parameter	CH2-SurOUT	CH3-SurOUT	CH4-SurOUT	CH2-UndOUT	CH3-UndOUT	CH4-UndOUT
Copper, Total	34.8	25.6	17.0	64.8	68.1	48.8
Copper, Dissolved	**18.4**	**-0.7**	**2.5**	**31.5**	**43.9**	**28.8**
Dissolved Organic Carbon	18.3	3.3	5.6	-16.6	2.1	3.2
Fecal Coliform	-4	-5	4	89	92	42
Hardness	3.1	16.3	-5.1	45.5	-30.6	-83.0
Lead, Total	40.6	47.0	35.4	94.3	94.3	74.7
Lead, Dissolved	19.7	-4.5	1.4	46.5	74.7	37.6
Nitrate + Nitrite	12.8	15.8	-5.8	-245.9	-155.9	-172.3
Ortho-Phosphate	15.9	2.3	-8.5	-363.6	75.9	-24.2
TPH-Diesel	16	23	6	34	37	30
TPH-Motor Oil	29.0	33.0	-6.0	54.0	51.0	47.0
Phosphorus, Total	**33.2**	**29.4**	**14.5**	**-58.4**	**75.8**	**27.6**
Solids, Total Suspended	**62.8**	**65.2**	**48.4**	**96.2**	**90.6**	**82.8**
Zinc, Total	-61.2	30.0	17.5	-30.6	92.5	56.9
Zinc, Dissolved	**-102.3**	**10.0**	**10.1**	**-169.2**	**89.2**	**41.7**

[a] CH2-UndOUT zinc concentrations affected by galvanized metal in the weir box. Intake repositioned on Feb 18, 2020, two sampled events afterward showed improvement with effluent concentrations decreasing by an order of magnitude.

All n-values equal 6, except for CH3-SurOUT which was sampled for five of the six events.

Bold black text indicates performance meets TAPE standards (Ecology 2011).

Bold red text indicates performance does not meet TAPE standards (Ecology 2011).

2020 Pollutant Loading Results

In addition to comparing the performance of the swales on a concentration basis, it was also an objective of the study to analyze total pollutant load reduction of all four swales combined, as well as pollutant load reduction per swale. Pollutant load reduction by individual pathway cannot be calculated because the pathways are hydraulically connected. Table 16 presents the results from the pollutant load analysis.

The total loads reductions for CH3 and CH4 were calculated by multiplying the average influent concentration by the total volume treated by each swale. As mentioned in the Hydrologic Monitoring Results section, influent and treated effluent volumes were deemed equivalent for these swales, so multiplying the influent concentration by the effluent total volume is a valid method for determining influent load. Next, effluent load was calculated by multiplying the volume-weighted combination of the surface and underdrain effluent concentrations by the total effluent volume. This was subtracted from the influent load to determine the total load retained by the swale. For CH2, this same process was used but the total effluent volume was multiplied by 1.17 to represent the influent volume. This was to account for this swale's 17 percent water loss indicated in the Hydrologic Monitoring Results section.

Because one of the primary goals of this study was to estimate total facility (all four swales) TSS load reduction, the performance of the unmonitored swale (CH1) had to be estimated. Because CH1 and CH3 were built at the same time and shared the same BSM specification, the performance of CH1 was assumed to be equal to CH3 (Table 16).

Once the TSS load reductions for each swale were summed, the result was an annual TSS load reduction of 12,400 kilograms (kg). The design target for the CHWQP was 22,500 kg/yr; hence, the system ended up with a TSS load reduction that was 46 percent below this target, a result consistent with the finding that the facility received 40 percent less stormwater than design expectations.

For most parameters, CH3 retained the greatest pollutant load (Table 16). The primary exception of note was TSS; CH4, which received the greatest volumes of stormwater, removed slightly more TSS on a mass basis during the 2020 Campaign (Table 16). Also, it should be noted that the greatest nitrate+nitrite export came from CH3 (Table 16). This was because the highest underdrain flow path volumes (17.8 Mgal, Table 4)) moved through this swale when compared with the other swale underdrains (CH2-UndOUT = 4.5 Mgal, CH4-UndOUT = 8.9 Mgal). The nitrate+nitrite is sourced from the compost in the BSMs, so the underdrain flow path is the primary export pathway.

Table 16. CHWQP 2020 Load Reductions.						
Parameter	**Units**	**CH1 (est.)[a]**	**CH2[b]**	**CH3**	**CH4**	**All Swales**
Copper, Total	kg/yr	1.52	0.78	1.52	1.14	**4.97**
Copper, Dissolved	kg/yr	0.41	0.20	0.41	0.19	**1.21**
Dissolved Organic Carbon	kg/yr	14	30	14	37	**95**
Fecal Coliform	Billions of CFU/yr	4,724	1,819	4,724	1,568	**12,836**
Hardness	kg/yr	-400	448	-400	-878	**-1231**
Lead, Total	kg/yr	0.61	0.30	0.61	0.50	**2.01**
Lead, Dissolved	kg/yr	0.03	0.01	0.03	0.01	**0.07**
Nitrate + Nitrite	kg/yr	-54	-17	-54	-30	**-155**
Ortho-Phosphate	kg/yr	4.8	-3.6	4.8	-1.9	**4.1**
TPH-Diesel	kg/yr	6	3	6	5	**21**
TPH-Motor Oil	kg/yr	33	14	33	25	**105**
Phosphorus, Total	kg/yr	13.7	0.8	13.7	6	**35**
Solids, Total Suspended	kg/yr	3,374	1,694	3,374	3,958	**12,400[c]**
Zinc, Total	kg/yr	5.4	0.6	5.4	3.1	**12.7**
Zinc, Dissolved	kg/yr	2.5	-0.3	2.5	1.1	**4.3**

[a] CH1 (unmonitored swale) load reductions are assumed equivalent to CH3.

