Vancouver Green Infrastructure Performance Monitoring Report 2021-2023

City of Vancouver, Engineering Department, Green Infrastructure Implementation Branch

Authors: Cassandra Humes, Sylvie Spraakman, Robb Lukes

Published: January 2024

Executive Summary

The City of Vancouver is leading the way in constructing Green Rainwater Infrastructure (GRI) in Vancouver as a means of transforming how we view rainwater. GRI uses a suite of technologies such as bioswales, rainwater tree trenches, infiltration trenches, permeable pavements and green roofs that help mimic the natural hydrological cycle by capturing, treating, and infiltrating rainfall runoff close to where it lands. This results in the diversion of large amounts of rainwater runoff and associated pollution from the sewer system.

Although GRI systems are a proven technology implemented in cities around the world, monitoring is required to understand how local climate conditions and local materials impact the performance and maintenance requirement of these systems. During the 2021-2023 period, the Green Infrastructure Implementation Branch at the City of Vancouver conducted monitoring at twelve locations, including bioswales, subsurface infiltration, and rainwater tree trenches. Monitoring consisted of visual methods, synthetic runoff tests, and 23 sensors logging real-time water level or soil moisture data from our systems.

Using data from water level sensors, we found that GRI systems are well draining for the most part, and meeting our standards for surface drainage within 24 hours and subsurface drainage within 72 hours. This is occurring at sites across the City, representing a range of soil conditions, from very tight soils to very sandy soils. This is encouraging for deploying GRI even when soil conditions may suggest low infiltration potential. It also indicates that safety factors applied to design infiltration rates may be overly conservative. We would prefer to use safety factors of between 1 and 2, instead of safety factors >2.

In synthetic runoff tests conducted with external partners performed at two sites in the City, we found total suspended solids removal >99% by mass, and 6ppd-quinone (a tire wear chemical harmful to salmon) removal of >98% by mass. Our findings align with the academic literature on the water quality improvement potential of GRI.

We are also using data from monitoring our practices to improve design and maintenance activities. We can also adapt our designs post-construction based on monitoring, such as adding caps to underdrains at two sites that had better drawdown results in the field than expected at design. We use results from permeable pavement and infiltration trench condition assessments to inform maintenance practices, such as power washing and flushing, and frequency.

For the 2024-25 monitoring cycle, the Green Infrastructure Implementation Branch plans to continue monitoring water level and drawdown in newly built assets to determine their functionality. Also monitoring will continue at a few long-term sites to make conclusions about long term performance. We also have new types of assets to monitor: a new dry well type, oil-grit separators, and wetlands. To extend our monitoring resources and share findings, the Green Infrastructure Implementaion Branch will continue pursuing relationships with research partners to assist in water quality assessments and exploring opportunities to collaborate with and/or initiate citizen science monitoring programs.

Contents

Figures

Tables

Appendices

Introduction

The quality and volume of urban stormwater runoff from the City of Vancouver (City) are a hazard to the health of Vancouver's streams and coastal waterways. The Rain City Strategy and the Integrated Rainwater Management Plan target improving water quality using green rainwater infrastructure (GRI). GRI consists of a suite of technologies that retain and filter runoff close to where it falls, decreasing the volume of runoff directed to the sewer system, reducing combined sewer overflow, and removing pollutants from stormwater before it is discharged to receiving waters.

The Rain City Strategy outlines a volumetric target to treat and retain 90% of annual runoff volume. By capturing this volume of runoff using GRI, it is equivalent to removing 90% of annual stormwater runoff from entering the sewer system and more closely matches natural hydrology.

Because of its ability to deliver drainage services while providing climate resiliency and community benefits such as reduced urban heat and greener streets, GRI systems have been widely adopted across North America, Europe and Australia, and are moving into mainstream use in Canada and British Columbia. As the City of Vancouver is leading the way in implementing GRI systems, it is important to be open and transparent about the functioning of these systems. The City monitors GRI for the following reasons:

- Performance: Understanding the performance of GRI in the Vancouver climate and environmental context.
- Optimization: Improving and refining designs to improve the cost effectiveness and quality of construction and reduce the cost of operations and maintenance.

This report covers flow, water level and soil moisture monitoring that was conducted at 12 GRI assets using 23 sensors from July 2021 through to June 2023. The City of Vancouver Green Infrastructure Implementation Branch currently maintains more than three hundred GRI assets, which include bioretention systems, bioswales, rainwater tree trenches, permeable pavements and infiltration trenches. This report includes methodology (Section 2), and results for Performance Monitoring Objectives (Section 3) and Optimization Monitoring Results (Section 4). A description of GRI assets and the monitoring objectives are included in Section 1.

1.1 Green rainwater infrastructure in public right-of-ways

GRI functions to mimic natural hydrology and brings nature back to the City. The Green Infrastructure Implementation Branch has been designing and constructing GRI systems on public lands, primarily in the right-of-way, adjacent to roads, sidewalks and bike lanes. GRI systems in the right-of-way capture runoff from the City's most impervious and highly polluted surfaces, and treat and capture that water, diverting large amounts of annual runoff from our sewer system.

There are four types of GRI systems currently implemented in the City and covered in this report. Further GRI typologies are shown in Appendix B of the Rain City Strategy.

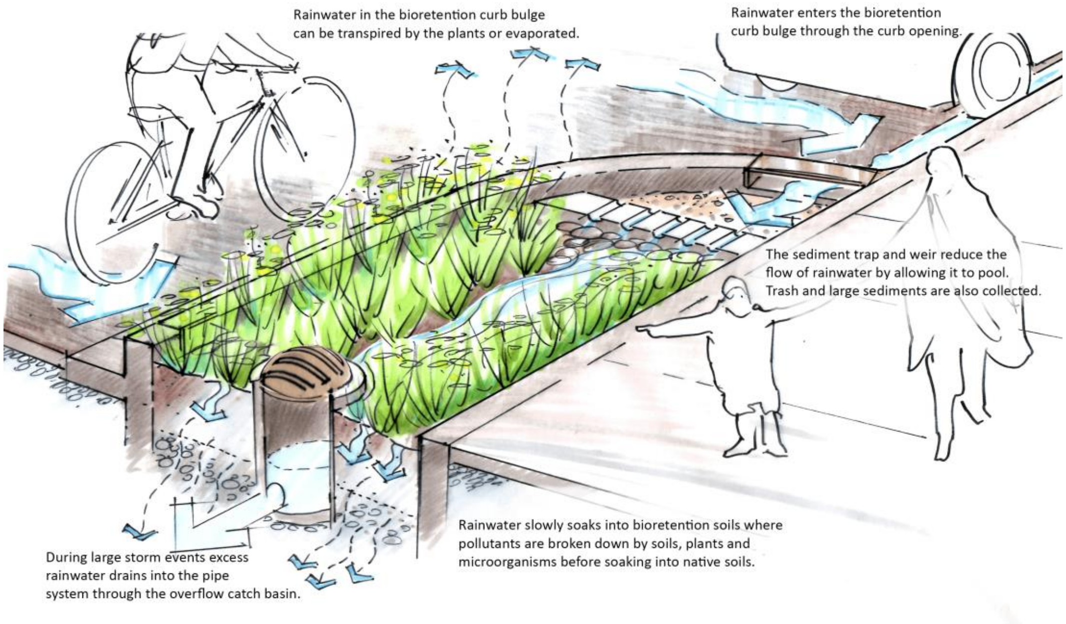


Figure 1 Bioretention schematic, from the Rain City Strategy Appendix B

Bioretention or bioswales: This common practice typically consists of a shallow depression or basin that features layers of rock, engineered soils, and resilient vegetation that can tolerate extreme rain and drought events. They can be designed as rain gardens, bioswales, bioretention cells, bioretention planters and bioretention corner bulges.

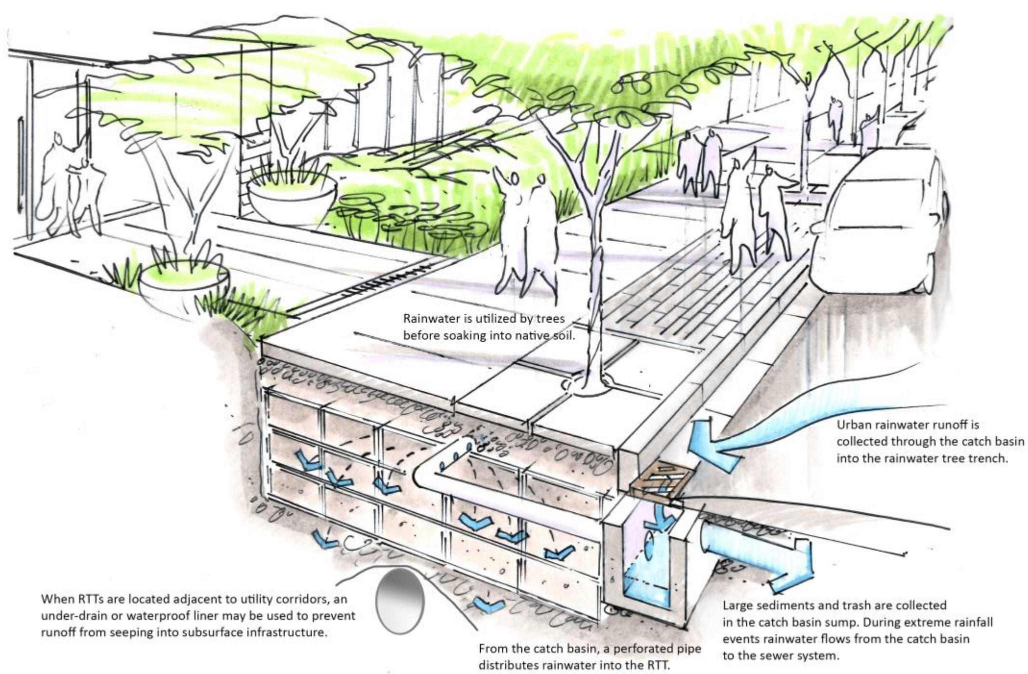


Figure 2 Rainwater tree trench schematic, from the Rain City Strategy Appendix B

Rainwater tree trench: Rainwater tree trenches (RTTs) are multifunctional GRI practices that provide storage for rainwater and supporting street trees with increased soil volume, nutrients and moisture. There are two types of RTTs in the City of Vancouver: structural soil and soil cells. Soil cells consists of plastic frames that are strong enough to bear the weight of surfaces like sidewalks. Soil fills the void left in the plastic frame, leaving space for tree roots. Structural soil uses a mix of large crushed stone and soil. The stone bears the weight of the surface while the soil and the space between the stone allows tree root growth.

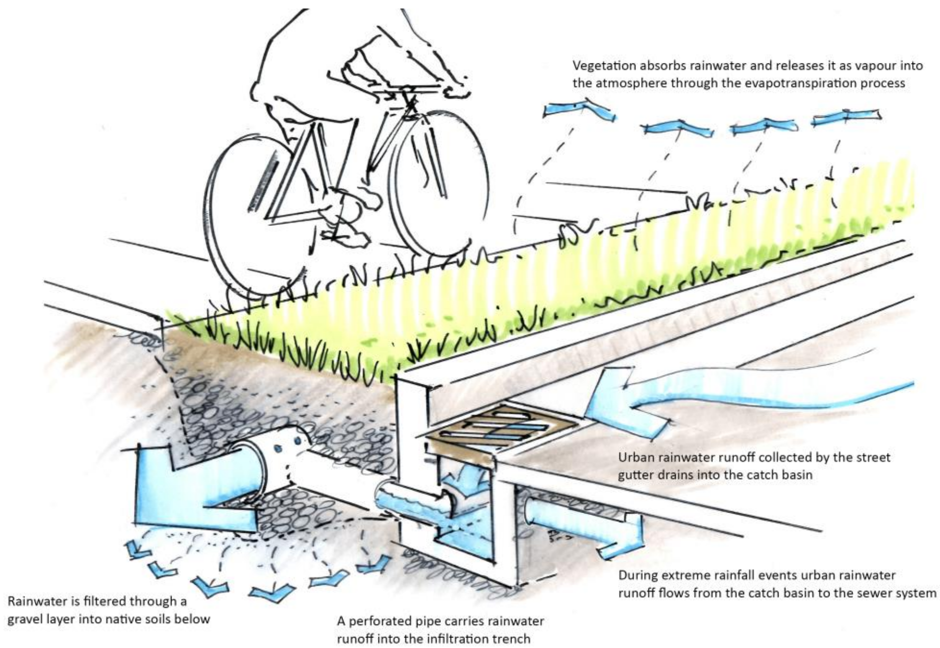


Figure 3 Infiltration trench schematic, from the Rain City Strategy Appendix B

Subsurface Infiltration: Subsurface infiltration practices use conventional grey rainwater infrastructure to collect and convey rainwater to areas where it can be stored and infiltrated. Large aggregate materials with void spaces and/or modular crates and arches are used to create storage space below the ground's surface. Rainwater is temporarily stored in these practices, giving it a chance to soak back into the ground. Subsurface infiltration practices include **infiltration trenches**, **dry wells**, soakways, chambers, arches and modular systems.

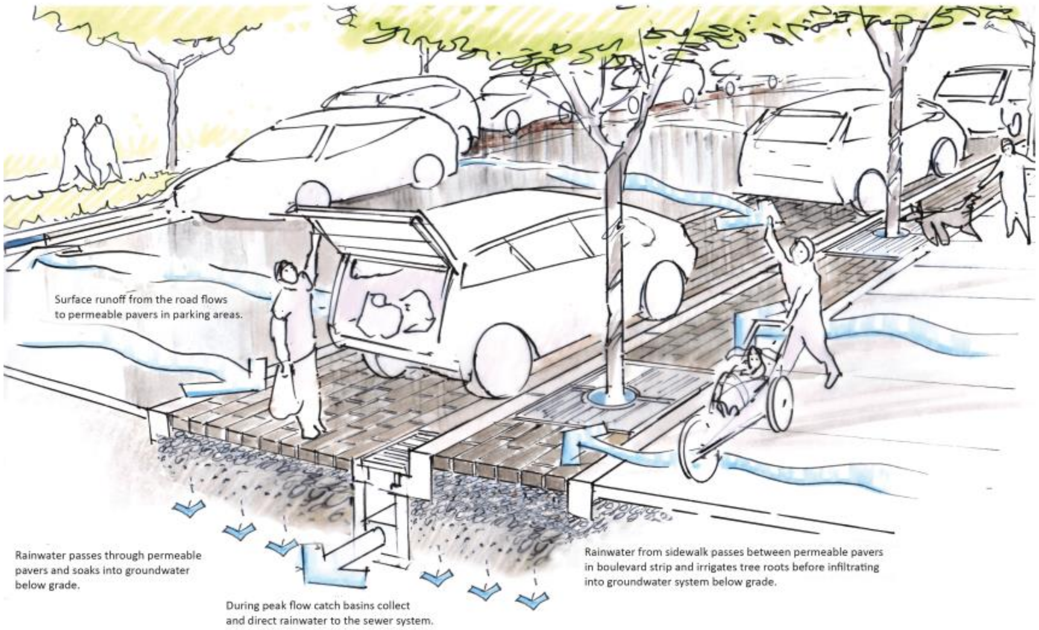


Figure 4 Permeable Pavement schematic, from the Raincity Strategy Appendix B

Permeable Pavement: Permeable pavement comes in a variety of forms, such as permeable interlocking concrete pavers (PICP) and porous versions of poured asphalt and concerete. All permeable pavement types allow rainfall to soak into an underlying reservoir base where it is either infiltrated to the ground or removed by a subsurface drain. Rainwater is filtered and cleaned through the different aggregate layers and the underlying subsoil layer. Permeable pavement provides a hard, usable surface, whether by cars, bikes, or pedestrians, while reducing runoff volume and improving water quality.

1.2 Monitoring Program Objectives

Objectives for monitoring green rainwater infrastructure fall into two categories: Performance Monitoring (determining how GRI functions and performs) and Optimization Monitoring (determining how best to design and maintain GRI over its life cycle). This report addresses nine program objectives under these two categories.

Performance Monitoring Objectives

Objective 1: Evaluate surface ponding: should not be ponded for longer than 24 hours. This is a City of Vancouver standard for infiltration systems with ponding zones, addressing public perception that ponding beyond 24 hours is generally unacceptable. While mosquito hatching is a commonly raised concern, mosquitoes need at least seven days of standing water to develop and hatch.

Objective 2: Evaluate subsurface storage: storage should empty in no more than 72 hours. This is a design requirement for the City of Vancouver, and relates to the average period between storm events. Ideally, the system receiving runoff would be dry before the next rain event so that storage space is maximized.

Objective 3: Evaluate whether design infiltration rates are matching drawdown rates. The process of determining in situ infiltration capacity is prone to uncertainty due to the high variability in subsoil conditions and instrumentation used. As such, a conservative design factor of safety of between 2 and 9 is applied to the in situ soil infiltration capacity. We would like to compare drawdown rates (the real rate at which water is leaving the system through exfiltration) to the design infiltration rates to determine (1) whether safety factors are correctly applied and (2) whether the drawdown rate decreases over time.

Objective 4: Monitor soil moisture for plant health. A common critique with vegetated GRI is that the plants are exposed to a wide variety of contaminants and tough conditions through a combination of flooding and drought. We would like to know whether the soil moisture range in the observed practices is amenable to vegetation health.

Objective 5: Determine if retention/filtration target is being met. GRI is designed to capture and infiltrate small and routine rainfall events, thereby reducing the total annual volume of stormwater entering the storm or combined sewers and eventually released to receiving water bodies. We conduct occasional synthetic runoff tests (adding the design storm volume to the system via hydrant or water truck) on our systems to determine if they are meeting the volume reductions targets for which they were designed.

Objective 6: Evaluate load reduction and effluent concentration of GRI for target pollutants: solids, nutrients, metals and organic contaminants. A major benefit of GRI is filtering stormwater and reducing loading of contaminants to surface water via infiltration. Many studies have shown the load reduction and filtration capacity of GRI, but GRI’s performance for reducing contaminants of concern is unknown in Vancouver.

<u>**Optimization Monitoring Objectives**</u>

Objective 7: Determine permeable pavement performance over time and necessary maintenance methods. Permeable pavement or other porous surfaces are often an ideal solution for both providing a hard flat surface in an urban space while also allowing stormwater to infiltrate. Permeability can decrease over time as the pore spaces become clogged with sediment, dust and debris and cleaning the porous product is required to maintain permeability. We conducted permeability testing for a subset of assets before and after cleaning to determine the appropriate maintenance tasks to ensure permeability is maintained,

Objective 8: Determine condition scores for all GRI assets. A key component of an asset management program and understanding life cycle costs of infrastructure is creating condition scores for individual assets. This can be used to determine trends over time and estimate maintenance and other life cycle costs.

Objective 9: Evaluate the impact of GRI on biodiversity in the City. GRI creates vegetated spaces for water to infiltrate using a diverse range of plant species to provide habitat for flora and fauna and thus increasing biodiversity. This co-benefit of GRI often goes unmeasured and unreported, and monitoring this aspect of GRI will help document the outcomes of this design intention.

Methods

This section describes the methods used to evaluate each objective. The two categories of objectives are Performance Monitoring and Optimization Monitoring. The previous monitoring report summarized monitoring results for 13 sites (City of Vancouver, 2022). Since then, monitoring has ceased at some sites, while new sites have been added. This report will cover monitoring results for 12 sites monitored between 2021-2023 using 23 different sensors. The locations of the monitoring sites, and City rain gauges are presented in Figure 5 along with the type of monitoring conducted. Full site descriptions are included with the results in Section 3.

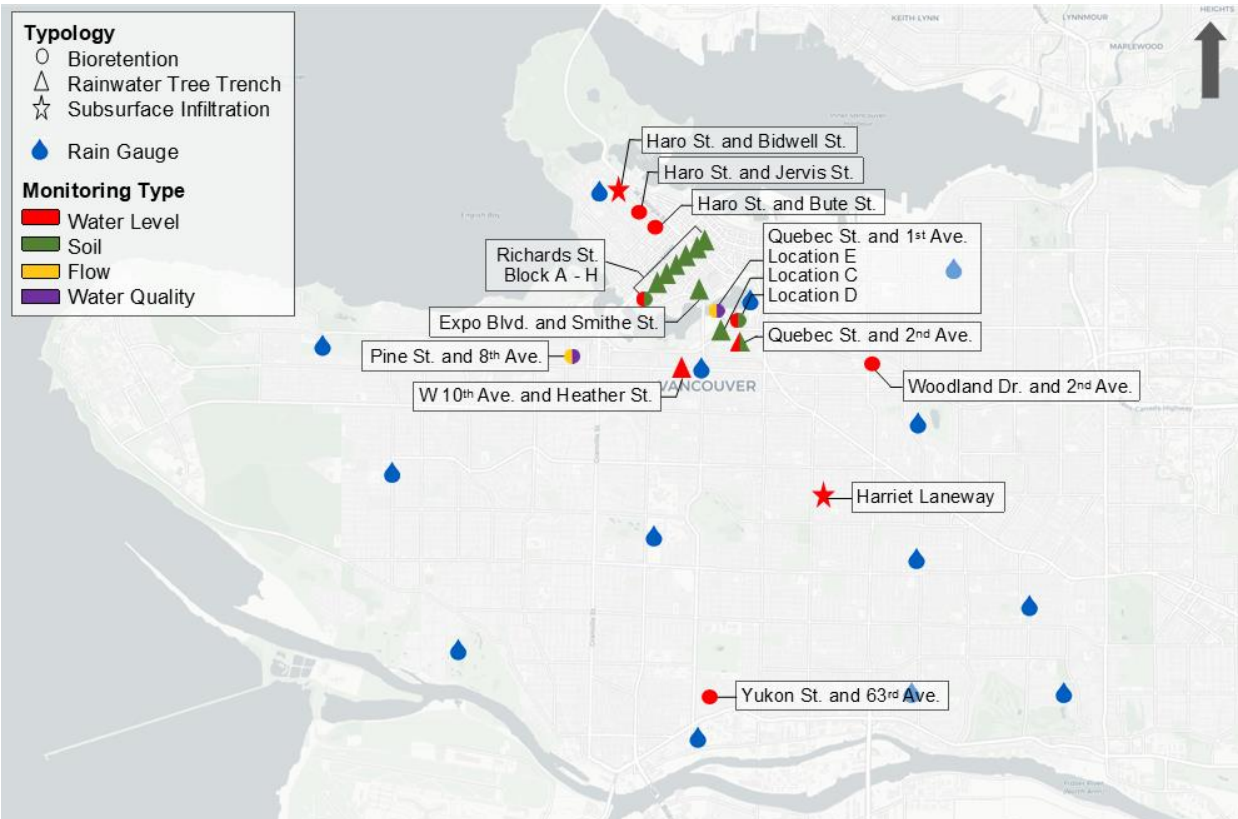


Figure 5 City of Vancouver monitoring sites, typology and rain gauges

1.3 Performance Monitoring

1.3.1 Rainfall data collection

The City of Vancouver has a tipping bucket rain gauge network across the City (Figure 5). Raw rainfall data is available at 5-minute intervals from the nearest rain gauge to each site and is downloaded using FlowWorks software. A rainfall event is defined as having a minimum cumulative rainfall of 2.0 mm and a minimum 6 hour antecedent dry period. Rainfall events are separated for analysis into three categories:

- Normal Event: ≤24 mm;
- Large Event >24 mm & ≤ 48 mm; and
- Extreme Event >48 mm

1.3.2 Water level monitoring

Water level monitoring was achieved through the installation of water level loggers in the monitoring wells of the GRI practices post-construction. Monitoring wells are incorporated into the design of each GRI practice. The wells consist of a 150-mm diameter perforated pipe that extends the vertical depth of the practice. The wells are wrapped in geotextile to prevent sediment from entering. A cap covers the well, and the entire structure is surrounded by a valve box with a bolted lid to prevent any theft or vandalism. Design changes have occurred to the monitoring wells, and newer assets are capped on the bottom of the well to keep a small volume of standing water for the logger to remain submerged.

There are two types of water level loggers that are currently in use for water level measurements. The first type are Onset HOBO U20-001-01 pressure transducers that are set to record pressure measurements at 5-minute intervals. These loggers are non-vented and need to be adjusted for atmospheric pressure. There are two methods that are used for this barometric compensation. The first is to use a central barometric sensor. However, if the site is located at too great a distance from the central sensor, or if the design does not allow for proper venting to the atmosphere then a secondary sensor is installed inside the well (Figure 6). Data is offloaded from the loggers manually using an optic USB Base station and coupler every 4-6 weeks. Data is offloaded using HOBOware Pro software, which also performs the barometric compensation. The data is then exported to Excel and plotted along with rainfall data to determine where water level changes occurred and locate any outliers in the data set.

The second type of water level loggers used are Seametrics PT12 pressure transducers. These sensors are vented and do not require the need for additional barometric compensation. They are set to record a measurement every 5-minutes. These loggers are connected to Novion® data loggers and data is sent to a cloud platform every three hours. Data is downloaded from the platform and exported to Excel and plotted with rainfall to determine water level changes and locate any outliers in the data set.

All loggers were installed in the monitoring well post-construction by suspending the logger in the well with a non-stretch rope above the bottom of the well to prevent any sediment accumulation from blocking the sensor. Well depth, level logger depth and standing water depth (if applicable) measurements are taken at time of deployment.

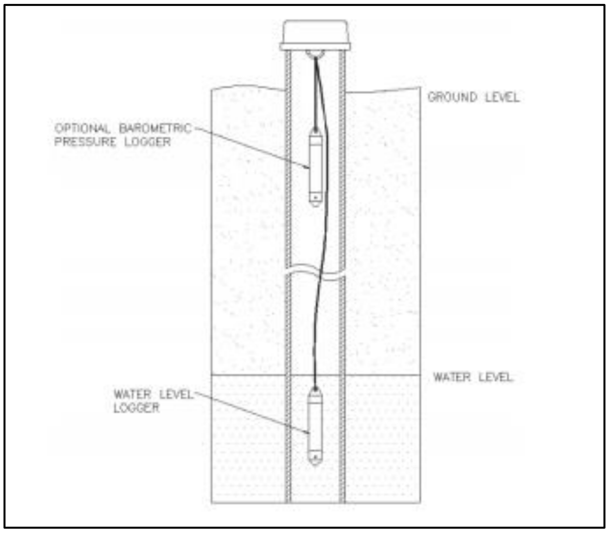


Figure 6 Schematic of HOBO water level logger installation inside a monitoring well (Onset, 2012)

Each individual storm event and water level change was analyzed to determine the drawdown rate and drawdown duration. Drawdown duration is the time between peak water level and the return to the pre-event water level (Figure 7). Drawdown rate is defined as the rate at which water exits the bioretention system during and following a rainfall event, and is calculated by dividing the drawdown level (from peak water level to water level before rainfall) by the drawdown duration. Drawdown rate is compared to the design infiltration rate. The design infiltration rate was determined by infiltration rate testing of native soils beneath the GRI system prior to construction and installation, and is a conservative estimate of the real drawdown rate.

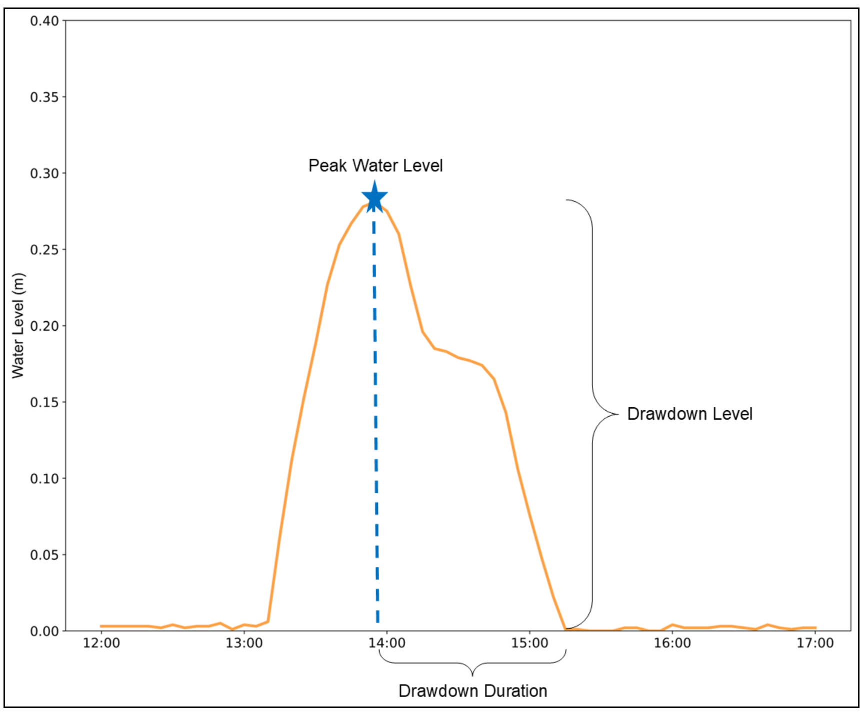


Figure 7 Example of water level response to show calculation of drawdown duration and drawdown rate.

1.3.3 Soil moisture monitoring

To monitor the soil moisture, temperature and electrical conductivity, TEROS 12 soil sensors are used. They consist of three prongs inserted into the soil to measure volumetric water content, electrical conductivity and temperature. The TEROS 12 sensors were installed in the soil during construction by placing the sensor prongs into the soil at the desired depth. The cables were fed through a narrow PVC pipe that led to a valve box. Once construction was complete, a data logger was connected to the soil sensor. A pelican box was used to house the data logger and the entire system is locked inside a valve box. The data logger is set to collect data at 5-minute intervals, allowing for 120 days of data to be stored in the EM50, or 2 years of data in the ZL6. Data is collected and batteries changed approximately every 12-16 weeks. Upon collection, each parameter is plotted with rainfall to determine any trends or locate any outliers in the data set.

1.3.4 Synthetic runoff testing

Synthetic runoff tests involve using a clean water source – either from a fire hydrant or water truck, that is then applied to the GRI practice in a controlled manner. From this, flow measurements can be taken at the inlet and outlet to determine the volume of water retained in the system. Flow measurements are taken using the bucket and timer approach – filling a bucket over a set amount of time, then measuring the volume using graduated cylinders. Flow measurements are taken from the water truck or hydrant hose at the inlet, and from the underdrain at the outlet. The synthetic runoff tests are set up so that there are no overflows, so all water in is either released through the underdrain or infiltrated into the ground. The main limitation of this method is that it does not simulate high-intensity or variable-intensity rainfall events. However, on a volumetric basis, this method is quite accurate. Also, this helps to overcome many of the challenges associated with flow monitoring – such as low flows, estimating the amount of inlet bypass, and space constraints in the inlet and outlet.

To test the ability of GRI systems to remove contaminants, pollutants of known mass are injected into the system, along with the flow of water from a water truck or hydrant. Samples are collected at the underdrain while it is flowing, and analyzed for the same water quality parameters. The concentration and known volume at the outlet determines the mass of contaminants at the outlet, and using mass balance, we can determine how much mass is removed from the GRI system. However, this does not break down how much contaminant mass remains within the GRI soil, and how much enters the vadose zone via exfiltration from the GRI system. Additional monitoring and modelling studies could assist in determining a more detailed mass balance of the GRI system.

1.4 Optimization Monitoring

1.4.1 Permeable pavement testing

We currently have 37 permeable pavement assets in the City of Vancouver, which range in size from 32 m^2 to 705 m^2, with the majority at around 100 m^2 or less. We conducted infiltration testing on a subset of these assets using the ASTM C1781 standard method (with an infiltration ring of 300 mm diameter, and two lines marked at 10 mm and 15 mm from the base of the ring). The assets we studied were all permeable interlocking concrete pavement (PICP). The ring was sealed to the surface using clay and a known mass of water was poured at a constant rate to keep the head of water between 10 mm and 15 mm. The time it takes for water to infiltrate was recorded and the infiltration rate is calculated using:

$$I = \frac{KM}{D^2T}$$

Where I=infiltration rate (mm/h)

K=constant 4.58 x 10^9

M=Mass of water infiltrated (kg)

D=Diameter of ring (300 mm)

T=Time required for water to infiltrate pavement surface (s)

We determined that a test time of greater than 30 minutes, or an infiltration rate of 100 mm/h, indicated system failure, based on guidance from ASTM C1781 and literature on permeable pavements. After an initial round of assessing the infiltration of a subset of assets, we found that all PICP assets failed. We then proceeded to clean and then repeat the permeablity testing. We found that vacuum street sweeping did not improve the infiltration rate, but that power washing was most effective. We then repeated permeability testing at six of the PICP assets over five months following the cleaning.

1.4.2 Condition assessments

The condition assessment program began in 2022 with the objective of identifying non-routine maintenance needs, identifying failed assets requiring rehabilitation and assigning condition scores to the bioretention assets. Condition values ranged from 1-5, with 1 being very good, and 5 being very poor. Different components of the systems were evaluated including the contributing drainage area, inlet, outlet, monitoring well, cleanouts, planting bed, ponding area, vegetation and soil. Wet weather and post-24 hour rain inspection data was also incorporated into the condition scoring to measure bypass, short-circuiting and excessive ponding. A copy of the bioretention condition assessment guide is included in Appendix A. All GRI assets (rainwater tree trenches, infiltration trenches, permeable pavement and bioretention) had condition assessments performed over 2022, and the results of the condition assessments on 147 bioretention sites are included in Section 4.

1.4.3 Biodiversity scoring

To better understand the impact of the co-benefits of GRI, we are attempting a new program of measuring biodiversity at GRI assets. We have monitored biodiversity before the construction of the St George Rainway (a 4-block long bioretention system currently under construction), and will continue monitoring this in the years after its construction. We used citizen science and iNaturalist to document the types of species along St George St. (between 5th Ave. and East Broadway) during 4 bioblitzes in 2022. We used this data to determine the number of species within a two block radius of St George St. We will then repeat bioblitzes following construction to measure changes. For the full methodology, results and recommendations, please see our biodiversity monitoring report (City of Vancouver, 2022). In the next monitoring report, we will include more detailed results of post-construction biodiversity monitoring at St George Rainway.

Performance Monitoring Results

1.5 Objective 1: Surface drawdown within 24 hours

After a large storm event (>120 mm in 24 hours) in November 2021, GI team members performed post-rain inspections more than 24 hours after rain stopped to evaluate standing water in bioretention systems. A total of 140 systems were evaluated, of which 92% had no standing water, and 8% had standing water. All the standing water present was under 10 cm. The sites that did contain standing water were built in a pre-GRI era at the City and are not designed to meet our current standards. Many of those sites have since been or will soon be upgraded to more closely meet our current design standard.

In October 2023, another post-rain inspection was conducted to evaluate standing water in the bioretention systems. A total of 138 sites were evaluated and none of them were found to have standing water 24 hours following a rainfall event of >60 mm in a day.

1.6 Objectives 2&3: Subsurface drawdown time and rate

1.6.1 Yukon St. and 63rd Ave. Bioretention

The bioretention practice located at Yukon St. and West 63rd Ave. was constructed in 2018. The location was highlighted in the Marpole Community Plan and features a rain garden and bioswale to manage rainwater runoff, as well as seating areas, a drinking fountain, and interpretative signage.

The bioretention practice is located along two boulevards of residential streets and manages stormwater runoff from a drainage area of 1170 m^2 from adjacent sidewalks and roads. In addition, this system is on a major flow path. During moderate to high intensity rain events, bypass of upstream catchbasins is frequently observed; thereby increasing flows to the Yukon St. and 63rd Ave. system beyond the 1170 m^2 area. Infiltration testing was performed prior to construction using the double ring infiltrometer method. After a factor of safety was applied to the infiltration results, the practice was sized using a design infiltration rate of 39 mm/h.

Sustained rainfall amounts and rainfall intensity above 5 mm/h would generate a water level response at the Yukon St. and 63rd Ave. system. The monitoring well generally demonstrated drawdown within a few hours and drawdown rates above 200 mm/h. The water level monitoring results from the 2018-2023 are shown in Figure 8. Between 2018 and 2023, 80 rainfall events produced a water level change for which the drawdown time and drawdown rate were calculated and compared to the design infiltration rate, as shown in Table 1.

This site was included in the previous monitoring report, and drawdown rates and times have since increased slightly (City of Vancouver, 2022). The average drawdown rate in 2018-2021 was 367 mm/h, and the average drawdown rate for 2021-2023 was 736 mm/h, with an average drawdown rate for the full 2018-2023 period of 497 mm/h, indicative of an increasing drawdown rate over time.

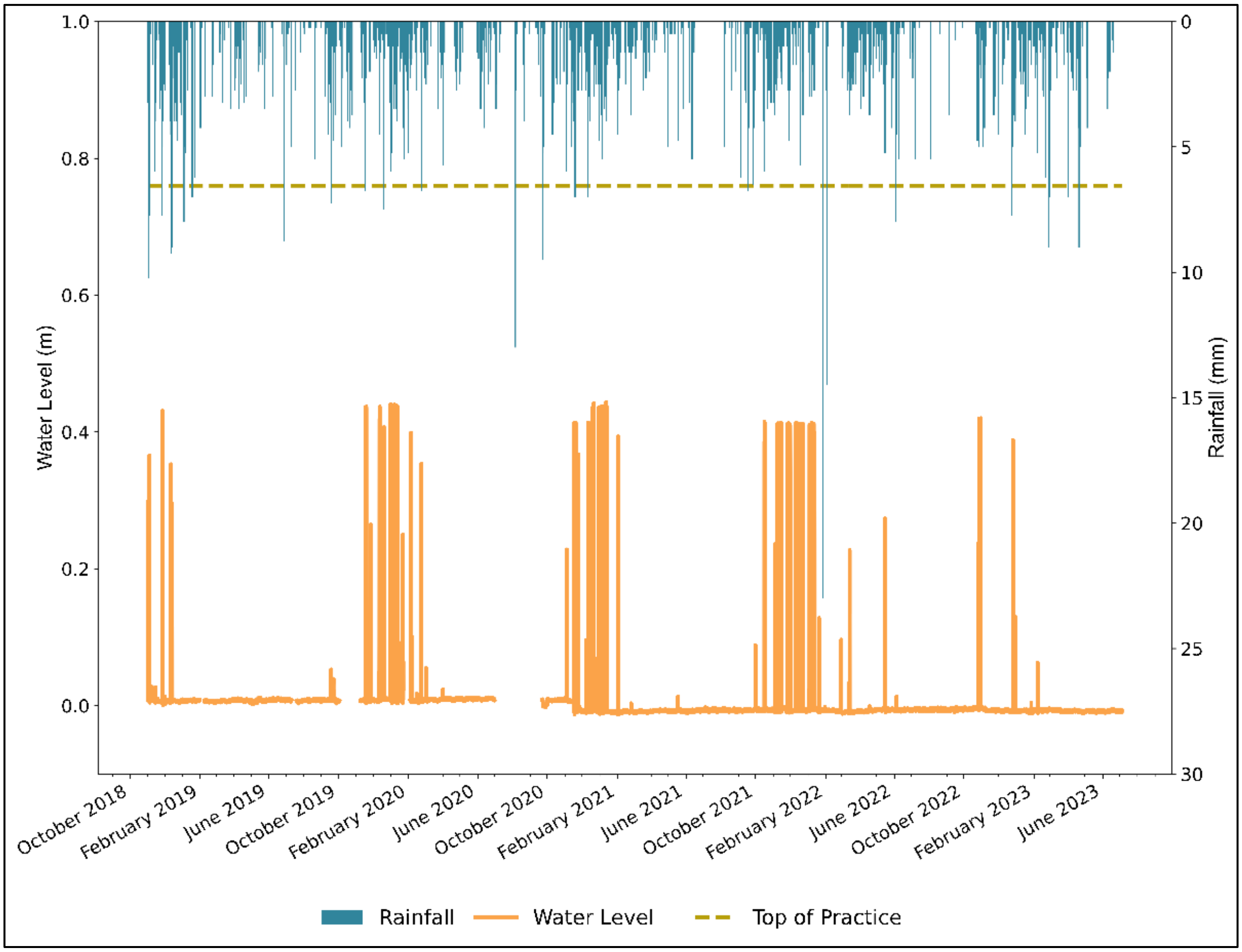


Figure 8 Hourly water level response at Yukon St. & 63rd Ave. and hourly rainfall response at Manitoba Yards rain gauge

Table 1 Yukon St. & 63rd Ave. water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	47	21	12	80
Drawdown Duration (h)	1.0	1.0	3.1	1.3
Drawdown Rate (mm/h)	466	583	465	497
Design Infiltration Rate (mm/h)	39			
% change	1095%	1394%	1092%	1173%

1.6.2 Quebec St. and 2nd Ave. RTT

The Quebec St. and 2nd Ave. GRI practice was constructed in 2019 and is part of the second phase of precinct upgrades along Quebec St. The GRI practice consists of soil cell RTTs that manages a drainage area of 610 m^2 and sized using a design infiltration rate of 10 mm/h. There are three monitoring wells installed, one in the north of the practice, one in the middle of the practice, and one in the south of the practice, each with water level loggers that were installed in March 2020. The middle well water level logger has since died and results are not included in this report. The south portion of the practice also contains a soil sensor that measures volumetric water content, electrical conductivity and temperature that was installed during construction. A data logger was connected to the soil sensor in September 2020. The soil sensor has since died and the monitoring results are not included in this report.

1.6.2.1 Quebec St. and 2nd Ave. North RTT

The North RTT monitoring well contained standing water above 40 cm for most of the monitoring period, with the exception of a few months in the summer when the water level drops and the well dries out. There are no observed issues with tree health or differential settlement with this constant water level. The well displays water level changes with nearly every rainfall event, and during times of frequent rainfall, often the water level has not returned to its initial level before another storm event causes the water level to rise again. Water levels changes for the 2020-2023 monitoring period are shown in Figure 9.

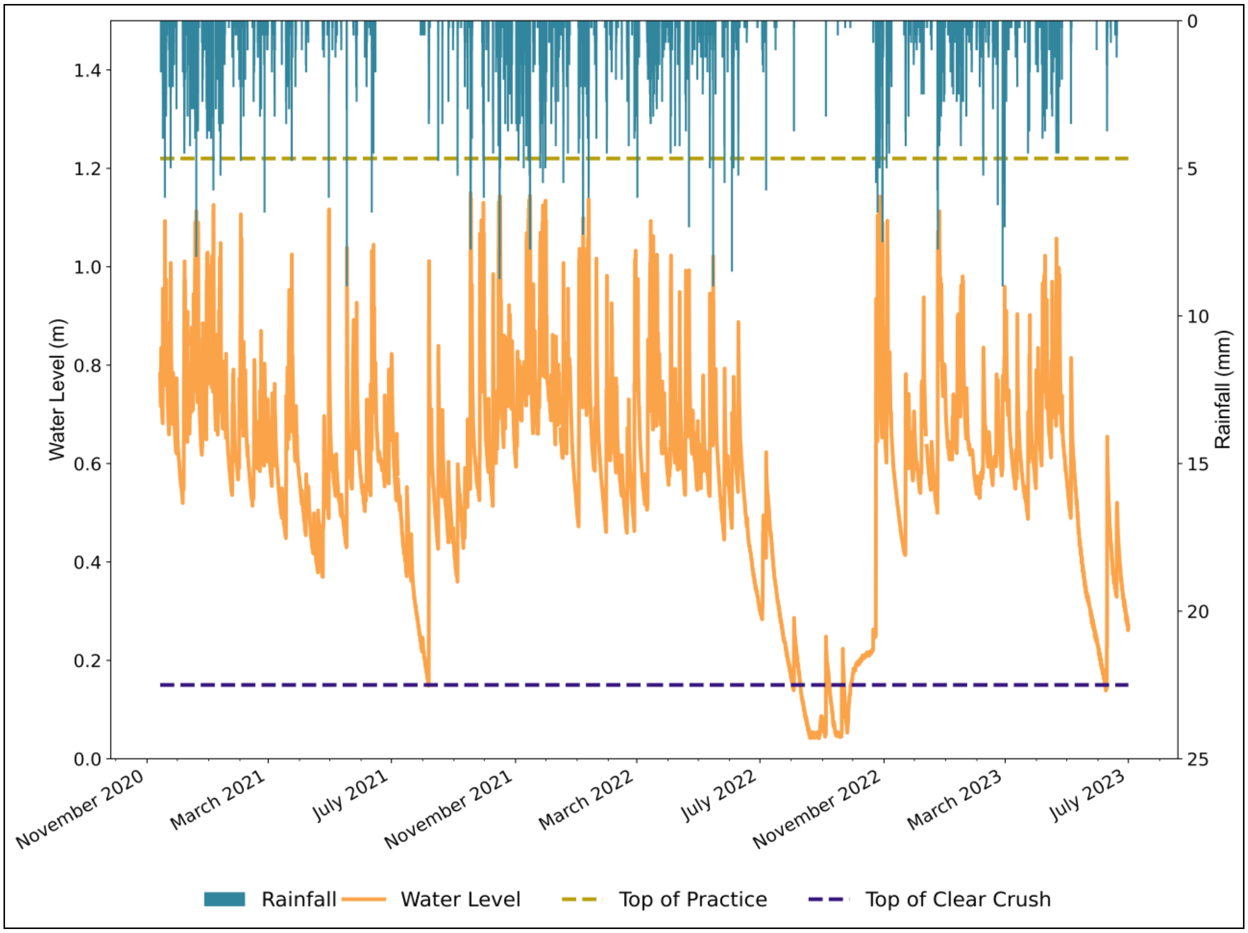


Figure 9 Hourly water level response at Quebec St. and 2nd Ave. North and hourly rainfall response at Creekside rain gauge

The North well displays high drawdown durations and overall infiltration rates that are under-performing compared to the design infiltration rate. Over 2020-2023, 154 events produced a water level change. This site was included in the previous monitoring report, but with only 7 months of data at the time. The average drawdown rate over 2020-2021 was 8 mm/h (City of Vancouver, 2022), and currently the average drawdown rate is 8.7 mm/h, so very similar. The drawdown duration, drawdown rates and comparison between design infiltration rate are shown in Table 2.

Table 2 Quebec St. and 2nd Ave. North well water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	106	33	15	154
Drawdown Duration (h)	35.9	35.9	35.3	35.9
Drawdown Rate (mm/h)	7.1	12.0	12.6	8.7
Design Infiltration Rate (mm/h)			10	
% change	-29%	20%	26%	-13%

1.6.2.2 Quebec St. and 2nd Ave. South RTT

Over the course of 2020-2023, 163 events produced a water level change with drawdown durations generally being greater than 25 hours. Unlike the North well, this well does fully drain and does not contain standing water for large portions of the year. Water levels changes for the 2020-2023 monitoring period are shown in Figure 10. Overall, the drawdown rate is slightly under-performing compared to the design infiltration rate. This site was also included in the previous monitoring report, though only for 7 months. The drawdown rate for 2020-2021 was 10 mm/h (City of Vancouver, 2022), whereas the drawdown rate for 2020-2023 is 9.4 mm/h, so very little changed across the two monitoring reports. Storm events, drawdown duration and rates and comparison to design infiltration rates are shown in Table 3.

Both the north and south wells have drawdown times below their intended design rate. We suspect that there maybe be clogging in the geotextile that surrounds the monitoring wells that is slowing the infiltration down. Additionally, on occasion over 2020-2022, the wells show a water level change when no rainfall event has occurred. During site visits we observed construction dewatering entering the catch basins for this system. This could also explain the introduction of additional sediment that might be clogging the geotextile. These observations of raised water levels not associated with rainfall were not observed in 2023, which is when construction for that area was all above grade.