[b] CH2 influent volumes was 17 percent greater than total effluent volume. CH3 and CH4 had equivalent influent and effluent volumes. Average concentrations were multiplied by volumes to determine load reductions.

[c] Design target was for the system to remove 22,500 kg of TSS, the 2020 measured value is 46 percent lower than the target.

Polishing Layer Performance over Time

The final study objective was to determine if the performance of the polishing layer would degrade over time. As shown in Figure 17, the ability of the filter to remove phosphorus does not diminish during the January 10, 2020 to September 23, 2020 monitoring period. The CH3 influent total phosphorus concentrations are also displayed in Figure 17. Percent removal is strongly influenced by influent concentration with higher influent concentrations resulting in higher percent removals independent of filter media performance. The data indicate that the constant and high percent total phosphorus removal during the 8-month monitoring period was not the result of increasing influent concentrations, but instead robust filter performance. It should be noted that this was only an 8-month monitoring period, to determine the long-term performance of the polishing layer, it is recommended that annual samples be collected from CH3 over an extended timeframe.

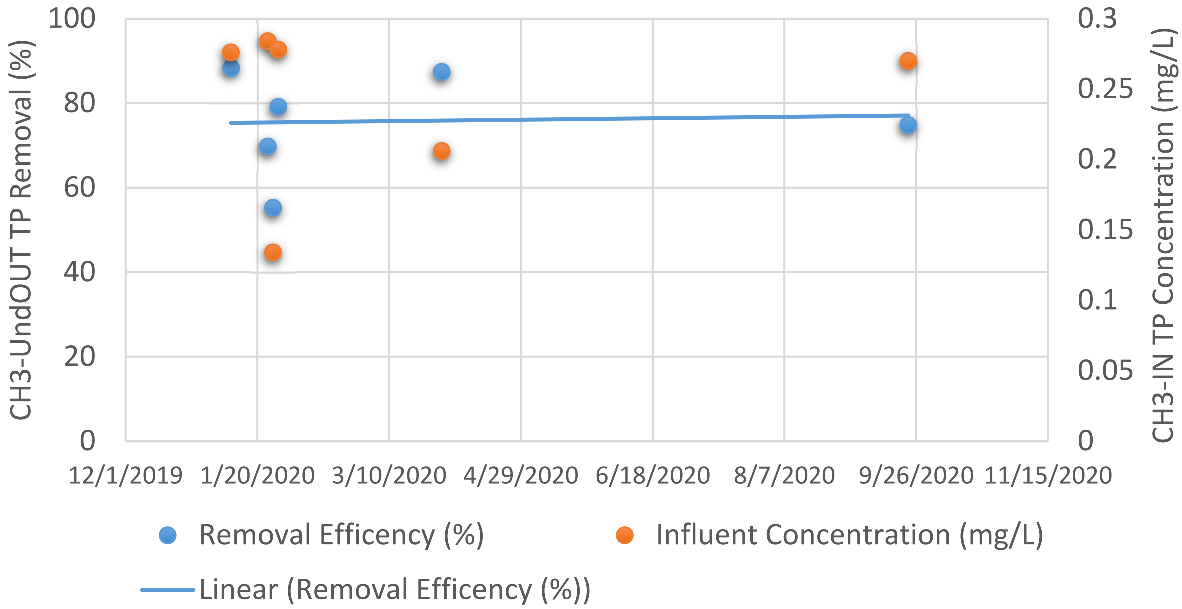


Figure 17. CH3-UndOUT Total Phosphorus Removal Trend During the 2020 Campaign.

CONCLUSIONS

The CHWQP is a regional stormwater treatment facility located in the Cascade neighborhood of Seattle, Washington. The system is designed to treat 153 Mgal annually through a combination of biofiltration (surface swale flow) and bioretention (flow through BSM). The facility consists of four swales, named CH1, CH2, CH3, and CH4. SPU had Herrera monitor influent and effluent flow and water quality at CH2 in 2016 and then CH2, CH3, and CH4 in 2020. Based on this data collection the following major conclusions were reached:

- From December 14, 2019 to December 14, 2020 (an annual duration with a typical rainfall depth), the CHWQP facility (all four swales) treated 91.2 Mgal. The facility was designed to treat 153 Mgal/yr, 40 percent more than measured in the field.

- During this same period the CHWQP removed 12,400 kg of TSS. The facility was designed to remove 46 percent more TSS per year (22,500 kg).

- The polishing layer installed at CH3 to reduce phosphorus export appeared to function as designed. CH3 (underdrain pathway) reduced influent TP concentrations by an average of 75.8 percent. TP reductions were -58.4 and 27.6 for the CH2 and CH4 (both systems without polishing layers) underdrain pathways, respectively.

- The ability of CH3 to remove TP did not deminish with time over the 8-month monitoring period (time from first sample to last sample) in 2020.

- CH4 was the worst performing swale, likely due to the constant saturation and excessive pollutant loading relative to the other swales.

Because the polishing layer installed at CH3 looks to be performing well, and because CH3 is the only fully implemented deployment of it in the field, it is recommended that SPU periodically revisit monitoring this system to determine long term performance.

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