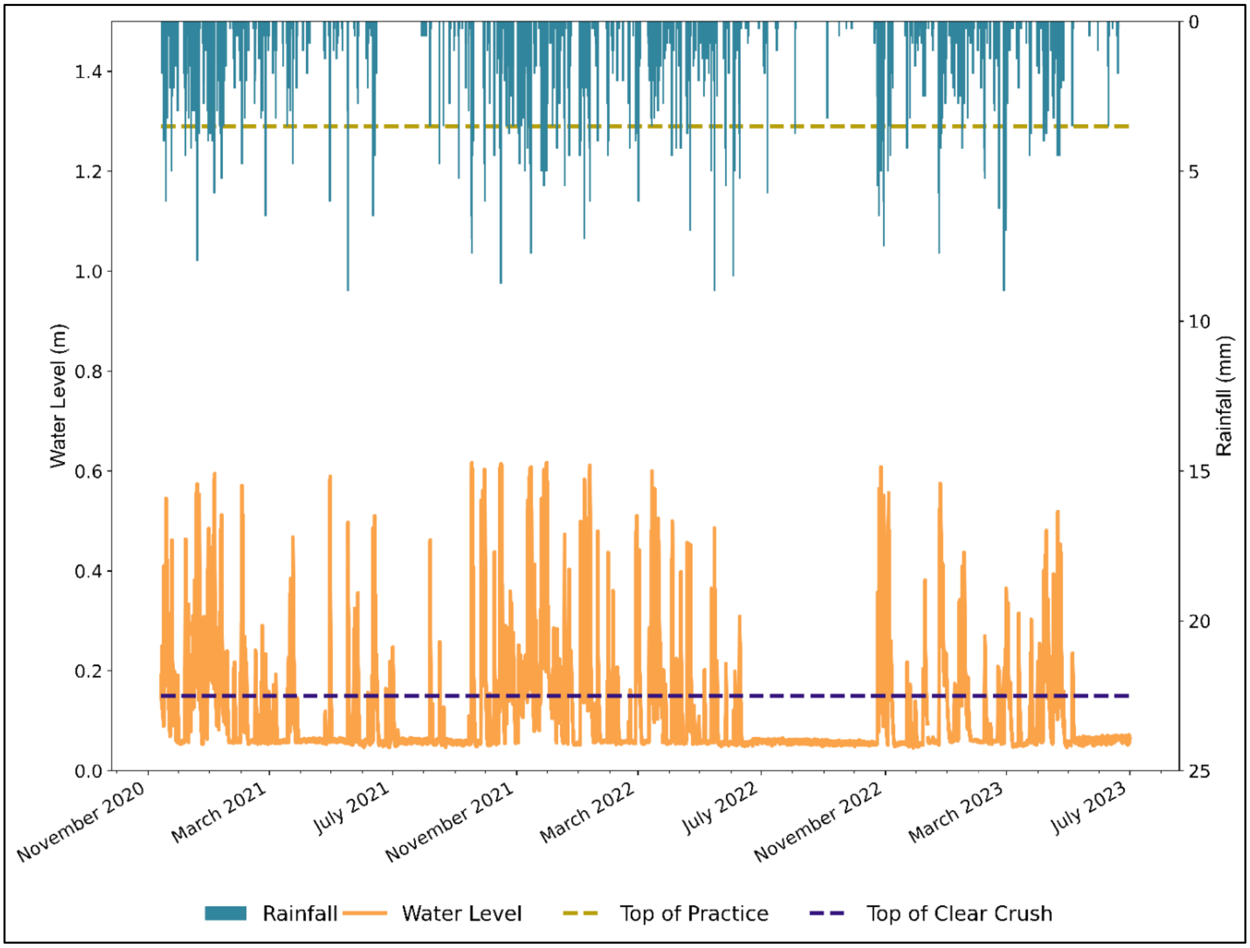


Figure 10 Hourly water level response at Quebec St. and 2nd Ave. South and hourly rainfall response at Creekside rain gauge

Table 3 Quebec St. and 2nd Ave. South well water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	116	31	16	163
Drawdown Duration (h)	25.0	33.6	38.2	27.9
Drawdown Rate (mm/h)	8.0	13.6	11.9	9.4
Design Infiltration Rate (mm/h)		10		
% change	-20%	36%	19%	-6%

1.6.3 Richards St. Block H Bioretention

The Richards Street project is an 8-block project located in downtown Vancouver between Dunsmuir St. and Pacific Blvd. As part of bike lane upgrades in the area, rainwater tree trenches were incorporated to collect runoff from the bikeway and roadway. This project features 100 new trees planted in the median, planting at the base of trees, and a bioswale near the intersection with Pacific Blvd. The project consisted of 2 phases and was under construction from May 2020 to November 2021. All blocks had monitoring wells and water level loggers installed, however we suspect that infiltration occurs too quickly in this system to trigger a water level response in monitoring wells located by the system outlets. The end of Block H consists of the only bioretention system for this block, and so unfortunately we do not have drawdown data for the rainwater tree trench portions. However, soil moisture data for all Richards St blocks is included in Section 3.3.4.

Block H bioretention manages an impervious area of 251 m^2 and was designed with an infiltration rate of 5 mm/h. The water level has been monitored at this site from November 2021-Present. Block H was very responsive to rainfall events, producing a water level change for 91 events. The drawdown time is very quick and the drawdown rate is much higher than the design infiltration rate. Storm events, drawdown duration and times and comparison to design infiltration rates are shown in Table 4.

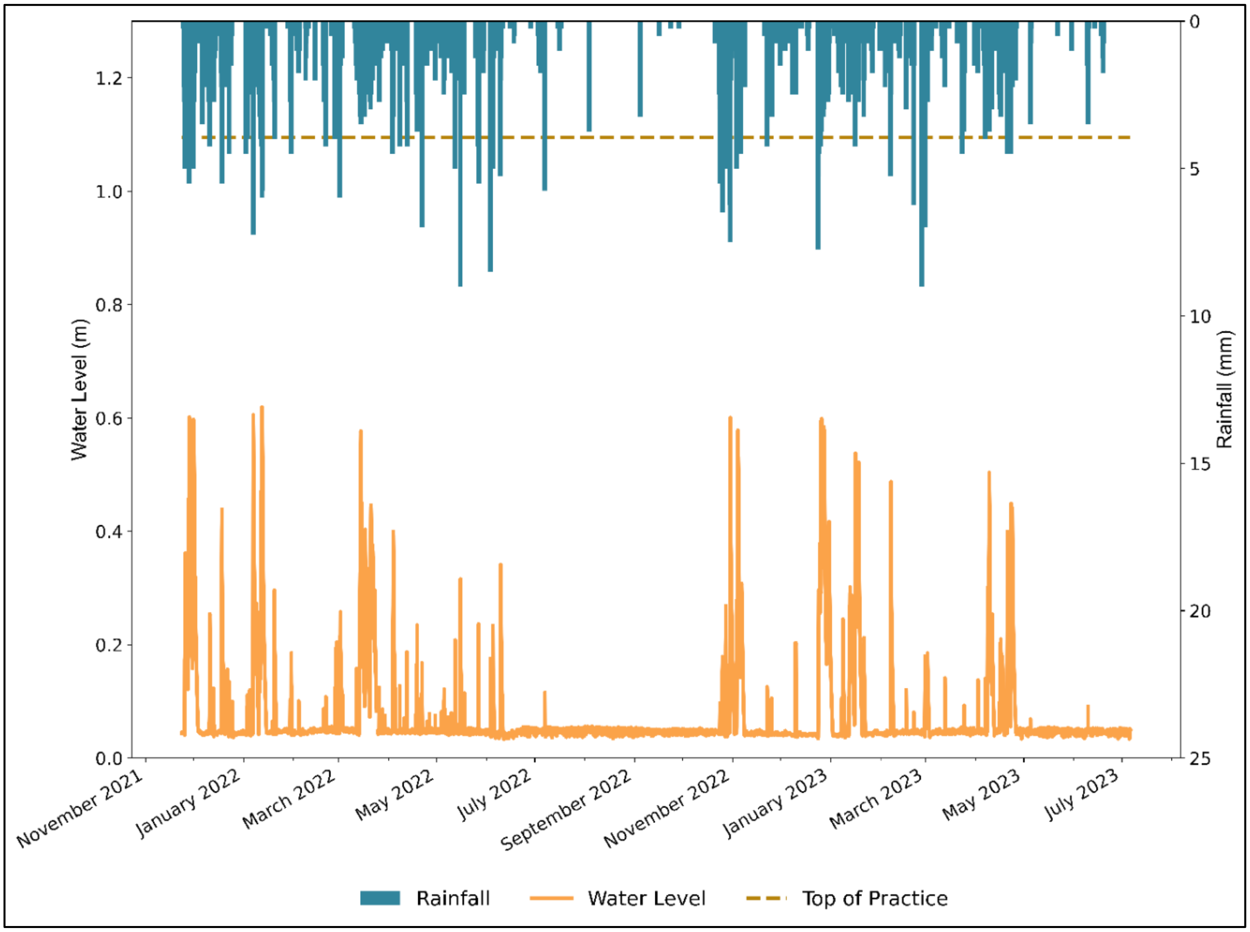


Figure 11 Hourly water level response at Richards St. Block H and hourly rainfall response at Creekside rain gauge

Table 4 Richards St. Block H water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	59	22	10	91
Drawdown Duration (h)	8.6	17.9	36.1	13.84
Drawdown Rate (mm/h)	50.4	26.6	10.9	40.3
Design Infiltration Rate (mm/h)			5	
% change	908%	432%	118%	706%

1.6.4 Haro St. and Bidwell St. Dry Well

As part of Transmission Main upgrades, roadworks improvements that included GRI were included along Haro Street. The entire project consists of several different typologies including dry well, an infiltration trench and bioretention systems.

The dry well was constructed in June 2021, and water level monitoring using Novion loggers covers the period of February 2022 to present. The dry well receives runoff from a catchbasin for a drainage area of 368 m^2. The dry well was constructed using a 1.5-m deep 600-mm diameter PVC chamber with perforations every 15 cm surrounded on all sides by 0.3 m of granular material. The active storage volume is 1.1 m^3. From geotechnical investigations, the soil type at 0-2 m below ground surface was coarse sand with trace to some silt and trace gravel with Ksat average of 504 mm/h. The dry well was designed with an infiltration rate of 47 mm/h.

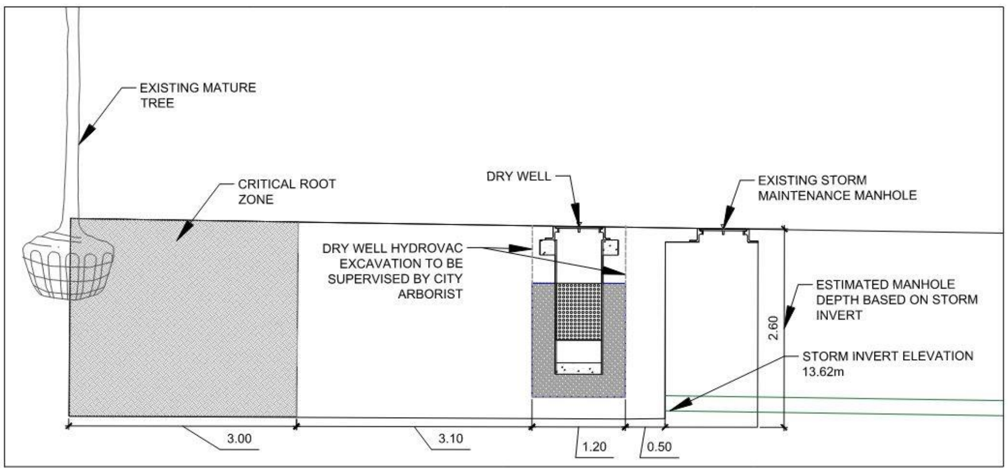


Figure 12 Schematic of Haro St. dry well

Water level monitoring at the dry well started in February 2022 and is ongoing. Novion water level sensors are deployed at this location, and results are shown in Figure 13.

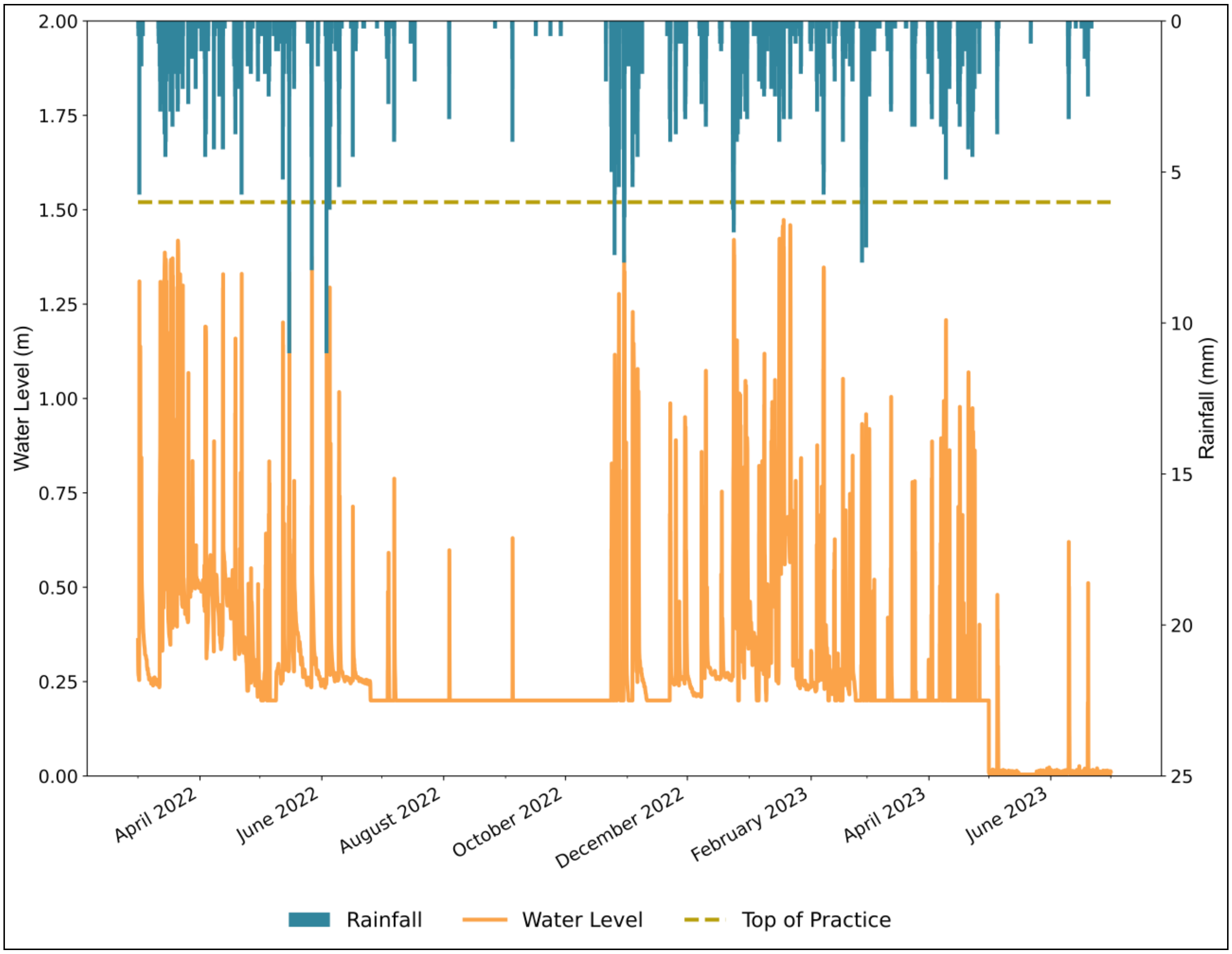


Figure 13 Hourly water level response at Haro St. and Bidwell St. dry well and hourly rainfall response at West End rain gauge

The water level in the dry well is very responsive to rain events. The water level does fill the dry well, but never reaches the top of the practice. The dry well contains standing water at the bottom for most of the year, which is to be expected since there is a portion at the bottom that is not perforated and the system is not free draining. During the summer months, the dry well does dry up completely (step change in May 2023 accounts for this by correcting the baseline, per Figure 13). Sediment monitoring has been occurring in the dry well since April 2022. Since the completion of construction in 2021 to May 2023, 10 cm of sediment has accumulated at the bottom, which accounts for 30% of the sump and less than 10% of the whole system. The dry well does have quick drawdown time, and a drawdown rate that is almost double the design infiltration rate. Storm events, drawdown duration and rates and comparison to design infiltration rates are shown in Table 5.

Table 5 Haro St. and Bidwell St. dry well water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	76	21	4	101
Drawdown Duration (h)	11.3	12.6	29.7	12.3
Drawdown Rate (mm/h)	98.5	77.8	43.0	92.0
Design Infiltration Rate (mm/h)	47			
% change	110%	65%	-8%	96%

1.6.5 Haro St. and Jervis St. Bioretention

The first of two systems on Haro Street constructed between March and June 2021, is a bioretention system receiving road runoff from a 530 m^2 residential area. This system features an inlet with a sediment pad, and an additional curb inlet at the downstream end to capture any bypass. Water level has been monitored between February 2022 to present using Novion loggers. The site had a design infiltration rate of 5 mm/h. This system has shown a response to 99 storm events since monitoring began, with quick drawdown durations averaging under 20 hours and drawdown rates greater than the design infiltration rate. Storm events, and water level analysis are shown in Table 6.

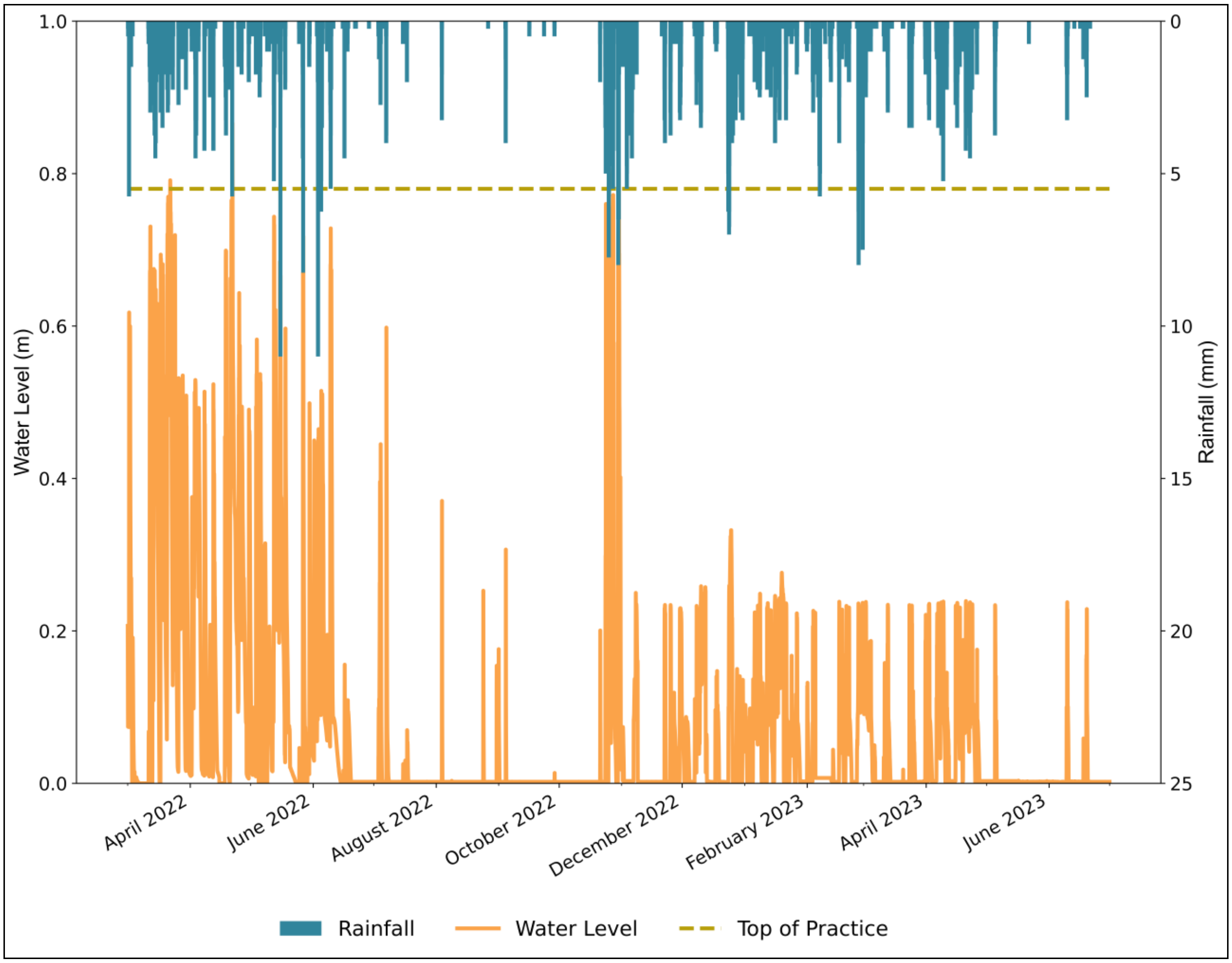


Figure 14 Hourly water level response at Haro St. and Jervis St. bioretention and hourly water level response at West End rain gauge

Table 6 Haro St. and Jervis St. bioretention water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	76	20	3	99
Drawdown Duration (h)	18.2	19.3	20.5	18.5
Drawdown Rate (mm/h)	20.9	18.9	24.4	20.6
Design Infiltration Rate (mm/h)	5			
% change	317%	278%	388%	311%

1.6.6 Haro St. and Bute St. Bioretention

The second of two systems on Haro Street constructed between March and June 2021, is a bioretention receiving road runoff from a 150 m^2 residential area. The subsoils in this area were described as being coarse sand with some gravel. This system has an inlet and outlet catchbasin that are quite close together, which was unavoidable due to the presence of other infrastructure. A ponding depth of 15 cm between the inlet and outlet help to spread out the water before overflow occurs. Water level has been monitored between February 2022 to present using Novion loggers. The site was design with a design infiltration rate of 5 mm/h. Due to the very small water level response of less than 5 cm per event for the majority of events (see Figure 15), the drawdown duration and drawdown rate was not analyzed.

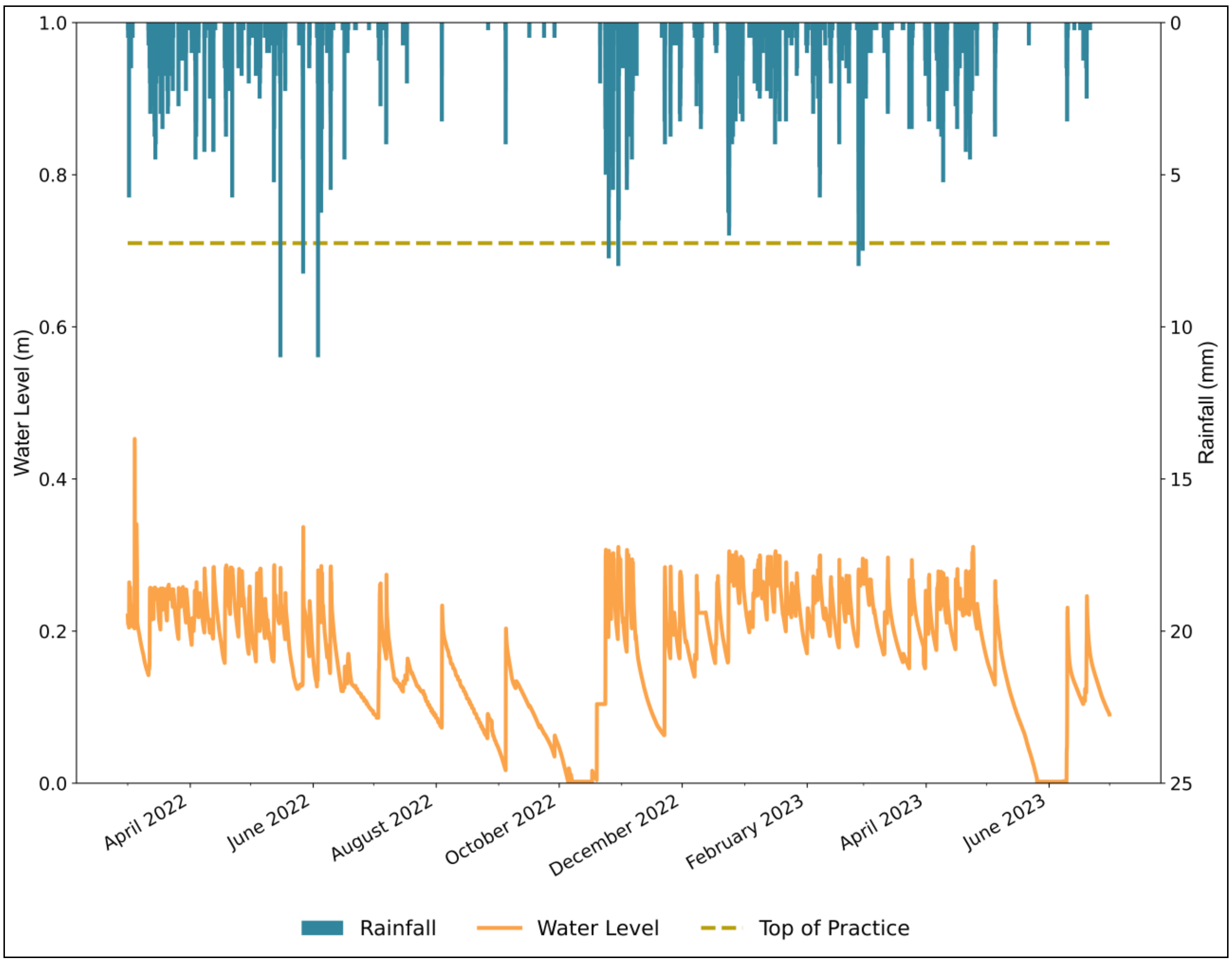


Figure 15 Hourly water level response at Haro St. and Bute St. bioretention and hourly rainfall response at West End rain gauge

1.6.7 W 10th Ave. and Heather St. RTT

A rainwater tree trench was constructed along West 10th Avenue in 2021. It manages a drainage area of 2,475 m^2, and has an area of 88 m^2 of structural soil for tree soil volume and water volume management. There are two monitoring wells, one near each inlet. There are two impermeable subsurface check dams, to encourage infiltration and force a flat area along this 2.5% sloped system. The design infiltration rate is 50 mm/h, and via boreholes, the native soil was found to be silty sand.

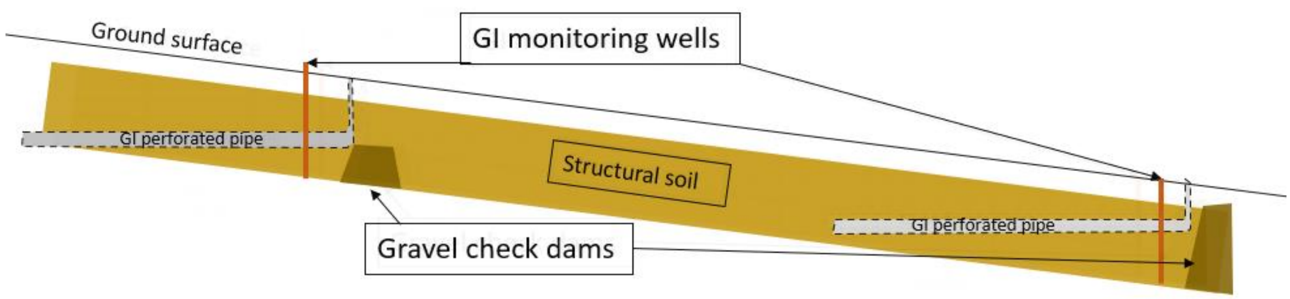


Figure 16 Schematic of W 10th Ave. and Heather St. RTT, with the West well on the left and the East well on the right

The two monitoring wells at this location use Novion loggers, and have been in place since February 2022.

1.6.7.1 W 10th Ave. and Heather St. RTT West Well

The West well had water level responses for most storm events. The water level never exceeds the check dam, as shown in Figure 17. Although, this well has very quick drawdown times, and an average drawdown rate of 35 mm/h, it is still slightly underperforming compared to its design infiltration rate of 50 mm/h. Storm events, drawdown duration and drawdown rate summary is found in Table 7.

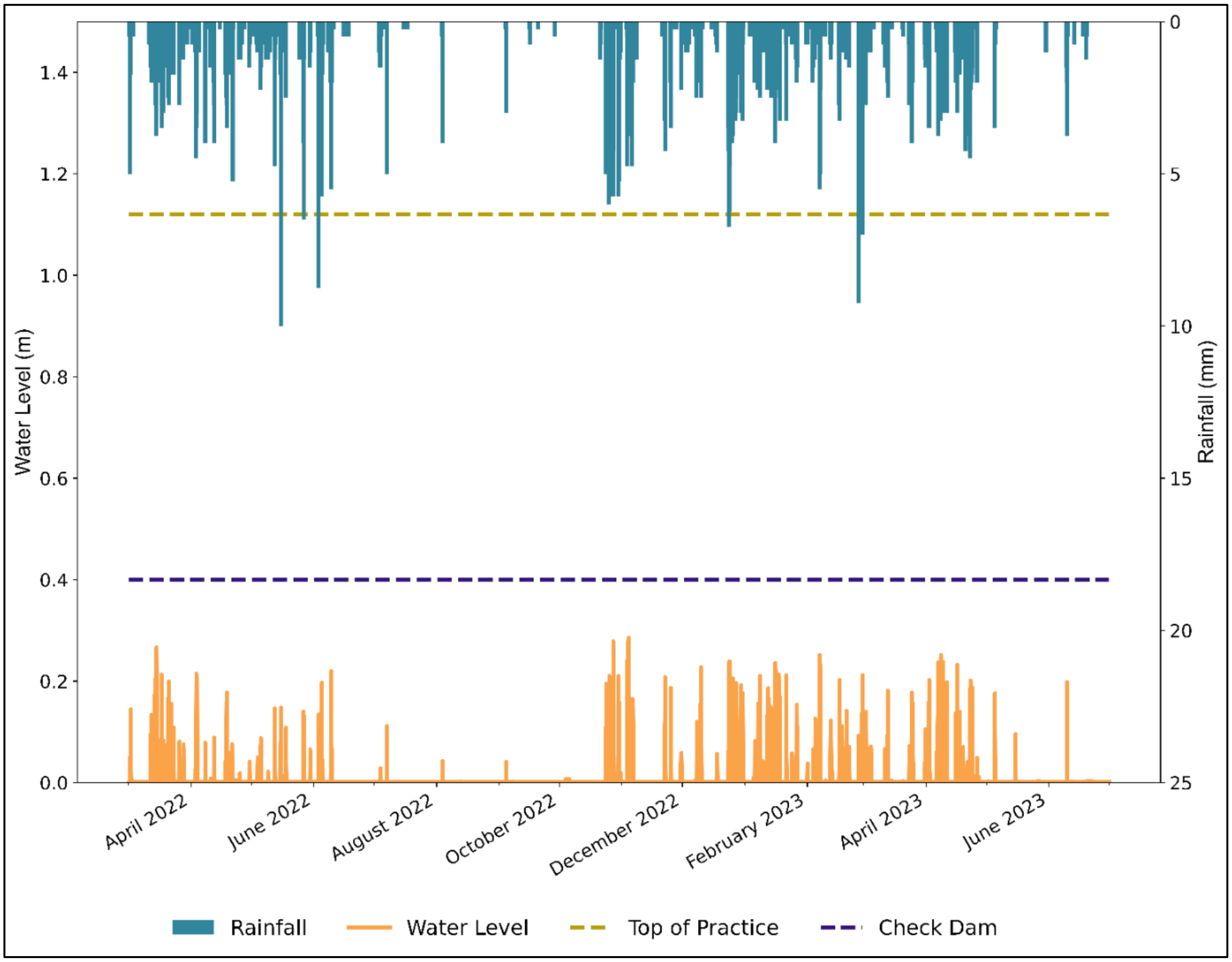


Figure 17 Hourly water level response and W 10th Ave. and Heather St. West RTT and hourly rainfall from Vancity rain gauge

Table 7 W 10th Ave. and Heather St. West RTT water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	77	16	4	97
Drawdown Duration (h)	4.3	8.2	8.6	5.2
Drawdown Rate (mm/h)	36.2	34.8	31.5	35.8
Design Infiltration Rate (mm/h)		50		
% change	-28%	-30%	-37%	-28%

1.6.7.2 W 10th Ave. and Heather St. RTT East Well

The East well is also very responsive to storm events, and water levels are much higher than in the West well. On one occasion, the water level exceeded the check dam at this location, but the water level has never reached the top of the practice (Figure 18). Similar to the west well, the drawdown times are high, but the drawdown rate is slightly underperforming compared to the design infiltration rate. Storm events, drawdown times and drawdown rate summary is found in Table 8.

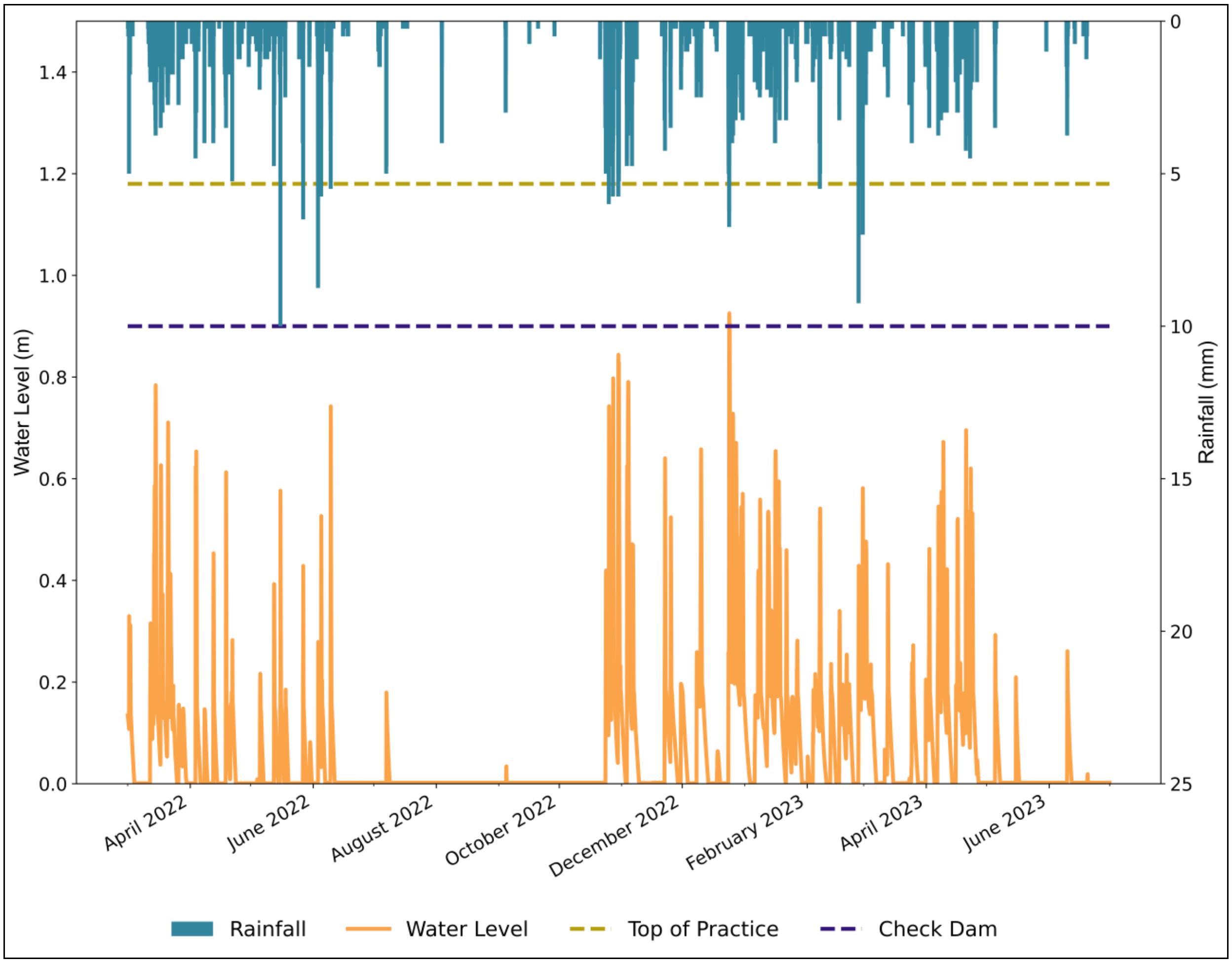


Figure 18 Hourly water level response at W 10th Ave. and Heather St. East RTT and hourly rainfall response at Vancity rain gauge

Table 8 W 10th Ave. and Heather St. East RTT water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	38	16	4	58
Drawdown Duration (h)	25.73	15.79	21.54	22.7
Drawdown Rate (mm/h)	18.9	53.6	36.8	29.7
Design Infiltration Rate (mm/h)	50			
% change	-62%	7%	-26%	-41%

1.6.8 Harriet Laneway Infiltration Trench

A laneway infiltration trench was constructed in summer 2022, and then extended to take on private property drainage in Fall 2023. Harriet Laneway has an impervious area of 924 m^2 which is managed by an infiltration trench with a footprint of 60 m^2. From geotechnical investigations, two boreholes were completed at this site and saturated hydraulic conductivity tests were performed using a Guelph Permeameter. Borehole 1 located at the south end of the practice had a soil type of silt, sandy with some trace gravel and clay at 1 m bgs. Guelph permeameter data collected at this location had a saturated hydraulic conductivity value of 3.4 mm/h. Borehole 2 located at the north end of the practice consisted of silt and sand with some to traces of clay and gravel (till-like) and had saturated hydraulic conductivity that ranged between 0.030 and 0.034 mm/h. Another infiltration test performed when the trench was freshly dug found a saturated hydraulic conductivity of 0.14 mm/h. The system was designed with an infiltration rate of 1 mm/h. The soil conditions were also indicative of seasonally variable groundwater conditions.

Water level monitoring using Novion loggers has occurred from September 2022 to present (see Figure 19). The results from Harriet Laneway show that there is quick drawdown whenever the driving head is high, and that there is a long tail and slower drawdown whenever the driving head is low (0.2 m or lower). This system did not see response to storm events that are smaller than 24 mm, likely as those were fully infiltrated before reaching the monitoring well. This is a fully infiltrating system, and the only overflow is via surface flow to the next downstream catchbasin. Storm events, drawdown durations and drawdown rate summary is found in Table 9.

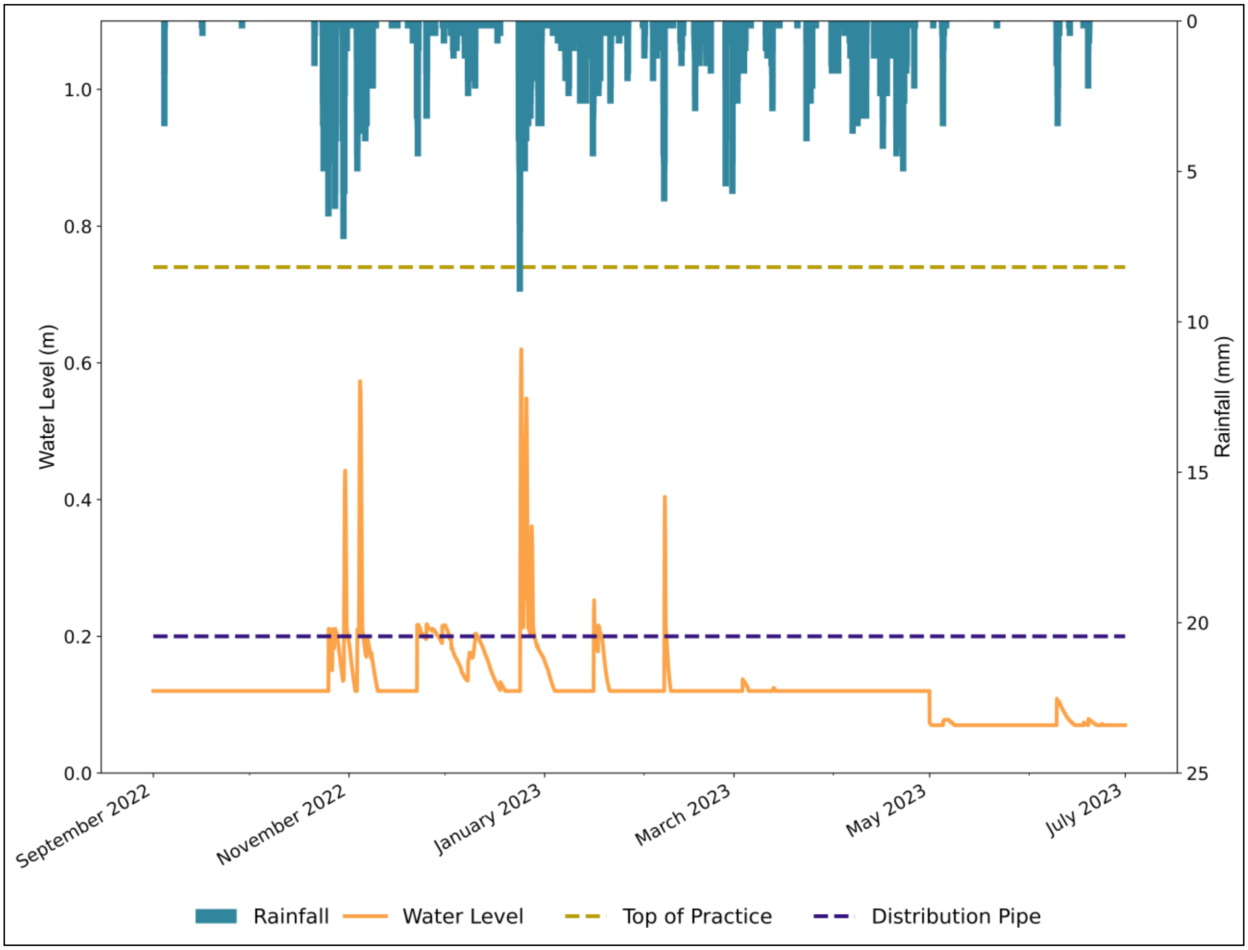


Figure 19 Hourly water level response at Harriet Laneway and hourly rainfall response at Trout Lake rain gauge

Table 9 Harriet Laneway infiltration trench water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	0	6	4	10
Drawdown Duration (h)	-	30.1	49.2	37.7
Drawdown Rate (mm/h)	-	4.1	11.2	6.9
Design Infiltration Rate (mm/h)			1	
% change	-	310%	1020%	590%

1.6.9 Woodland Dr. and 2nd Ave. Bioretention

A bioswale located on Woodland Drive between 1st and 2nd Ave. has a footprint of 140 m^2 managing runoff from a 2600 m^2 of impervious area. It was constructed between March and September 2022. Infiltration testing was done with a Guelph permeameter prior to install, and the saturated hydraulic conductivity was less than 1 mm/h. The system was designed with an infiltration rate of 1 mm/h. From geotechnical investigations, the soil type was found to be silty sand with trace gravel at 1 m below ground surface (bgs). No water was observed in the test hole, however mottled gray soil indicated a possible shallow perched groundwater table during the winter months.

The bioswale system contains three cells divided by granite blocks and log weir structures. The granite blocks are from recycled city curbs. The first cell receives runoff directly from the east side of Woodland Dr. (between 1st Ave. and the laneway), the second cell is an overflow to the second cell, and the third cell receives runoff via pipes from the west side of Woodland Dr. (between 1st Ave. and the laneway) and the laneway to the east of the bioswale. A HOBO water level logger installed by the City is in the first cell (North well), and a Novion logger is located in the third cell (in a smaller diameter monitoring well pipe, South well). The whole bioswale is connected at the subsurface, as a clear stone trench with an underdrain is connected under all three cells. Given the monitoring results below, we have begun a pilot where the underdrain outlet is restricted to a very small opening size (<25 mm), to see if we can see encourage further infiltration and reduce drainage to the sewer system, while ensuring we do not have overflows or over saturating the system.

1.6.9.1 Woodland Dr. and 2nd Ave. North Well

The North well experienced the most water level response in the heavy rainfall winter season as shown in Figure 20. This well experiences quick drawdown durations and drawdown rates well above the design infiltration rate. Storm events, and water level responses are shown in Table 10.

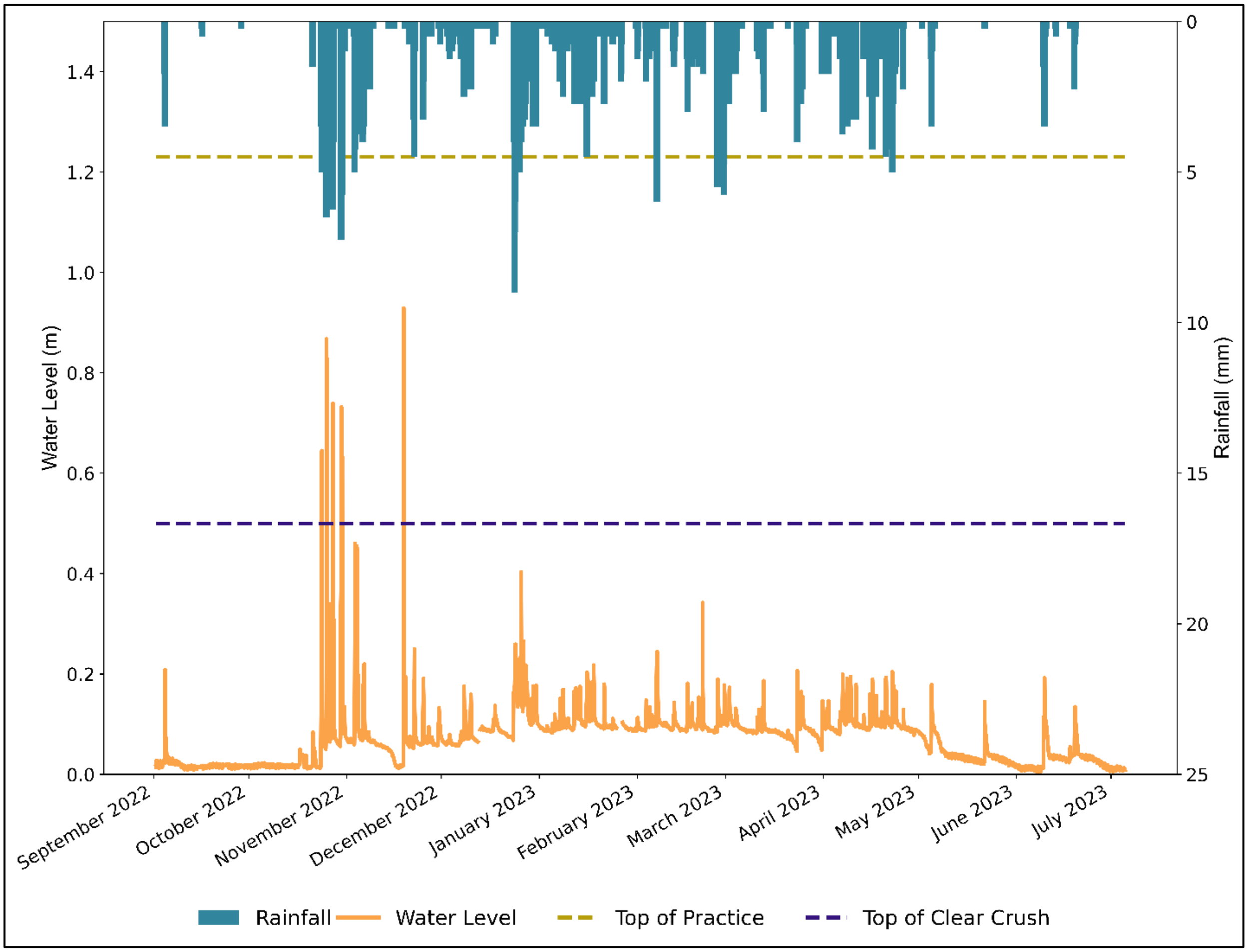


Figure 20 Hourly water level response at Woodland Dr. and 2nd Ave. North bioretention and hourly rainfall response at Trout Lake rain gauge

Table 10 Woodland Dr. and 2nd Ave. North bioretention water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	32	12	4	48
Drawdown Duration (h)	18.2	16.8	26.3	18.5
Drawdown Rate (mm/h)	8.0	25.1	18.5	13.1
Design Infiltration Rate (mm/h)		1		
% change	700%	2410%	1750%	1210%

1.6.9.2 Woodland Dr. and 2nd Ave South Well

The South well containing the Novion loggers was slightly less responsive to storm events than the North well. However, data for several storm events in January 2023 was removed from the analysis due to the venting tube in the logger becoming clogged causing erratic and unrepresentative water level responses. This well also experiences quick drawdown durations and drawdown rates greater than the design infiltration rate. Storm events and water level analysis are found in Table 11.

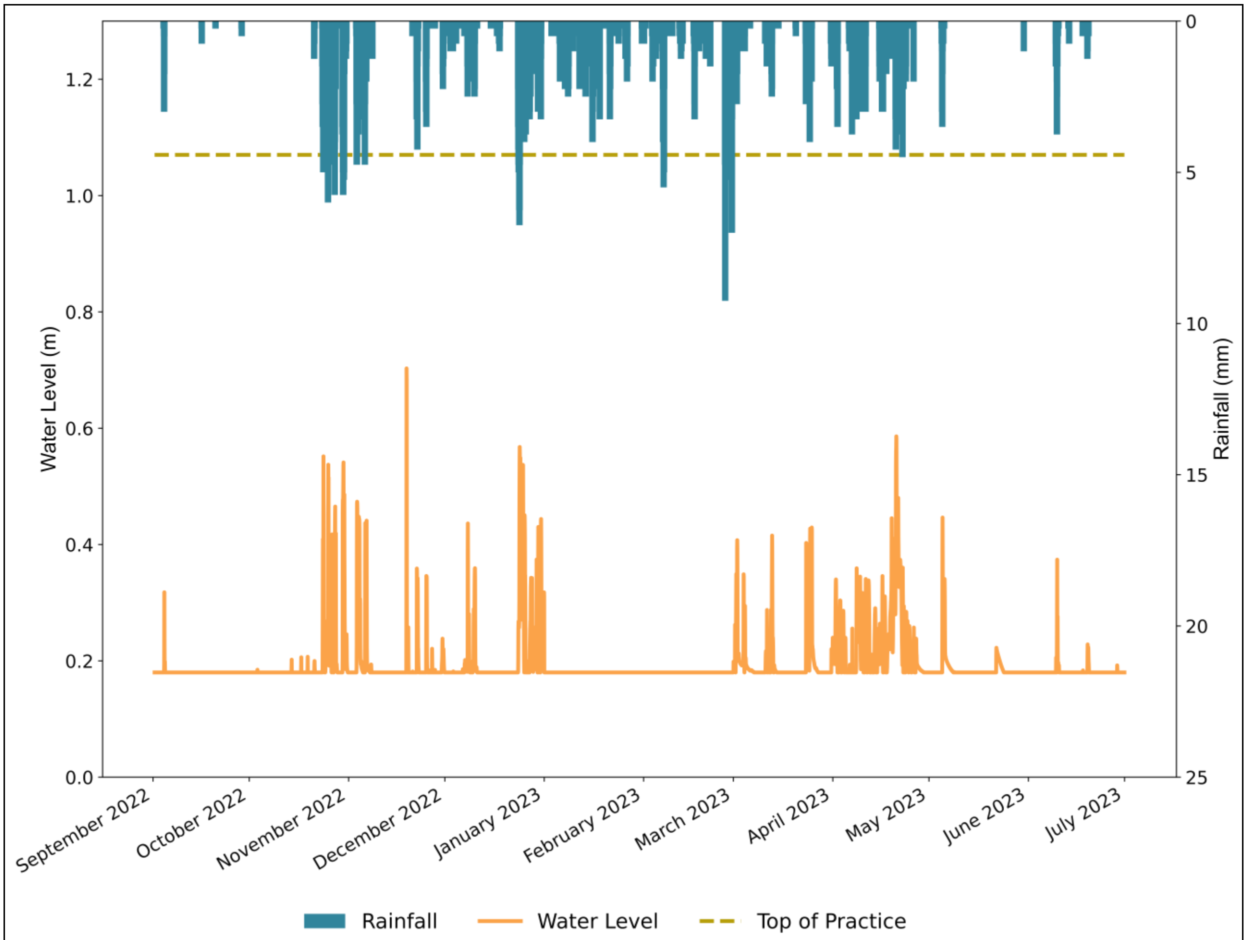


Figure 21 Hourly water level response at Woodland Dr. and 2nd Ave. South bioretention and hourly rainfall response at Trout Lake rain gauge

Table 11 Woodland Dr. and 2nd Ave. South bioretention water level analysis

Storm Category	Normal (under 24 mm)	Large (between 24 and 48 mm)	Extreme (larger than 48 mm)	Total and average (weighted)
Number of Storm Events	26	8	4	38
Drawdown Duration (h)	6.9	5.1	30.4	9.0
Drawdown Rate (mm/h)	39.7	68.8	22.2	44.0
Design Infiltration Rate (mm/h)		1		
% change	3870%	6780%	2120%	4300%

1.6.10 Summary of water level monitoring

Average drawdown rates and design infiltration rates are summarized in Table 12 below. The bioswales and infiltration trenches had drawdown rates in excess of the design infiltration rate by a considerable difference, with measured drawdown rates 1-43 times higher than design infiltration rate. As noted above, a longer drawdown period was observed at the RTTs on Quebec St. and at W 10th Ave. The slow drawdown at the RTT may be due to media or geotextile layer clogging, though we cannot be certain of the cause. Regardless, the drawdown rates in RTTs are close to the design infiltration rate.

The site with the longest monitoring period, Yukon St. and 63rd Ave. bioretention, shows continued high drawdown rates, including an increase in the average drawdown rate in 2021-2023 compared to 2018-2021.

The purpose of continuous monitoring of water levels in the GRI assets was to compare drawdown rates (the real rate at which water is leaving the system through exfiltration) to the design infiltration rates to determine (1) whether safety factors are correctly applied and (2) whether the drawdown rate decreases over time. A safety factor will be applied at design to a measured in-situ infiltration rate to come up with a design infiltration rate. A high safety factor ensures very conservative designs are implemented, meaning that these systems lose water much more quickly than anticipated. Guidance for design infiltration rates in Ontario previously recommended 2 to 9 (TRCA, CVC, 2010), with more recent updates advising safety factors of 2-3 (STEP, 2020). Based on our monitoring results, we recommend reducing the safety factor to between 1 and 2, instead of higher safety factors of 2 to 9.

Table 12 Summary of water level analysis from all sites

Site	Typology	Average Drawdown Time (h)	Average Drawdown Rate (mm/h)	Design Infiltration Rate (mm/h)	Difference between Drawdown Rate and Design Infiltration Rate (%)
Yukon St. and 63rd Ave.	Bioswale	1.3	497	39	1173
Quebec St. and 2nd Ave.					
South	Soil Cell RTT	27.9	9.4	10	-6
North	Soil Cell RTT	35.9	8.7	10	-13
Richards St.					
Block H	Bioretention	13.8	40.3	5	706
Haro St. and Bidwell St.	Dry Well	12.3	92	47	96
Haro St. and Jervis St.	Bioretention	18.5	20.6	5	311
Haro St. and Bute St.	Bioretention	N/A	N/A	N/A	N/A
W 10th Ave. and Heather St.					
East	RTT	22.7	29.7	50	-41
West	RTT	5.15	35.8	50	-28
Harriet Laneway	Infiltration Trench	37.7	6.9	1	590
Woodland Dr. and 2nd Ave.					
North	Bioretention	18.5	13.1	1	1210
South	Bioretention	9	44	1	4300
Average		16.5	72.5		

1.7 Objective 4: Soil moisture monitoring

We would like to know whether the soil moisture range in the observed practices is amenable to vegetation health. Soils used in GRI practices are typically sandy (>70% sand content), and as the wilting point for sand is usually 5-10%, we want to ensure that our GRI systems remain above 5% moisture content. We also know that overly saturated conditions are also detrimental for some plants, and saturation for sandy soils is 35-40% or greater. While saturation may occur for short periods during rain events, GRI systems should drain within 72 hours.

1.7.1 Quebec St. and 1st Ave. Location C RTT

Location C RTTs manages stormwater runoff from a drainage area of 415 m^2. Location C has three soil sensors measuring volumetric water content, electrical conductivity and temperature that were installed during construction at depths of 20-cm, 40-cm and 60-cm. The 40-cm sensor displays erratic readings and is believed to have been damaged during construction. For this reason, data from the 40-cm sensor has been omitted from the analysis. A data logger was connected post-construction to continuously log the data. Soil monitoring has been occurring since September 2018.

The soil moisture in the RTT displays very little seasonal variation throughout the monitoring period. The soil moisture at the 60-cm depth varies between 21%-40%, and the 20-cm depth varies between 23-33%. Slight dips in volumentric water content (VWC) readings are noticeable in August and September of 2021 and 2022, which correlates to a period of less rainfall. The placement of the sensors in the structural soil under the bike path may be able to explain how little seasonal variation there is, as moisture is not lost through soil evaporation. Rainfall and VWC for the entire monitoring period along with several data gaps are shown in Figure 22.

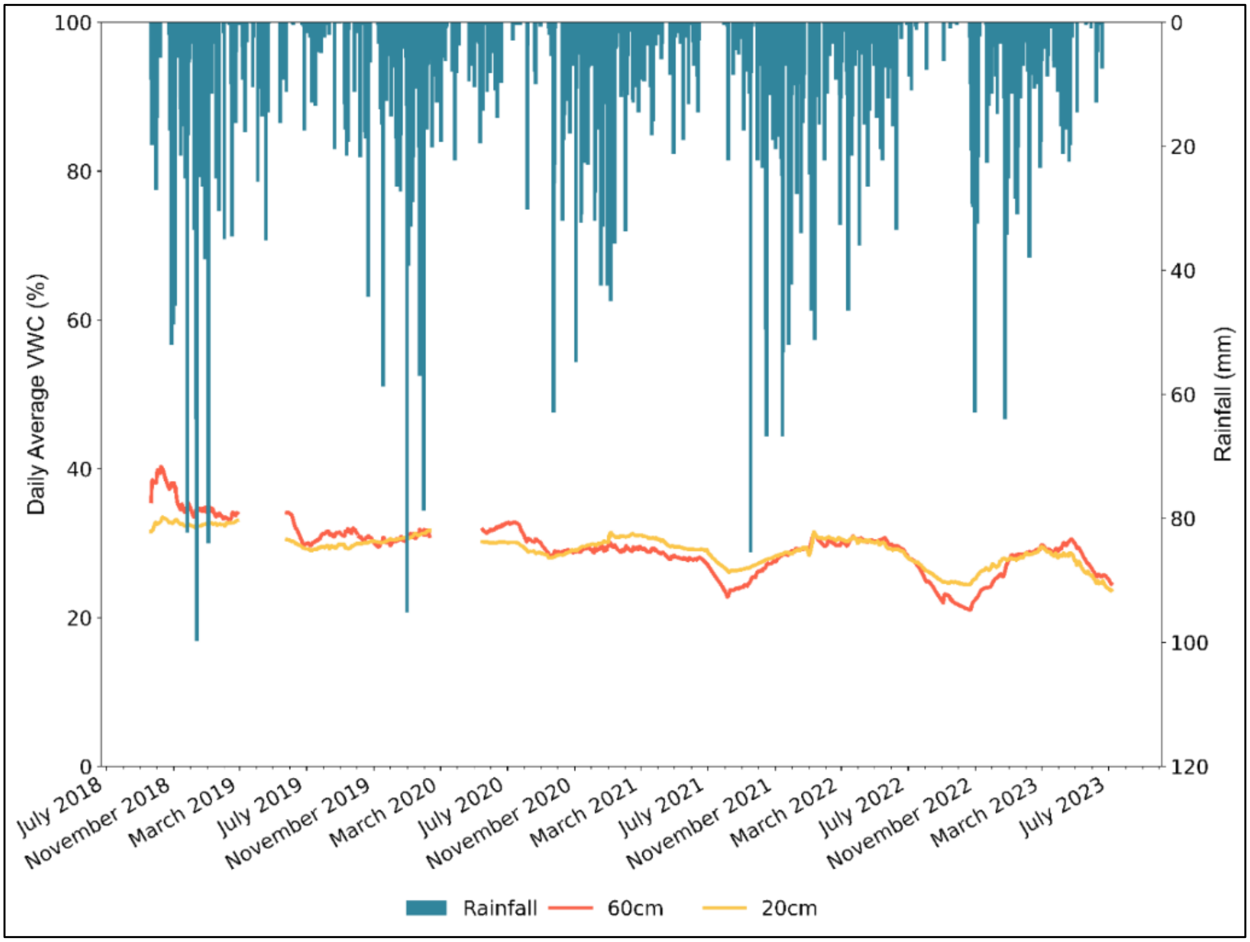


Figure 22 Daily average volumetric water content at 20-cm and 60-cm depth at Quebec St. and 1st Ave. Location C RTT and daily rainfall at Creekside rain gauge

1.7.2 Quebec St. and 1st Ave. Location D Bioswale

Location D bioswale manages stormwater runoff from a drainage area of 630 m^2. Location D has a monitoring well with a water level logger that was installed in October 2018, with an additional in situ barometric logger installed in March 2020. The water level loggers has since died and the resutls are not included in this report. Two soil sensors installed during construction at depths of 20-cm and 40-cm measure volumetric water content, electrical conductivity and temperature. A data logger was connected post-construction to continuously log the data. Soil monitoring has been occurring since September 2018.

Both soil sensors installed in the bioswale are functional and provide data on volumetric water content, electrical conductivity and temperature since October 2018, however there are some intermittent data gaps where sensors disconnected from the logger, and it is likely that the 20-cm sensor is no longer functioning given the lack of rainfall response in 2023. Seasonal variation in moisture levels is very apparent, with moisture levels being at the highest during the wet seasons when there is the greatest amount of rainfall, and the lowest during the hot dry summer months. The moisture levels at 20-cm depth range between 5-46% over the monitoring period and the moisture levels at 40-cm range between 5-50%. The moisture levels at 40-cm depth are generally greater than at the 20-cm depth. The pronounced seasonal variation compared to the other sites is likely influenced by the GRI typology. Being in a bioswale, the soils are more exposed to evaporation and transpiration that can cause moisture loss. The rainfall and volumetric water content for the entire monitoring period is shown in Figure 23.

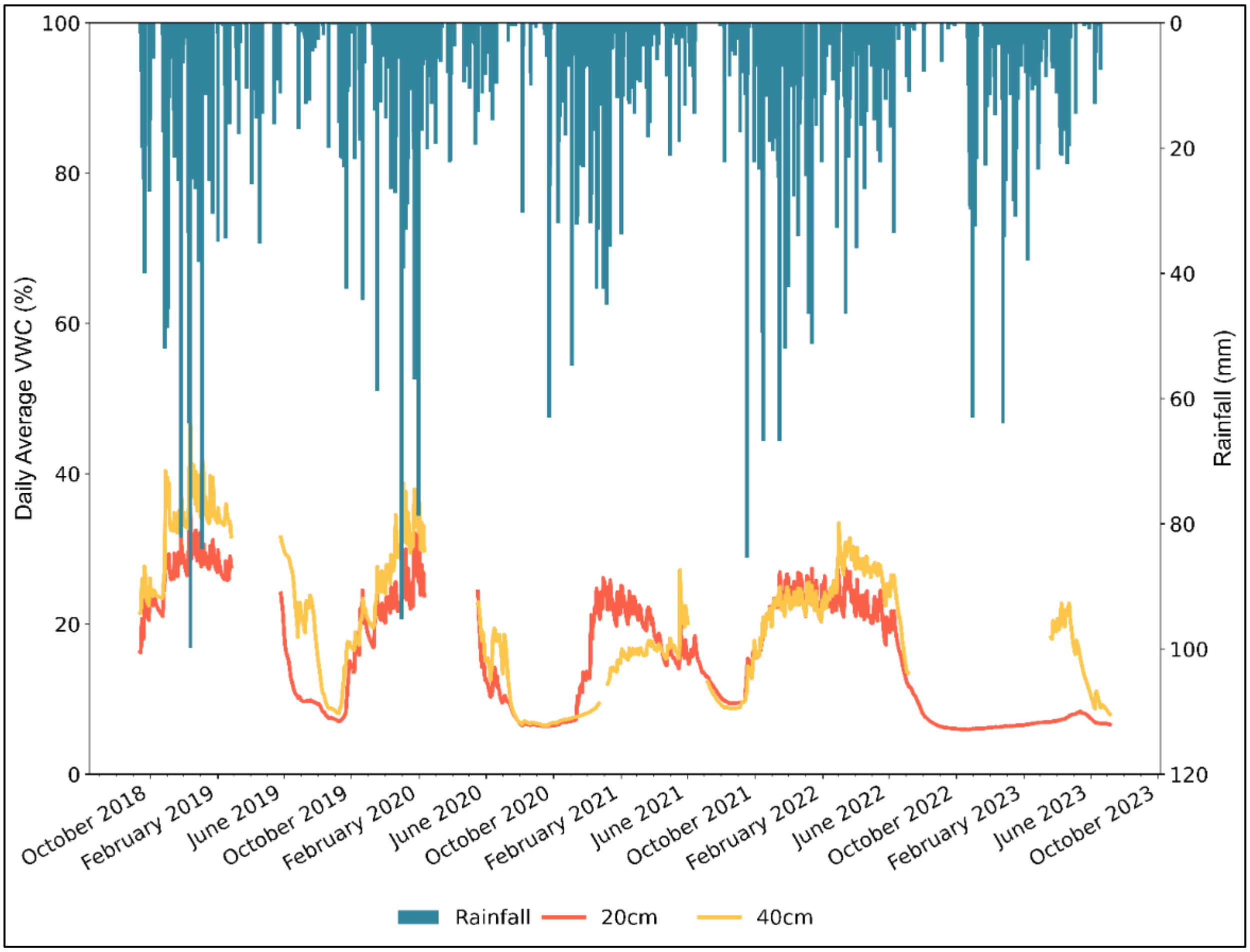


Figure 23 Daily average volumetric water content at 20-cm and 40-cm depth at Quebec St. and 1st Ave. Location D bioswale and daily rainfall at Creekside rain gauge

1.7.3 Expo Blvd. and Smithe St. RTT

The triangle island located at the intersection of Smithe St. and Expo Blvd was identified as a suitable location for a GRI practice. It was constructed starting in late 2018, extending into 2019. The practice uses soil cells to treat the stormwater runoff and support tree health. This practice manages a drainage area of 351 m^2. The design also features an underdrain that drains excess treated stormwater to the storm sewer system, and permeable pavers that allow for rainwater to infiltrate. The design assumes low or zero infiltration at this location. Two soil sensors that measure volumetric water content, electrical conductivity and temperature were installed at depths of 20-cm and 40-cm during construction. The soil sensors were connected to a data logger in September 2020.

Soil moisture monitoring at this site has been very variable throughout the monitoring period. The 20-cm sensor has been very reactive to rainfall events, especially during the wet weather seasons, but drops over the dry seasons. Overall, the 20-cm soil VWC ranges from 20%-60% over the course of the monitoring period. The 40-cm sensor displays a large drop in December 2021, and remains below 20% VWC after that time, except for large rain events where it peaks sharply. This large decrease in VWC in December occurs only over a span of 10 minutes, leading us to believe that something may have happened to the sensor tip or the surrounding area leading to this change, and may not be representative of the soil moisture at this location. The 40-cm soil VWC ranges from 3-63% (see Figure 24).

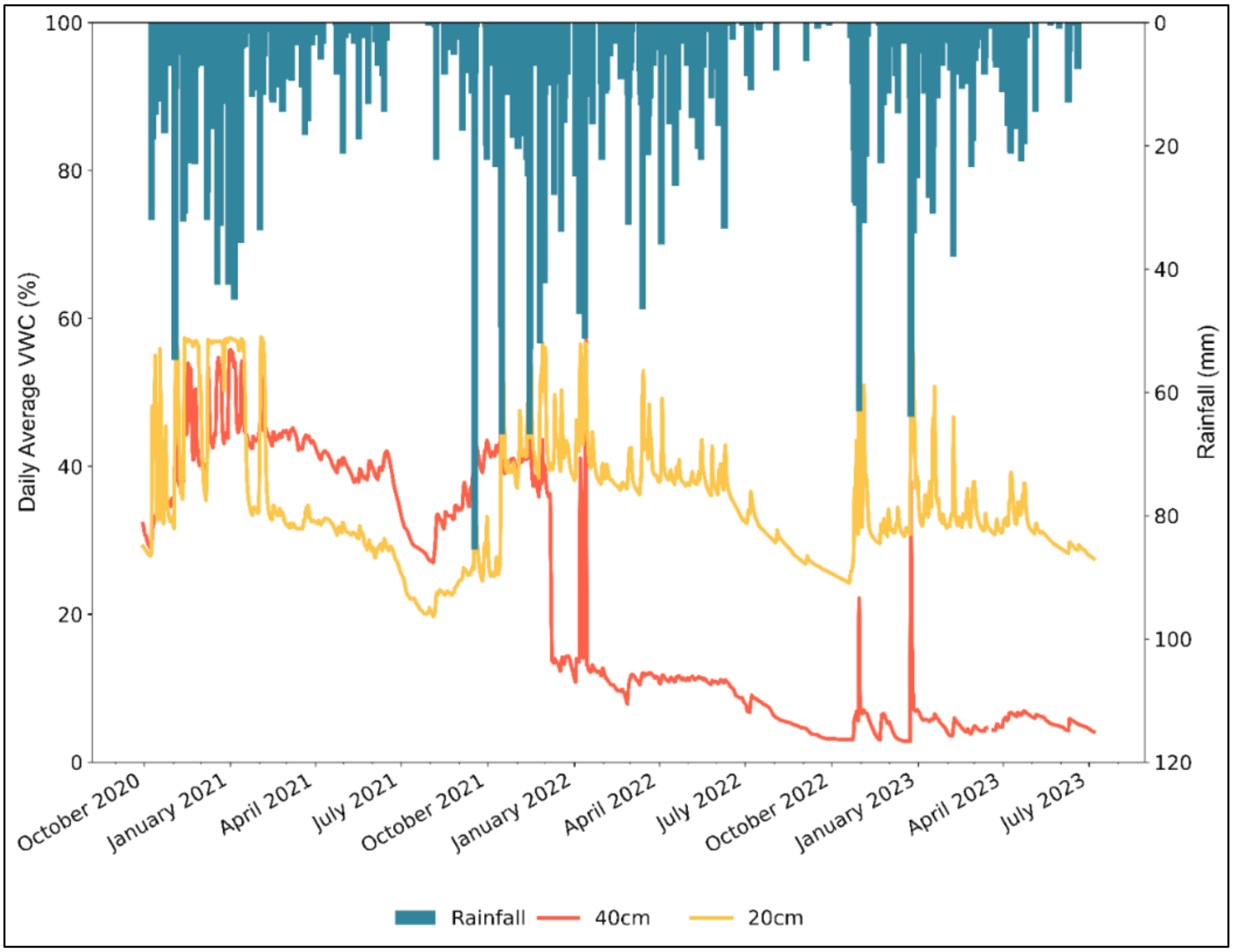


Figure 24 Daily average volumetric water content at 20-cm and 40-cm depth at Expo Blvd and Smithe St. and daily rainfall from Creekside rain gauge

At site visits, the tree appears in good health. Weeds have been noticed to grow out from the joints of the permeable pavement, reaching heights of greater than 1 m in some cases, requiring additional summer maintenance. We suspect due to the location, there is not a lot of foot traffic over the permeable pavement to prevent this level of growth.

Photo of permeable pavement at Expo & Smithe, September 2020

1.7.4 Richards St. RTT and Bioretention

The Richards Street project is an eight block GI-led project located in downtown Vancouver between Dunsmuir St. and Pacific St. As part of bike lane upgrades being made in the area, rainwater tree trenches were incorporated into the design to collect runoff from the bikeway and roadway. The project also features permeable pavers that allow water to infiltrate through the surface. The project consists of 100 new street trees planted in the median – a mixture of Brandon Elms, American Hornbeams and River Birches, as well as a bioswale with Permavoid drainage units. Construction took place from May 2020-November 2021.

Soil moisture sensors were installed here to monitor plant health and to ensure moisture levels around electrical conduits remain above 10%. All the blocks at Richards St. with the exception of Block B and Block E have intact soil sensors providing data on volumetric water content, electrical conductivity and temperature. The Block B sensor is not included as it had highly variable readings and it was determined the data was unreliable. The sensor in Block B is installed directly into structural soil, and perhaps the prongs of the sensor may either be in an air pocket and not in proper contact with the soil or might have been damaged during the remaining construction of the block.

All sites had free draining soils, except for Block H which had a tank product with wicking tiles, called permavoid, beneath the soil, which allows plants to access the water in the tank via wicking. Block H soil moisture was always above 20%, but then so were other free-draining blocks in structural soil, such as Blocks C, D and F. Block A demonstrates the greatest variation of all the blocks, with the VWC dropping during the summer months when there is less rainfall. We are unsure what characteristics lead to Block A having more moisture loss in the summer than the other blocks. The rest of the blocks remain above the 10% minimum. Monthly maximum, monthly minimum and monthly mean VWC can be seen in Figure 25 for all blocks over the course of their respective monitoring periods.

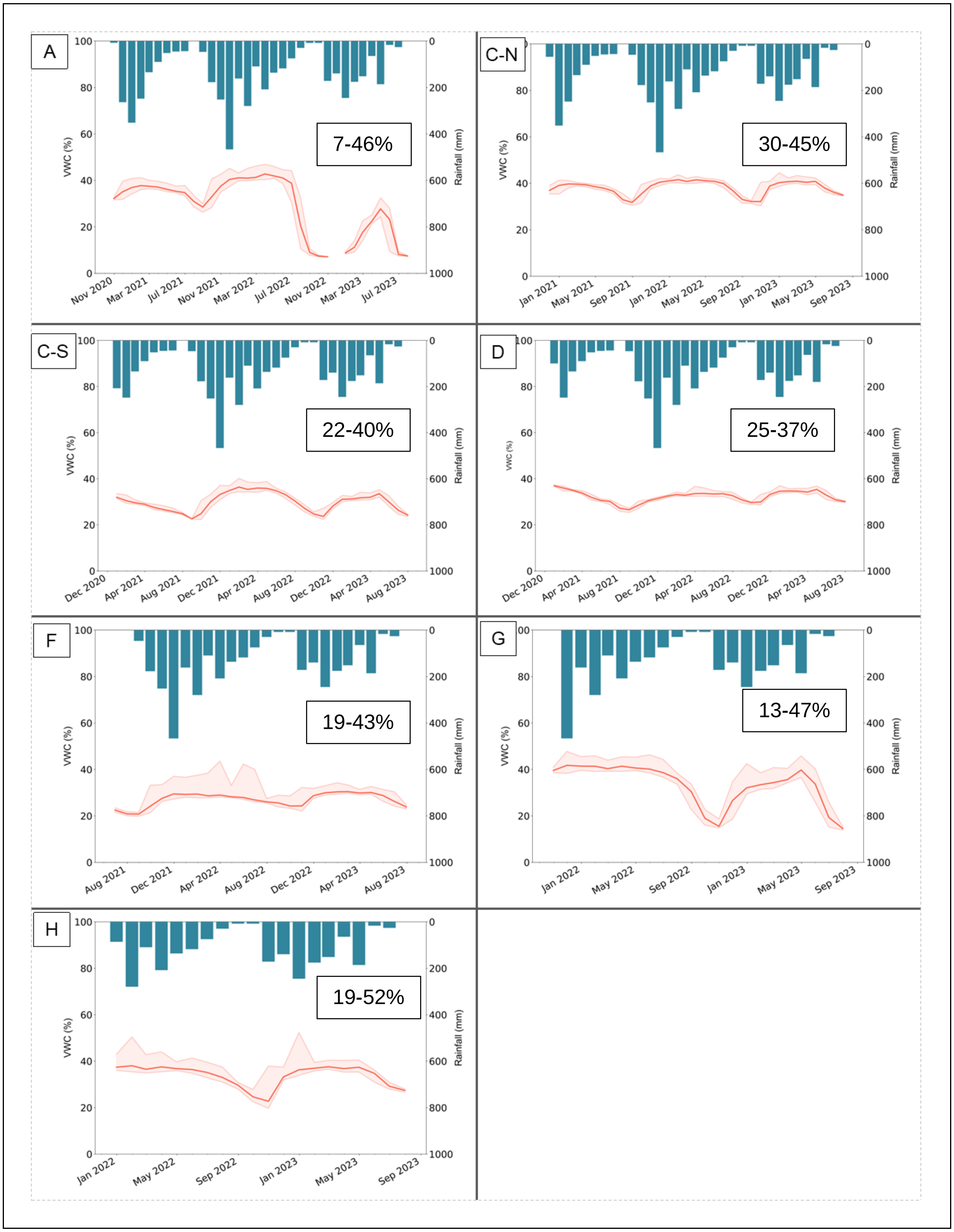


Figure 25 Monthly maximum, monthly minimum, and monthly mean volumetric water content of Richards St. project, with full ranges shown in text, for A) Block A, C-N) Block C North, C-S) Block C-South, D) Block D, F) Block F, G) Block G, H) Block H and rainfall from Creekside rain gauge

1.7.5 Summary of soil moisture monitoring for plant health

The effect of soil moisture on plant health is not easily discerned from the data collected at the bioswales and RTTs during the monitoring period. During the dry summer periods, a decrease in soil moisture was observed at all monitored sites, though the volumetric water content was not below 5% at any sites. Plant die-off associated with extended summer dry periods was not observed, however this is not a reliable evaluation metric as all sites are newly constructed and under an establishment period with supplemental watering provided. Given this, continued monitoring of plant health and soil moisture over the long term and post-establishment period will be necessary to discern any trends. For example, Richards Street RTTs were constructed in 2020-2021 and so limited soil moisture data is currently available. Future monitoring reports will contain results related to tree growth along Richards Street, which will contribute to our understanding of plant health in GRI systems.

As can be seen throughout this section, there are several issues with reliability of sensors as they age within subsurface systems, and we cannot change or update the sensor without removing paved surfaces and a significant construction effort. It is difficult to know when a large drop is due to loss of soil moisture, or an issue with the sensor or the location of the sensor in soil.

1.8 Objective 5&6: Volume managed and water quality

We conducted synthetic runoff tests at two bioretention systems in 2021 and 2022. The first purpose of these tests was to determine the water volume managed by the GRI system. The second purpose was water quality, and contaminants were injected into the bioretention system to determine their mass removal.

1.8.1 Study 1: Quebec St. and 1st Ave.; TSS, metals and nutrients

In 2021 at Quebec St. & 1st Ave. Location E bioswale, we used a hydrant to inject approximately 14,000 L of clean water into the bioswale. We were attempting to mimic a storm event of 48 mm, and injected the equivalent of 52 mm across the 270 m^2 catchment area. We also applied a total suspended solids (TSS) concentration equivalent to approximately 130 mg/L via injecting solids collected from the City's street sweeping program. Only 2,900 L of water was measured leaving the underdrain, which corresponds to a volume reduction of 77%. The remaining water was either absorbed or exfiltrated. From a mass removal perspective, we saw a TSS load reduction of >99% (Kerr Wood Leidel, 2022). Approximately 1,600 g of solids were injected at the inlet, and only 6.75 g of solids were measured at the outlet. The full study methodology and results are shown in Appendix B. The results from the flow portion of study were used to calibrate hydrologic models for the performance of GRI assets internally.

1.8.2 Study 2: Pine St. and 8th Ave., 6PPD-quinone and emerging contaminants of concern

In 2022, we conducted another synthetic runoff test to assess the volume managed portion of our active systems. We arranged a water truck to inject 14,172 L of clean water into our system, and we measured the rate of flow at the inlet and at the underdrain outlet with the bucket-timer method. This volume was equivalent to a 21 mm event across the 676 m^2 catchment area for the Pine St. and 8th Ave. bioretention system. Figure 26 shows the hydrograph at the inlet and underdrain outlet for this test. A total of 3,366 L were estimated to flow out of the underdrain outlet, meaning that 76% of water was retained in the bioretention system.

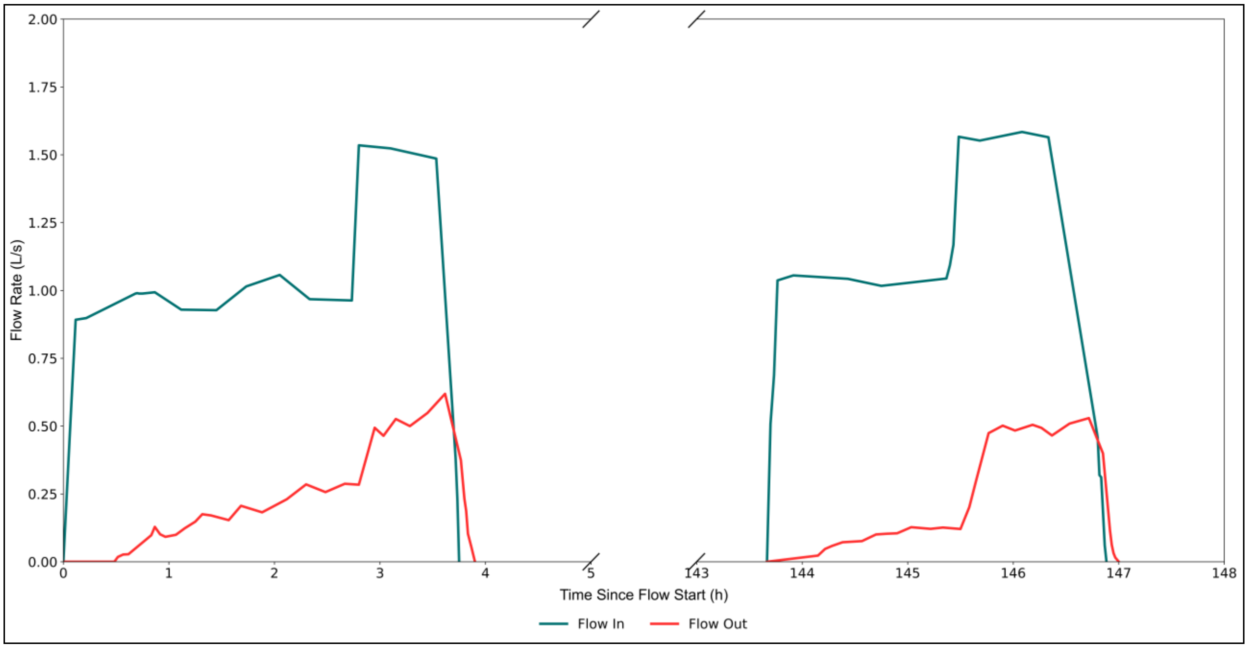


Figure 26 Hydrograph at the inlet and outlet of Pine St. and 8th Ave. synthetic run-off test, July 2022

We were also contacted by researchers at the University of British Columbia about testing GRI for emerging contaminants of concern. A mixture of rhodamine (tracer dye), 6PPD-quinone and bromide (a conservative tracer) were mixed with water and then injected at the inlet. Once pink water was seen at the underdrain outlet, we began to collect samples. One week following the injection test, a second injection of clean water from a water truck occurred, and samples were collected at the underdrain outlet. The researchers found an almost 98% mass removal of 6PPD-quinone from this bioretention system during this test (Rodgers et al, 2023). Refer to the study by Rodgers et al (2023), located in the Environmental Sciences Letters and in Appendix C.

Optimization Monitoring Results

1.9 Objective 7: Permeable pavement cleaning

Several permeable interlocking concrete paver (PICP) assets were built beginning in 2008, and did not receive maintenance prior to 2021. To determine what maintenance activities would be required and at what frequency, we began by conducting infiltration testing combined with cleaning activities. First we conducted infiltration testing without cleaning, and found that all assets failed (test took longer than 30 minutes, or infiltration rate <100 mm/h). Then we conducted vacuum street sweeping and redid the tests, and the infiltration tests were not improved. Next we tried power washing, and found that the infiltration rates were vastly improved, and all assets had >1200 mm/h as their infiltration rate. We then monitored six PICP sites for a period of 5 months after they had received cleaning. All PICP assets monitored failed the infiltration test 1 year after maintenance cleaning. This indicates that the power washing frequency should be annual for PICP assets. Also, we found that some assets could not recover sufficiently after cleaning, such as Site #2 and Site #3 in Table 13, which failed only 7 months after its last cleaning. Sites 1-4 were older assets (2008-2010 construction) that had not been maintained in the intervening time, and so the inability for the asset to recover permeability was to be expected. However Site #5 and Site #6 were newly constructed and were not expected to fail, and further failure in a year following cleaning was also unexpected.

Table 13 PICP infiltration testing results

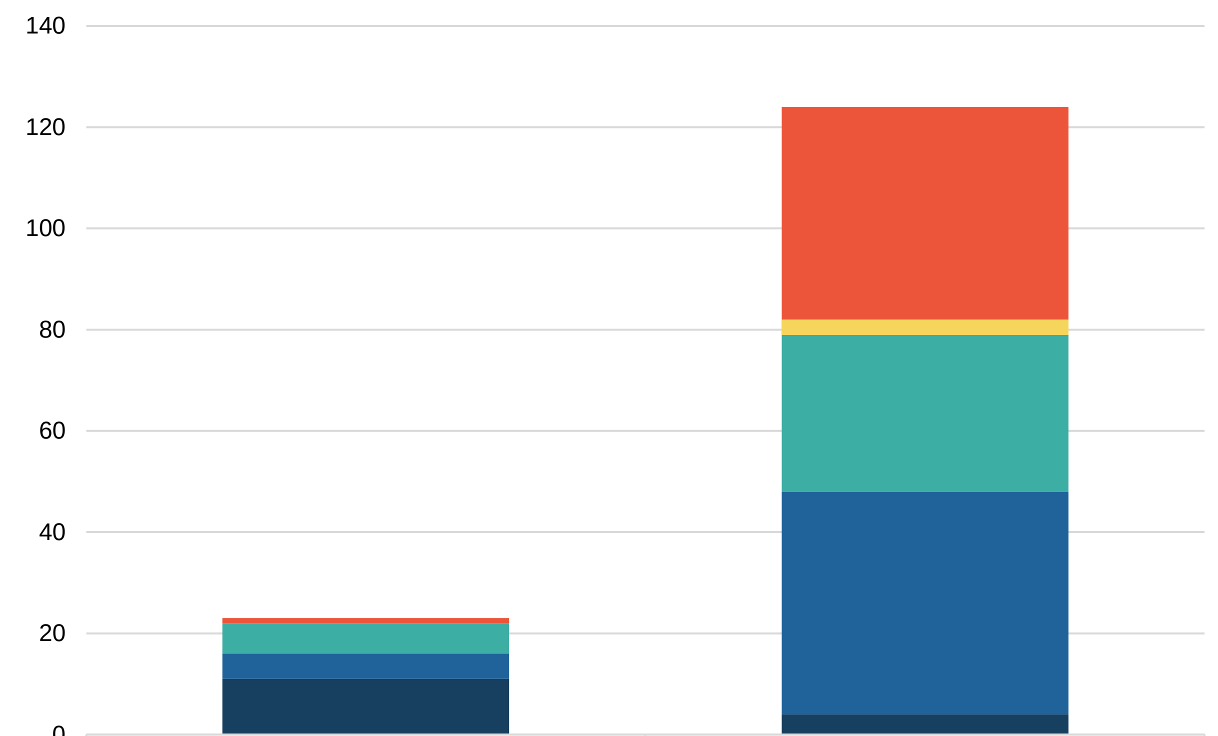
					Infiltration Rate (mm/h)						
Site #	Site Description	Built Year	Practice Size (m^2)	Date of Power Washing	After Power Washing	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	# of Months to <100mm/h
1	Parking layby, Olympic Village	2010	35.1	Aug-21	1200	152	<100	<100	<100	<100	11
2	Parking layby, Olympic Village	2010	35.5	Dec-21	1200	<100	<100	<100	113	<100	6
3	Parking layby, Olympic Village	2010	54.2	Dec-21	1200	<100	<100	<100	<100	<100	6
4	Parking layby, downtown	2008	34.3	Dec-21	1200	132	<100	<100	<100	<100	7
5	Median, downtown	2019	94.9	Sep-21	1200	122	<100	<100	<100	<100	10
6	Median, downtown	2020	113.3	Sep-21	1200	138	450	203	138	<100	13

1.10 Objective 8: Condition assessments of bioretention systems

Condition assessments for 147 bioretention assets were performed in 2022. The scoring system used is 1-5, where 1 indicates best condition, and 5 indicates very poor or failing, which is explained further in Table 14. There were several criteria that were deemed as auto-fails and any site that fit into one of these criteria were given an automatic score of 5. These auto-fail criteria include: missing or demolished, complete short-circuiting at the inlet, complete short-circuiting at the outlet, no ponding depth or standing water after 24 hours. As many of our bioretention assets are corner bulges that were retrofitted for traffic calming, and were not purposefully designed to be bioretention, the results have been divided up by GII Era (designed and implemented following GII Branch establishment in 2016), and Pre-GII Era (not designed by GII staff, prior to 2016) (see Figure 27). Most bioretention assets (124) are from Pre-GII Era, and 42 of them are had condition score 5, indicating failing condition in need of rehabilitation. We currently have a program to rehabilitate a portion of these assets annually. The majority of Pre-GII assets are in condition scores 2 and 3, meaning that they are functioning and require only routine maintenance. For assets designed and constructed since the forming of the GI branch (23 assets), the majority of these are in condition scores 1-3, also meaning only routine maintenance is required. Only one asset is in a failing category, and further investigation is being carried out to determine how to rehabilitate its performance.

Table 14 Condition scores, actions and descriptions

Condition Score	Action	Condition Description
1 - Very Good	No Action Required / Establishment Period	New or nearly new asset (Asset Age <= 2 Year)
2 - Good	Continue Routine Maintenance	Asset has no noticeable issues; but is no longer a new asset. No Action Required. Continue routine maintenance.
3 - Moderate	Continue Routine Maintenance + Priority Maintenance (or Partial Restorative Maintenance)	Noticeable issues which may affect functionality in the near future. May require prioritized maintenance. Continue monitoring progression of issue during next inspection. If performance of asset is questionable, plan performance assessment of the system.
4 - Poor	Performance Assessment and Restorative Maintenance	Noticeable issues which may have an immediate impact on the functionality of the asset. Needs immediate investigation to determine repairs needed. If performance of asset is questionable, plan performance assessment of the system.
5 - Very Poor	Replace / Rehab / Redesign	Asset has failed and is not functional. Immediate action maybe required.



	GII Era	Pre-GII Era
5	1	42
4		3
3	6	31
2	5	44
1	11	4

Figure 27 Bioretention condition scores (1-5) for assets constructed prior to the GI branch being formed (pre-GII era), and for assets designed and delivered by our branch (GII Era)

Conclusion and Next Steps

Using data from monitored sites, we can determine that GRI assets across the City of Vancouver are performing as expected to manage rainwater where it falls and reduce the amount of runoff going to our sewer system, all while increasing biodiversity in our neighbourhoods and contributing to greenery that stays healthy even during hot summer months. Below are the conclusions of this monitoring work, per monitoring objective.

Performance Monitoring Objectives

Objective 1: Evaluate surface ponding: should not be ponded for longer than 24 hours. Nearly half of all GRI assets are bioretention systems with ponding areas, and all of the bioretention assets were visually inspected for ponding after two large rain events. None of the bioretention assets had visual ponding 24 hours after a rainfall event.

Objective 2: Evaluate subsurface storage: storage should empty in no more than 72 hours. All monitored wells had short drawdown times, with an overall average of 16.5 hours. Two sites had longer drainage times on average of greater than 24 hours, but are located in areas with tight soils where we were expecting slower drawdown rates. We can conclude there is capacity for more subsurface storage.

Objective 3: Evaluate whether design infiltration rates are matching drawdown rates. Six of the nine sites with water level monitoring displayed drawdown times equal to or greater than the design infiltration rate. Two of nine sites had lower than expected drawdown rates, but not by significant amounts (10-30% different), and the ninth did not have sufficient water level response for analysis. This is similar to findings from the previous monitoring report, where five of seven sites had drawdown rates greater than infiltration rates.

Objective 4: Monitor soil moisture for plant health. Soil moisture was variable throughout the monitoring period at different GRI typologies. All sites had moisture contents > 5%, and most were over 20%. Overall, the moisture range was amenable to the health of the vegetation. As soil moisture sensors cannot be removed or replaced once in situ, and the sensors do deteriorate over time, the data from these sensors is becoming less reliable. Spot checks of soil moisture may be needed. Also, more complete visual condition assessments of plants will allow a greater correlation to soil moisture and plant health in the future.

Objective 5: Determine if retention/filtration target is being met. We conducted synthetic flow tests at two sites by adding the volume equivalent to the design retention volume to the systems. Each site was able to retain the full volume without overflowing, and this data is encouraging us to add caps to underdrains to encourage as much water as possible to exfiltrate from the GRI system instead of adding to sewer flow.

Objective 6: Determine water quality treatment capacity of GRI. We conducted different water quality spike tests at two bioretention systems. We found that mass removals across these systems were very high, even with underdrain flow. In one test we found a 99% mass removal of total suspended solids, which is also a typical indicator for a range of pollutants that make up sediment, such as plastics and metals, or adhere to sediment like hydrocarbons. In another test we found a 98% mass removal of 6PPD-quinone, a tire wear chemical harmful to salmon.

Optimization Monitoring Objectives

Objective 7: Determine permeability performance over time and necessary maintenance methods. We monitored permeability at six permeable interlocking concrete pavement sites following a cleaning that restored a system's permeability. We found that permeable pavements clog within 1-2 years post-construction and within 6-12 months of cleaning that restores permeability.

Objective 8: Determine condition scores for all GRI assets. Condition assessments were conducted for 147 bioretention assets, which is the first of its kind for GRI assets at the City of Vancouver. This provides a baseline of information to determine long term asset performance and causes for decline.

Objective 9: Evaluate the impact of GRI on biodiversity in the City. We began monitoring the impact of GRI on biodiversity in 2022 by conducting bioblitzes in an area where GRI will be constructed. We plan to measure biodiversity following GRI construction at the St George Rainway, and for years following, via citizen science bioblitzes.

Next Steps for the Monitoring Program

The City of Vancouver Green Infrastructure Implementation Branch plans to continue monitor water level and drawdown in newly built assets to determine their functionality and continue monitoring at a few long-term sites to make conclusions about long-term performance. Soil moisture monitroing will gradually decrease over time, mainly due to the cost of the sensors and not being able to recover the sensors once they are no longer functional, as most are installed under concrete or pavers. Water quality and volume will continue to be assessed when opportunities arise, such as when there is a research partnership. However due to the difficulty of synthetic runoff tests and generating enough water to fully test the volume managed (often requiring multiple water trucks), this will continue to be conducted infrequently.

We are looking forward to continuing visual inspections around rain events, condition assessments, permeability testing of porous pavements, and evaluating biodiversity via citizen science bioblitzes. These programs will continue to provide vital information for both understanding long-term performance and co-benefits, but also life cycle operations and maintenance costs.

Design of GRI systems is being improved through learnings from monitoring, and we can even adapt GRI practices after their installation. For example at Woodland Dr. and 2nd Ave. bioretention, after observing how it performs during rainfall, we decided to restrict underdrain outflow to encourage further infiltration. We plan on adding capped underdrains or options to turn underdrains off/on in future GRI systems.

We also have new types of assets to monitor: dry wells, oil-grit separators and wetlands. We monitored water level drawdown in one dry well in 2021-2023, and have built several new dry wells in 2023 which have just started monitoring. We are also collecting sediment buildup data on dry wells and on GRI pre-treatment technologies (e.g. oil-grit separator, sediment pads, catchbasin filter baskets, etc.). There is also one existing wetland and several under construction which will be monitored in the near future.

Network connected monitoring devices are of particular interest to the GI branch as they would reduce the burden of data collection and allow for continuous data collection and analysis. We have completed a trial using network-connected devices with a local company, and the City is exploring whether a network of sensors could be connected to LoRaWAN instead of cellular data. LoRaWAN, Low Power Wide Area Network, is gradually being installed across the City as part of the street lighting upgrades.

The GI branch is currently pursuing relationships with research partners to assist in water quality assessments and exploring opportunities to collaborate with and/or initiate citizen science monitoring programs. University and college partnerships may also provide resources to expand the monitoring program.

References

City of Vancouver. (2019). *Rain City Strategy.* Retrieved from https://vancouver.ca/files/cov/rain-city-strategy.pdf

City of Vancouver. (2022). *St George Rainway 2022 Bioblitz Report-back.*

City of Vancouver. (2022). *Vancouver Green Infrastructure Performance Monitoring Report.*

Kerr Wood Leidel. (2022). *Quebec Street Bioswale Stormwater Injection Tests.*

Onset. (2012). HOBO U20 Water Level Logger (U20-001-0x and U20-001-0x-Ti) Manual.

Rodgers et al. (2023, 10). Bioretention Cells Provide a 10-fold reduction in 6PPD-Quinone Mass Loadings to Receiving Waters: Evidence from a Field Experiment and Modeling. *Environmental Science and Technologies Letters*, pp. 582-588.

STEP. (2020, May 6). *Design Infiltration Rate*. Retrieved from STEP Wiki: https://wiki.sustainabletechnologies.ca/wiki/Design_infiltration_rate#Safety_correction

TRCA, CVC. (2010). *Low Impact Development Stormwater Management Planning and Design Guide, Appendix C, Site Evaluation and Soil Testing Protocol*. Retrieved from https://sustainabletechnologies.ca/app/uploads/2013/02/LID-SWM-Guide-v1.0_2010_4_Appendix-C_Site-Evaluation-and-Soil-Testing-Protocol.pdf

Appendix A

City of Vancouver Bioretention Condition Assessment Handbook

Bioretention Condition Assessment Inspector Guidebook

Bioretention Condition Assessment Rating System

We are using a 5 point scale for most of our condition assessment fields. To make our evaluations as consistent as possible, here is what each number means in the condition score. When thinking about functionalist, consider the three Rain City Strategy Goals:

- Improve and protect water quality
- Increase resilience through sustainable water management
- Enhance livability by improving natural and urban ecosystems

1 **Very Good/ No Issues**
Everything is awesome. Works perfectly, don't change a thing!

2 **Good/Minimal Issues**
In great shape. A few minor issues, but they aren't impacting overall function, and could be solved with routine maintenance. Functionality greater than 75%

3 **Fair/ Some issues**
Still functions, but not to its design specifications, or site has noticeable issues that may impact function in the near future. Functionality between 25-75%. Requires routine maintenance and/or minor repairs.

4 **Poor/ Moderate issues**
Functioning at 25% or less and requires rehabilitation.

5 **Very poor/ Extensive Issues**
Pintrest level fail. Extensive damage and is non-functional. If the failure is a health and safety risk to the community, it should automatically be scored a 5.

Bioretention Condition Assessment Process

Select Bioretention Condition Assessment 2022 on Fulcrum App, and then select site you are inspecting. The form will autofill certain data for you.

Take a quick walk around the site, noticing where the different components are. Take a moment up front to assess site safety as well.

Evaluate the different components of the bioretention asset

Contributing Drainage Area

↓

Inlet

↓

Pre-treatment

↓

Monitoring well/ clean-outs

↓

Planting Bed/Ponding Area

↓

Outlet/overflow

↓

Vegetation

↓

Soil

↓

Livability

Contributing Drainage Area

The contributing drainage area (CDA) is the area from which water drains into the bioretention asset. Your visual inspection will evaluate:

- Effectiveness of erosion and sediment controls if the site is in an active construction zone.
- Street grading

If active construction is taking place in the CDA, are proper erosion and sediment controls set up to prevent clogging of GI asset?	
Yes ESC is set up to prevent any construction sediment from entering the asset	
No There is no ESC set up, the ESC is insufficient, or the ESC has failed	

Contributing Drainage Area

<table>
<tr><td colspan="2">Is street grading preventing water from entering the asset?

Note: use visual indicators to determine grade, such as gaps between the curb and road. The level can be used here as well, provided it is safe to do so.</td></tr>
<tr><td>Yes

Road grade is below inlet, causing all rainwater to bypass</td><td></td></tr>
<tr><td>Somewhat

Road grade allows some water into asset but also causes bypass</td><td></td></tr>
<tr><td>No

Road is grading to let all rainwater flow into asset</td><td></td></tr>
</table>

Inlet

Inlets are where water enters into the bioretention asset, but does not include the pre-treatment. This is evaluated separately. There are three main types of inlets you will see:

- Curb cuts with metal grates
- Curb cuts without metal grates
- Sheet flow

Inspections will focus on the inlet structure as well as any erosion that may be impacting the flow of water into the asset.

Structural inspections
When looking at the inlet structure look for signs of deterioration, spalling or damage. This could include:

- Dents in the metal curb cover
- Broken concrete or asphalt
- Spalling (broken asphalt or concrete)
- Heaving (displacement or upward movement of concrete)
- Graffiti
- Rust or other discolouration

Inlet

Is there any structural deterioration, spalling or damage to the inlet structure?	
1 None	
2 Minimal damage not causing issues to function or risk to public	
3 Damage present and in need of repair	
4 Substantial damage causing some water flow blockages	
5 Damage is blocking flows and/or causing risk to public	

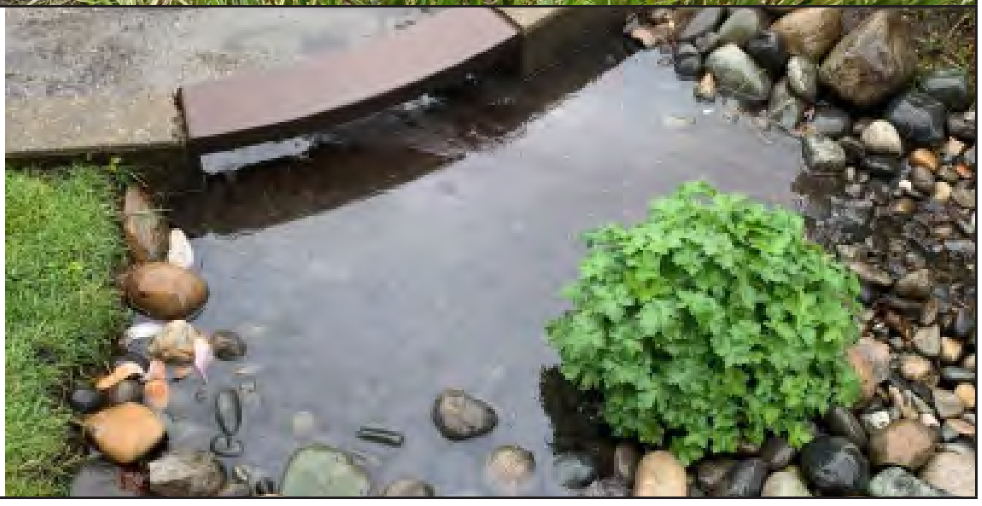
Inlet

Is there erosion visible at the inlet?	
1 None	
2 Minimal erosion, not impacting function	
3 Some erosion, minimal impact to function	
4 Moderate erosion, impacting most water flow	
5 Heavy erosion blocking water flow	

Pre-treatment River Rock

What is the condition of the river rock? Note: looking at the quantity and placement- NOT the sediment. Look to see if there is enough river rock, if it is too dense, and whether it is graded to allow water flow.	
1 Very good	
2 Good Less than 25% of water bypassing pre-treatment. River rock may have some displacement but overall function not impaired	
3 Fair -25-50 % of water bypass pre-treatment due to any of: -Displacement -Too much river rock -Not enough river rock	
4 Poor -More than 50% of water bypassing pre-treatment due to any of: -Displacement -Too much river rock -Not enough river rock	
5 Very poor -All water is bypassing pre-treatment	

Pre-treatment River Rock

Is the pre-treatment area graded to allow proper flow of water into asset?	
Yes	
No	

If the answer is no, please provide photos and written details highlighting the grading error. Try to ensure inspection reviewers understand what will be needed to repair the error:

- Minor errors, can be re-graded by hand by contractor
- Major errors, requires re-design of pre-treatment area

Pre-treatment Sediment Pad

What is the condition of the sediment pad? Note: check for damage and cracks to the concrete	
1 Very good	
2 Good Minimal damage, impacts to overall function or public safety <25%	
3 Fair Some damage impacting 25-75% of function	
4 Poor Extensive damage impacting >75% function	
5 Damaged causing asset to malfunction and/or risk to community	

Ponding Area
Ponding depth

Instructions for measuring ponding depth

1. Locate the lowest point in the ponding area
2. Place the laser level at the overflow point in line with the lowest point in the ponding area.
3. Hold the ruler or measuring tape in the low point of the ponding area, lined up with the laser level. Take note of the measurement in cm.
4. If vegetation is blocking the view of the laser, you can use the tape measure or a piece of string to follow the laser level line to the ruler.

Measuring ponding depth near outlet with no vegetation blocking laser

Measuring ponding depth when vegetation is blocking laser

Ponding Area
Ponding depth

What is the ponding depth? Note: use ruler or tape measure in cm to find the ponding depth. Measure from the lowest point of the asset to the height of the outlet	
1 15 cm	
2 11-14 cm	
3 6-10 cm	
4 1-5 cm	
5 0 cm	

Ponding Area
Perimeter curb

Is there any damage, cracking or spalling on the perimeter curb? Note: check for damage and cracks to the concrete.	
1 Very good	
2 Good Minimal damage, impacts to overall function or public safety <25%	
3 Fair Some damage impacting 25-75% of function	
4 Poor Extensive damage impacting >75% function	
5 Damaged causing asset to malfunction and/or risk to community	

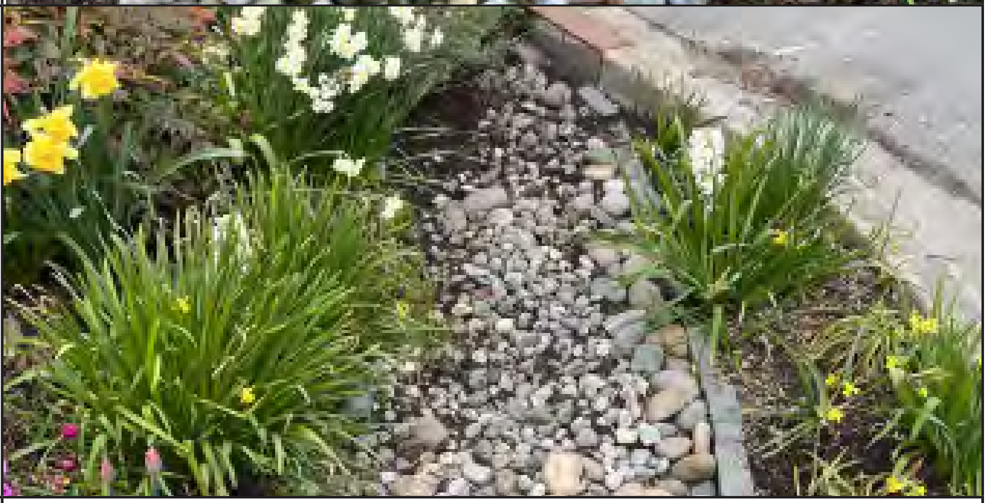
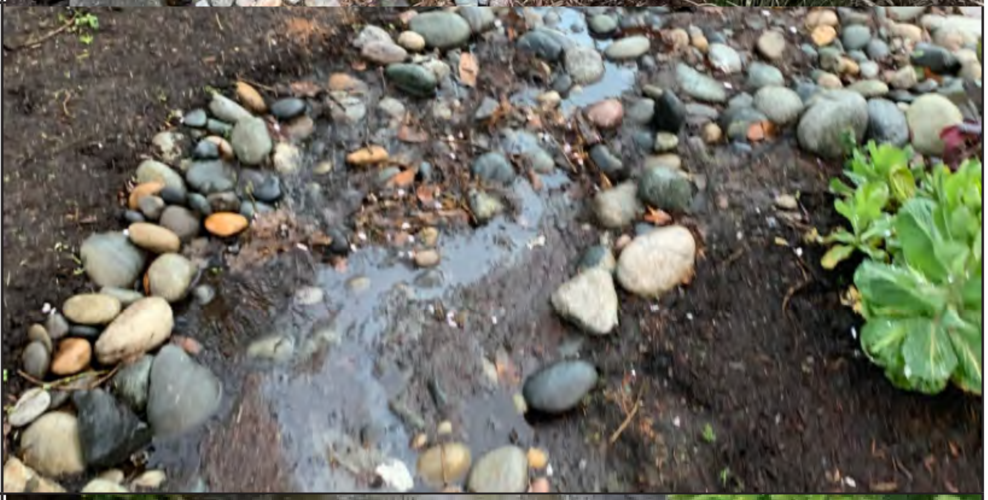
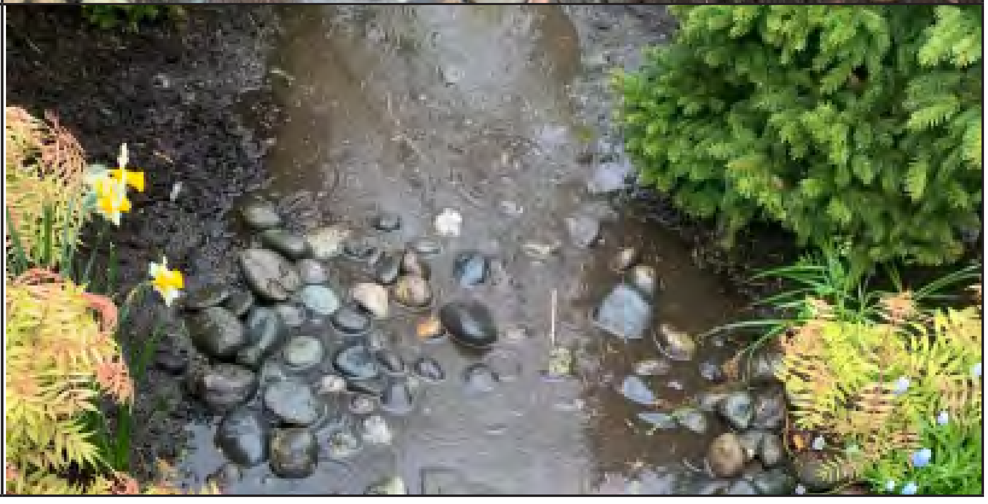
Ponding Area
Weirs

If site has weirs, Is there any damage, cracking or spalling? Note: check for damage and cracks to the concrete. Take particular note of areas that may impact water movement	
1 Very good	
2 Good Minimal damage, impacts to overall function or public safety <25%	
3 Fair Some damage impacting 25-75% of function	
4 Poor Extensive damage impacting >75% function	
5 Damaged causing asset to malfunction and/or risk to community	

Ponding Area Erosion

Is erosion present in the ponding area? Note: look at both the flow path and the side slopes. Please include photos and description that indicate exactly which areas of the asset are eroding and the extend of effort that will be required to repair.	
1 None	
2 Minimal Erosion present but not impacting function	
3 Some Erosion is channeling some flows (<50%)	
4 Moderate Erosion is channeling the majority of flows	
5 Extensive Complete re-direction of flows, will require extensive re-grading to repair	

Ponding Area
River rock

What is the condition of the river rock? Note: looking at the quantity and placement- NOT the sediment. Look to see if there is enough river rock, if it is too dense, and whether it is graded to allow water flow.	
1 Very good	
2 Good River rock may have some displacement but overall function not impaired	
3 Fair -River rock has some displacement impacting water flow	
4 Poor - river rock is displaced or improperly graded causing erosion, bypass -River rock is too dense	
5 Very poor -All water is bypassing river rock	

Monitoring Well and Clean-outs

Some assets, particularly newer ones, may have monitoring wells and/or clean-out pipes. If you find either on site, please open the lid and examine the condition. Use a flashlight to help you see inside of the monitoring well.

Please assess the monitoring well for the following:

Are Trash, sediment and debris present in the monitoring well

Is there any damage to the inside or outside of the monitoring well, such as cracks or root intrusions?

1	2	3	4	5
None	Minimal Not impeding overall function or safety (<25%)	Some Impacting some function (25-75%)	Moderate Damage impacting function (>75%)	Moderate Damaged causing asset to malfunction and/or risk to community

Example of a monitoring well with minimal sediment and no damage.
Condition score: 1

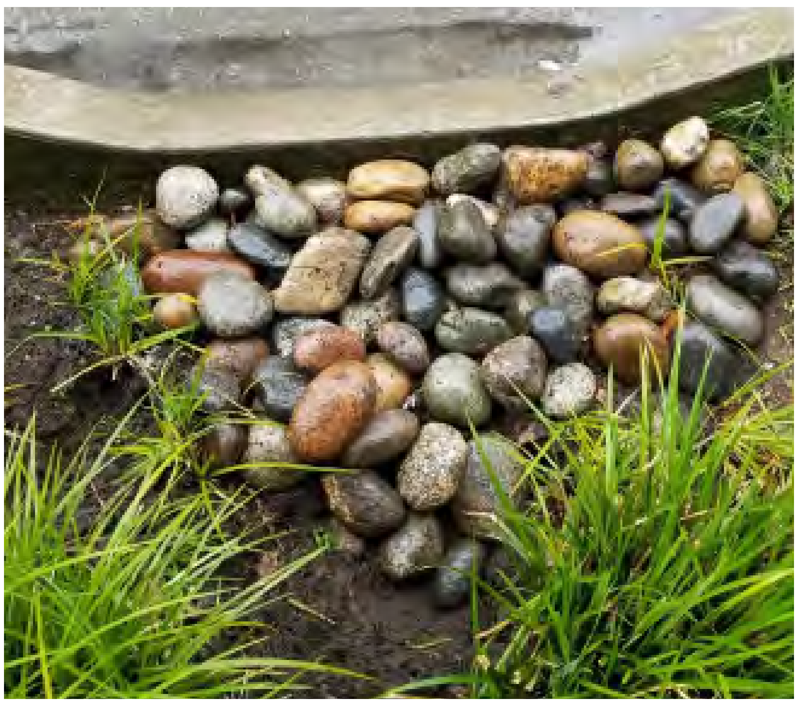
Example of a monitoring well extensive build up of debris and is non-functional.
Condition score: 5

Outlet/ Overflow

There are three types of overflow you will see in bioretention systems:

Catchbasins

Beehive outlets



Surface outlets

Outlet/ Overflow Catchbasins

Examine the exterior and interior of the catchbasin, including:
- The outside concrete structure for visible spalling and/or deterioration
- The metal grate cover of the CB for damage or deterioration
- The interior of the CB for trash, sediment and debris.
- Damage to the interior structure of the CB such as cracking or spalling
- Whether water level in the CB is above or below the invert

Note: You may not need to lift the lid of the CB. Try using your flashlight to look into the CB first, and only remove the lid if needed.

1	2	3	4	5
None	Minimal Not impeding overall function or safety (<25%)	Some Impacting some function (25-75%)	Moderate Damage impacting function (>75%)	Moderate Damaged causing asset to malfunction and/or risk to community

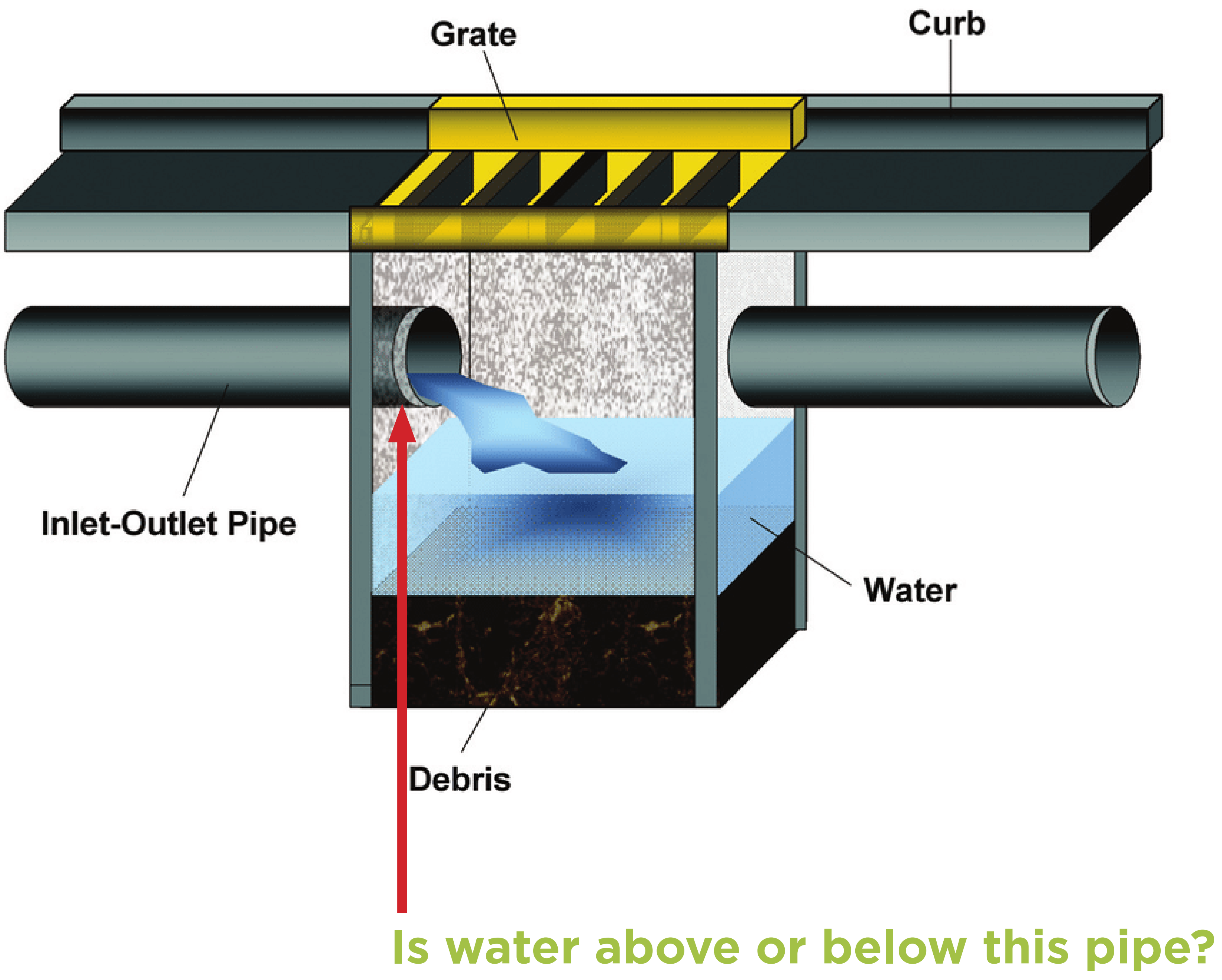
CB with minimal spalling on exterior
Condition score: 2

Moderate damage to concrete around CB, could be sign of water leakage.
Condition score: 3

CB is filled with debris and non-functional. Could cause backups that create community risk.
Condition score: 5

Outlet/ Overflow Catchbasins

The invert is a pipe within the catchbasin allowing water to safely exit the CB. Please note whether water in the CB is above or below the invert.



Overflow Beehive Outlet

Examine the exterior and interior of the beehive outlet including:

- Grate cover for damage or breakage allowing larger pieces of debris to enter
- The interior of the CB for trash, sediment and debris.
- Damage to the interior structure of the CB such as cracking or spalling
- Whether water level in the CB is above or below the invert

Note: You may not need to lift the lid. Try using your flashlight to look into the CB first, and only remove the lid if needed.

1	2	3	4	5
None	Minimal Not impeding overall function or safety (<25%)	Some Impacting some function (25-75%)	Moderate Damage impacting function (>75%)	Moderate Damaged causing asset to malfunction and/or risk to community

Overflow Surface Outlet

Some systems overflow via surface flow back onto the road or another landscaped area.

Use the level to confirm the outlet is graded downwards towards the outlet, allowing water to safety exit through the overflow.

Check for visible erosion at the outlet as well as any debris or blockages that may be preventing water from safely exiting the system.

1	2	3	4	5
None	Minimal Not impeding overall function or safety (<25%)	Some Impacting some function (25-75%)	Moderate Damage impacting function (>75%)	Moderate Damaged causing asset to malfunction and/or risk to community

Vegetation Health

How healthy is the vegetation present?

1	2	3	4	5
100% of vegetation is healthy	Minimal <75% is healthy, the remainder is dead or declining	Some 25-75% is healthy, the remainder dead or declining	Moderate >25% is healthy, the remainder is dead and declining	Extensive, no vegetation is healthy

Signs of poor plant health

Discolouration of leaves (brown, yellow, powdery white)

Drooping leaves

Holes or spots in leaves

Bare stems, gap areas

Note: Juncus grasses tend to flop and fall when they get too tall. This is not a sign they are unhealthy, but could impact the flow of water!

Vegetation Invasive Species

What percentage of the planting bed is invasive species?

1
0%

2
Minimal
>25 % plant coverage is invasive

3
Some
25-75% plant coverage is invasive

4
Moderate
<75% plant coverage is invasive

5
Extensive
100% plant coverage is invasive

Invasives of concern

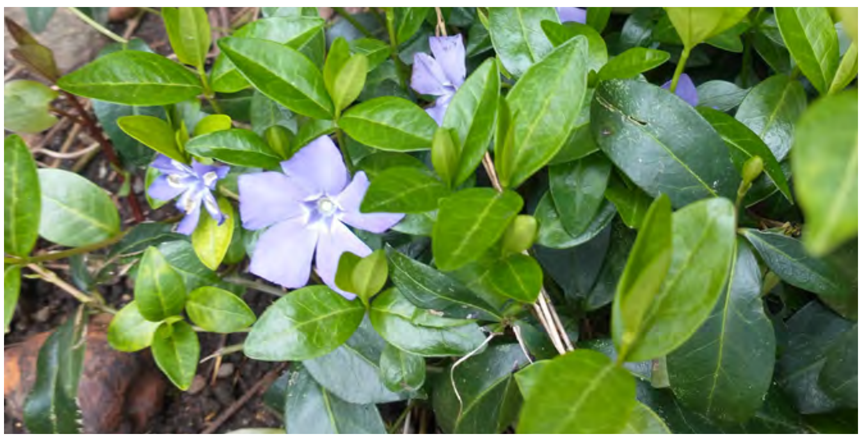
Morning Glory
Calystegia sepium
Also known as Bindweed

English Holly
Ilex aquifolium

Himalayan Blackberry
Rubus armeniacus

Spurge Laurel/ Daphne
Daphne laureola

English Ivy
Hedera helix



Common Periwinkle
Vinca minor

Vegetation
Species diversity

How diverse are the plant species in the asset?

1 Very good
10 species or more

2 Good
6-9 plant species present

3 Fair
4-5 plant species present

4 Poor
2-3 plant species present

5 Very poor
0-1 plant species present

Tips for differentiating plants

Leaves - every plant type has a unique leaf. Look at the size, shape and colour to differentiate species.

Flowers - looking to see what plants have flowers, and how they differ can help you distinguish separate plant species

Height and shape- differences in height and shape of plants can also help you determine whether they are different species.

Common GI plants

Juncus

Carex

Spiraea

Lavender

Douglas Iris

Liriope

Astilbe

Black-eyed Susans

Soil Testing

Soil Testing

We will be using a soil probe, as well as a ribbon test to determine soil type and health.

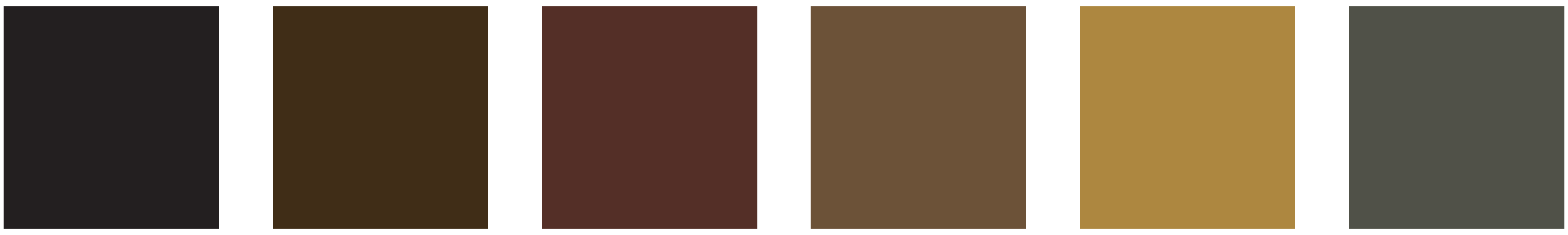
Start with the soil probe, inserting into a bare area of soil to a depth of 30 cm.

Determine depth of top soil

Measure the depth of top soil in the probe. Note: top soil will be the darker soil towards the top of the probe.

Soil Colour

Choose the best match for the colour of the soil below the top soil.



Black | Dark brown | Red | Medium brown | Yellow/ light brown | Greenish grey

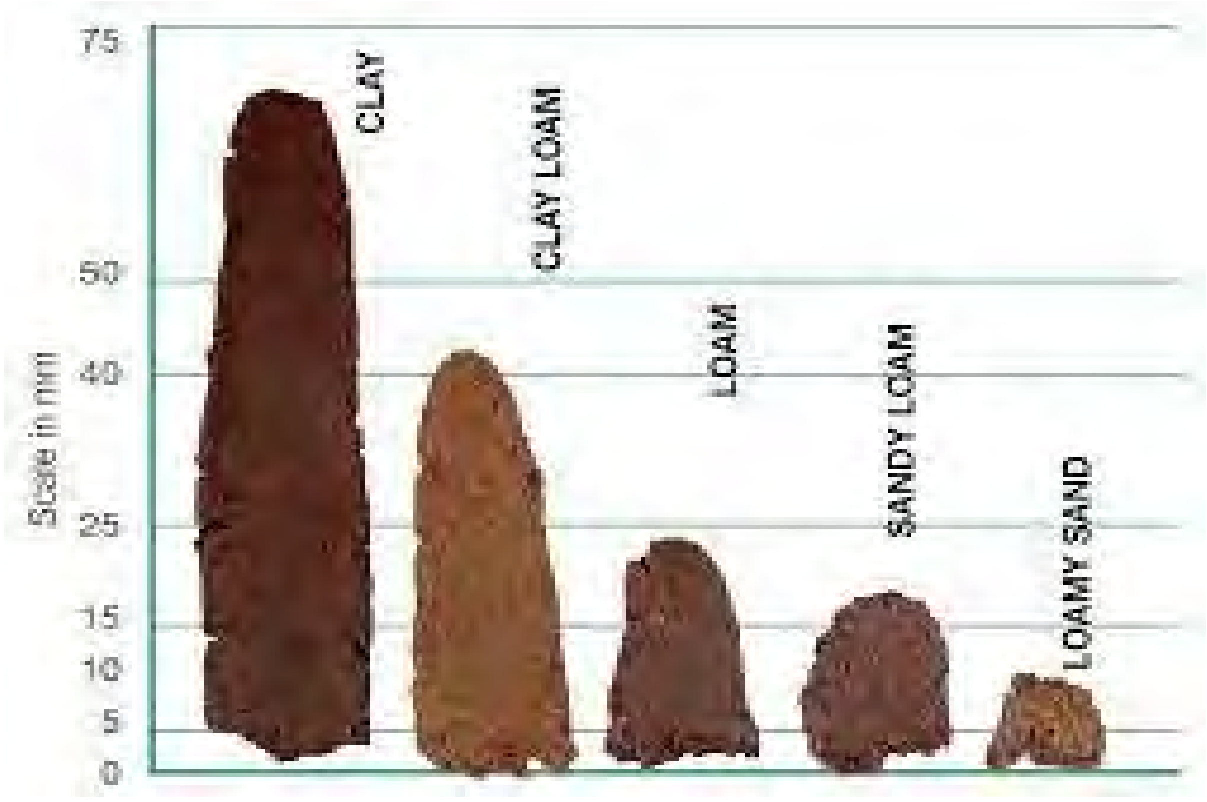
Soil Moisture

Take some soil from the probe (the stuff below the top soil) in your hand and crumble it. Record:

- Whether it crumbles easily or is difficult to break apart (is it compacted)
- Is there any moisture in the soil?

Soil Type

Spray the soil with a bit of water and try to form the soil into a ribbon. The length of the ribbon that forms without breaking will tell you the type of soil.



Appendix B

Quebec St Bioswale Injection Tests

KERR WOOD LEIDAL
consulting engineers

Greater Vancouver
200 - 4185A Still Creek Drive
Burnaby, BC V5C 6G9
T 604 294 2088
F 604 294 2090

Green Infrastructure Asset Effectiveness Monitoring Program

Quebec Street Bioswale Stormwater Injection Tests

Final Report
April 28, 2022
KWL Project No. 42.158-300

Prepared for:
City of Vancouver

Contents

Figures

Tables

Appendices

Executive Summary

Kerr Wood Leidal Associates Ltd. was engaged by the City to perform water quality monitoring of a mature bioswale with established vegetation, located along Quebec Street. The studied bioswale was constructed in 2018 and designed to receive runoff from adjacent paved surfaces. The objective of the project was to perform two controlled injection tests – one with tap water and one with synthetic stormwater – for better understanding how green rainwater infrastructure (GRI) like bioswales can contribute to improved stormwater management in the City. The objective of the water injection pre-test was to investigate the water flows and volumes needed to achieve flow in the bioswale's underdrain. Outcomes of the water injection pre-test were then used for optimizing the injection test with synthetic stormwater. The objective of the synthetic stormwater injection test was to investigate the typical pollution load reduction of a bioswale in the City.

In the water injection pre-test, dechlorinated tap water was applied to the bioswale, and rhodamine dye was used to track when applied water would appear in the underdrain of the swale. In the synthetic stormwater injection test, a mix of dechlorinated tap water and road-deposited sediments collected from street sweeping was injected into the bioswale. Water quality analyses verified that the synthetic stormwater contained nutrients, metals, and bacteria, in addition to solids. During the synthetic stormwater injection test, inlet flows were manually checked with a bucket while flows in the outlet underdrain were logged using automatic monitoring equipment. Discrete outlet water samples were collected every 10 min during the synthetic stormwater injection test and analyzed for a range of water quality parameters. Key results from the two injection tests are as follows:

- The infiltration lag time is approximately 2 h when the bioswale is not saturated with water. The infiltration lag time appeared to be reduced during the synthetic stormwater injection test when soils were assumed to be more saturated prior to the start of the injection testing.
- The peak flow rate was reduced from approximately 0.7 L/s to 0.24 L/s, which corresponds to a 66% reduction.
- The applied volume of water was reduced from approximately 14,000 L (12,600 L injected, 150 L direct rainfall, 1,300 L runoff) to 2,900 L, which corresponds to a 77% reduction.
- The injected TSS concentration throughout the stormwater injection test was estimated to 130 mg/L, and the highest TSS concentration measured in the outlet was 13.5 mg/L, which corresponds to a 90% reduction.
- At the end of the synthetic stormwater injection test, approximately 1,600 g of solids had been applied to the bioswale, and from flow and water quality measurements in the underdrain, the outlet load was estimated to 6.75 g TSS. The estimated removal efficiency of TSS loads during the injection test is >99%.
- During the pre-test, the bioswale released nutrients and metals with outlet water. Higher outlet concentrations of these compounds were found during the pre-test than during the synthetic stormwater injection test, suggesting that nutrients and metals, assumed to be attached to particles in the synthetic stormwater, were removed during the injection test, but dissolved species of these compounds were leached in the pre-test. Other studies have also observed leaching of dissolved pollutants, specifically nitrogen and phosphorous species, from bioretention.
- Outlet water quality measured during the injection test was improved, with fewer exceedances of AMF thresholds compared to monitoring data collected in 2018. However, the limited data (mostly TSS) make it difficult to draw any conclusions on whether maturation of the bioswale, i.e., establishment of plants, has led to improved pollutant reduction capacity and improved outlet water quality.
- Water quality data collected during the injection tests and in the 2018/2019 monitoring program suggest that GRI practices such as bioswale and stormwater tree trenches are not effective at attaining water quality guidelines for copper.

The stormwater injection tests proved to be time-efficient procedures for studying a bioswale in detail and generating time series of data to evaluate its efficiency to reduce runoff flows and volumes as well as applied pollutant loads. The outcomes of the injection tests reported here are only an indication of how well a bioswale may function under certain conditions. It is recommended to evaluate the efficiency of frequently implemented GRI practices in the City, to make sure they are well designed for the intended purpose, whether it be flow rate reduction or pollution removal. Injection tests can be used for evaluating both hydraulics and pollutant removal in GRI practices.

The injection tests indicated that nutrients, both nitrogen and phosphorous species, can leach from the bioswale. If the City is concerned about leached nutrient levels, it is recommended to perform additional research, desktop research may suffice, on available soil amendments and bioretention designs to reduce nutrient leaching. To further reduce copper levels in stormwater, the City may want to look into additional pre- or post-treatment practices as well as pollution prevention measures.

1. Introduction

The City of Vancouver ('the City') has a target to capture and treat 90% of Vancouver's average annual rainfall by using green rainwater infrastructure (GRI) and design guidelines on public and private property. Green infrastructure is an approach to rainwater management that uses both engineered practices and natural landscape features to mitigate the impacts of increased runoff and pollution as close to the source as possible. GRI uses soils, plants, and trees in built infrastructure, such as rain gardens, swales, and tree trenches, to capture, store, and remove pollutants from runoff, resulting in reduced runoff rates and volumes, and improved water quality.

Kerr Wood Leidal Associates Ltd. (KWL) was engaged by the City to perform water quality monitoring of a mature bioswale with established vegetation, located along Quebec Street in the Southeast False Creek neighbourhood. Bioswales are linear bioretention practices designed as shallow depressions that feature vegetation and engineered soils. Bioretention practices are commonly designed for runoff to temporarily pool, allowing evaporation to reduce runoff volumes and volatilization and sedimentation to reduce pollutants. Runoff is then infiltrated into a soil layer, where further pollutant reduction is achieved through chemical and biological processes. Runoff volumes are reduced through plant uptake, evaporation, and infiltration into the underlying soil.

The studied bioswale was constructed in 2018 and designed to receive runoff from adjacent paved surfaces. The bioswale is designed with an underdrain that discharges treated runoff into the stormwater sewer system. In late 2018 and early 2019, before vegetation was established, flow and water quality monitoring of the bioswale was performed by the City. The monitoring is described in the report *2020 Green Infrastructure Asset Effectiveness Monitoring Program – Final Report*[1] prepared by KWL and issued on 2021-12-10.

The current monitoring of the bioswale was performed to further the understanding of the practice's performance over time, as it has matured, and plants and trees are established. The original scope of the project was to collect time-weighted, composite water quality samples from three storm events at three GRI practices: 2 bioswales and 1 stormwater tree trench. Because of numerous challenges with the timing and feasibility of sample collection, the scope of work was changed to perform two controlled injection tests at only one bioswale. Monitoring of the other practices was abandoned because the stormwater tree trench showed signs of clogging and flow monitoring at the other bioswale is made difficult due to sewer backups. Injection testing using "synthetic stormwater", i.e., a mix of tap water and road-deposited sediments, allows for a controlled procedure where known volumes of water and pollutant loads are added to the bioswale. In addition, weather conditions become irrelevant for sample collection and the procedure is, therefore, easier to schedule than sampling during storm events.

The objective of the project was to perform two controlled injection tests – one with tap water and one with synthetic stormwater – for better understanding how GRI can contribute to improved stormwater management in the City. The project aims to advance knowledge on what type of runoff events can be managed using bioswales and expected reduction of pollutants, as well as potential benefits and implications for receiving water health.

[1] 2020 Green Infrastructure Asset Effectiveness Monitoring Program – Final Report. Prepared by KWL for the City of Vancouver. December 10, 2021.

2. Injection Tests

2.1 Bioswale #2

The injection tests were performed on one of the bioswales along Quebec Street, in previous work referred to as Bioswale #2. The approximate UTM coordinates for Bioswale #2 are Easting 492564, Northing 5457601 (Zone 10U). The practice receives runoff from adjacent sections of the sidewalk, bicycle lane, and road (Quebec Street).

The design of the bioswale is described in detail in the Masters thesis *Green Infrastructure in the City of Vancouver: Performance Monitoring of Stormwater Tree Trenches and Bioswales* completed by Osvaldo Miguel Vega in the Civil Engineering Program at the University of British Columbia (Vega 2019)[2]. Key design features are summarized:

- Approximate impervious area that has direct hydraulic connection to the bioswale: 270 m^2;
- Approximate area of bioswale: 25.5 m^2;
- Approximate depth of bioswale soil media: 0.5 m^2;
- Soil blend used: Veratec® bioretention blend, which is a proprietary bioretention mix engineered to improve pollutant reduction of metals, nutrients, and hydrocarbons.

As-built drawings of the bioswale are found in Appendix A.

Bioswale #2 has a perforated 100 mm PVC underdrain that is laid at 0% gradient across the length of the swale. The perforated underdrain connects to a solid 150 mm PVC pipe, laid at 1% gradient, that discharges to the stormwater sewer. A monitoring manhole installed between the practice and the stormwater sewer discharge point allows for monitoring of outlet flows and water quality. A 0.6 m × 0.08 m opening has been cut in the top of the 150 mm PVC pipe to facilitate flow monitoring and sample collection. The monitoring manhole, with flow monitoring equipment installed by the City, is shown in Photo 2-1.

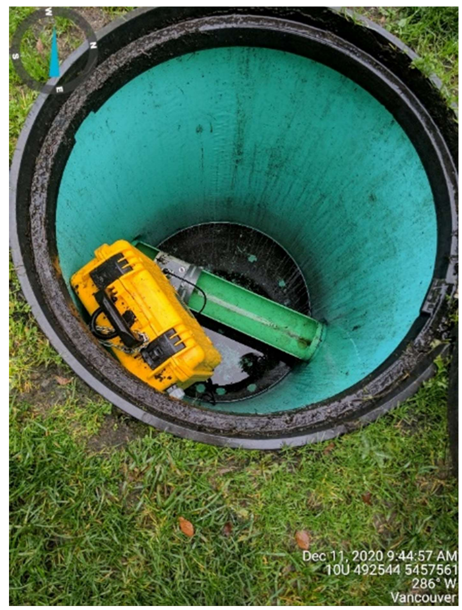


Photo 2-1: Monitoring Manhole at Bioswale #2 on Quebec Street

[2] Vega, Osvaldo Miguel. (2019). Green Infrastructure in the City of Vancouver: Performance Monitoring of Stormwater Tree Trenches and Bioswales. Department of Civil Engineering, Faculty of Applied Science, University of British Columbia, Vancouver, BC. Available at: https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0378388 (accessed 2021-03-16).

2.2 Flow Monitoring

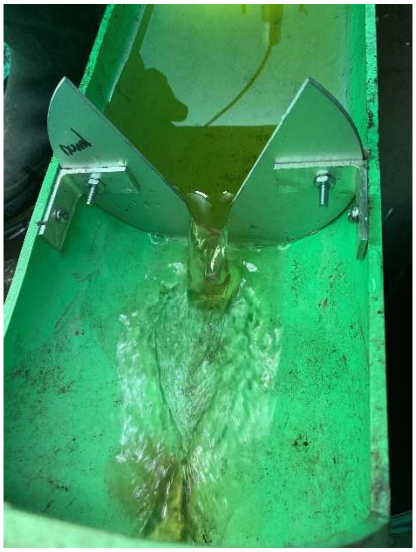


Photo 2-2: 45-degree V-notch Weir Installed to Facilitate Level Logging in the Underdrain of Bioswale #2

To estimate influent and effluent hydrographs (i.e., a plot of flow rate in relation to time), volume, and flow reduction in the bioswale, the inflow and outflow need to be known. Known flows and volumes of water were applied during the injection test, while the outgoing flows in the underdrain were monitored using automated monitoring equipment.

Bioswale #2 has a functional monitoring manhole, but existing flow monitoring equipment was not operating and needed to be reconfigured or replaced.

The original setup at the monitoring manhole used an Onset Hobo Energy datalogger to record voltage output from a Senix Toughsonic ultrasonic level transducer. For the duration of the injection test, KWL installed a 45-degree V-notch weir to the monitoring manhole, which increased the level response and thus the resolution of the flow calculation (Photo 2-2). The existing Senix Toughsonic transducer was re-programmed and reused; the existing datalogger was not functional so a Telog datalogger was used instead. Ultrasonic level data was recorded at one-minute intervals.

After injection testing was complete, ultrasonic level data was retrieved from the datalogger. To calculate flow, the ultrasonic level was zeroed relative to the point (bottom) of the weir. Then, flow was calculated from that level using the 45-degree weir equation.

2.3 Precipitation Monitoring

For precipitation data to characterize antecedent conditions, the City rain gauge installed at the Creekside Community Recreation Centre (also known as the Creekside Rain Gauge), located within 300 m from the Bioswale #2, was accessed through FlowWorks (FlowWorks, Inc., Seattle, WA, USA). The resolution of the data is in 5-minute intervals.

2.4 Injection Test Procedures

Two different injection tests were performed: a water injection pre-test and a synthetic stormwater injection test. The objective of the water injection pre-test was to investigate the water flows and volumes needed to achieve flow in the bioswale's underdrain. Outcomes of the water injection pre-test were used for optimizing the injection test with synthetic stormwater. The objective of the synthetic stormwater injection test was to investigate the typical pollution load reduction of a bioswale in the City.

Water Injection Pre-Test

Antecedent Conditions

The water injection pre-test was performed on 2021-10-19 during dry weather. In the week prior to the water injection pre-test, approximately 145 mm precipitation was registered at the Creekside Rain Gauge. No precipitation was registered between 2021-10-17 at 16:50 until the start of the water injection pre-test at approximately 09:00 on 2021-10-19, hence the antecedent dry period was approximately 40 h.

Procedure

In the water injection pre-test, only dechlorinated tap water was applied to the bioswale. A nearby fire hydrant was used as a tap water source, connected to a fire hose with a ball valve to adjust flows. Water was applied close to the centre of the bioswale. The tap water was allowed to flow through a mesh bag with sodium thiosulphate to remove residual chlorine and minimize any potential harm to the environment before being infiltrated into the bioswale's soil media. To avoid purchasing inflow monitoring equipment with limited use (e.g., flow meters), simple timed bucket filling measurements were performed to verify flows/volumes applied to the bioswale. Rhodamine dye was used to track when applied water would appear in the underdrain.

The key procedures and observations, as well as approximate timeline of the water injection test are summarized as follows:

1. 0 min: The test was started by applying tap water to the bioswale at a flow of 0.55 L/s.
2. 5 min: Approximately 5 min after the water injection started and flows were stabilized, rhodamine was added to the bioswale, where water was starting to pond.
3. 30 min: Flow appeared in the underdrain but there were no signs of dye.
4. 1 h 30 min: More dye was added to the bioswale, and water flow was increased from 0.55 L/s to 1.1 L/s.
5. 2 h: First hint of dye was observed in the underdrain.

It was observed that water ponded on the surface of the soil media before infiltration through the soil media began. The ponding area extended approximately 1–2 m from where the fire hose was discharging water into the bioswale. This likely means that only a portion of the bioswale's soil media volume was contributing to water infiltration and pollutant removal during the injection tests.

Synthetic Stormwater Injection Test

Antecedent Conditions

The synthetic stormwater injection test was performed on 2021-10-20 during wet weather. 5.75 mm of precipitation was recorded at the Creekside Rain Gauge between the water injection pre-test on 2021-10-19 and the start of the synthetic stormwater injection test, and an additional 5.75 mm precipitation was recorded between the start and the end of the synthetic stormwater injection test.

5.75 mm of rainfall equals to approximately 150 L, or 0.15 m^3, of direct rainfall into the bioswale. Around 270 m^2 of impervious surface has direct hydraulic connection to the bioswale and may have contributed runoff to the bioswale during the infiltration test. Assuming a runoff coefficient of 0.83 for asphalt surfaces[3], the potential runoff volume infiltrated into the bioswale during the infiltration test was estimated to be 1,300 L, or 1.3 m^3.

[3] Runoff coefficients for different surfaces are found in the City of Vancouver Engineering Design Manual (2019): https://vancouver.ca/files/cov/engineering-design-manual.PDF p. 125

Preparation of Synthetic Stormwater

Synthetic stormwater, a mix of dechlorinated tap water and road-deposited sediments collected from street sweeping was used in the injection test. The required mass of street sweeping material for the test was estimated from expected TSS concentrations in road runoff from urban areas. Street sweeping material was collected by the City's routine street sweeping program, dried at room temperature, and sieved through 300 and 600 µm mesh sizes; material greater than 600 µm was discarded. The sieved material was then dried at about 90°C for an additional 60 minutes to further reduce the moisture content.

The synthetic stormwater was prepared in several batches by mixing a known mass of the dried sediment with a known volume of water prior to being dosed to the bioswale. Each batch was prepared by mixing 200 g of dried sediment in 20 L of tap water to produce a synthetic stormwater concentrate, which was then added to dechlorinated tap water.

A portion of the road-deposited sediment was analyzed for its content of nitrogen, phosphorous, organic matter, total metals, as well as pH. However, data are only indicative as the samples had not been stored properly until analysis and recommended holding times were exceeded, e.g., for nitrogen species.

Procedure

The synthetic stormwater injection test procedure consisted of four main actions:

1. Flow monitoring;
2. Injection of dechlorinated tap water;
3. Dosing of synthetic stormwater; and
4. Collection of inlet and outlet water samples.

Logging of water level data at the monitoring manhole was started before the first injection of dechlorinated tap water, to make sure flows were registered during the injection test. Level logging was ended approximately 40 min after the tap water injection was ended. At that time, the outlet flow had ceased (logged flow < 0.0001 L/s).

Dechlorinated tap water was injected at a flow of 1.1 L/s a short while before dosing of the synthetic stormwater concentrate began. The tap water flow fluctuated during the test procedure and was regularly checked and adjusted; the average injected flow was approximately 0.7 L/s.

Each 20 L batch of synthetic stormwater concentrate was applied to the bioswale over a period of 30 min and a total of 8 batches were applied during the injection test. Tap water injection was ended when all synthetic stormwater was assumed to have infiltrated, approximately 45 min after the last batch of synthetic stormwater concentrate was applied and approximately 5 h after the start of the tap water injection. Inlet (synthetic stormwater) and outlet (from the underdrain) water samples were collected on several occasions during the injection procedure, further described in Section 2.5. The approximate timeline of the test, with tap water injection start and end, dosing of the synthetic stormwater concentrate, and collection of inlet and outlet samples, is shown in Figure 2-1.

At the end of the injection test, approximately 12,600 L (12.6 m^3) of dechlorinated tap water and approximately 1,600 g of dried sediment, corresponding to 130 mg TSS/L, had been applied to the bioswale over almost 5 h. In addition to tap water, approximately 1,400 L (1.4 m^3) of direct rainfall and road runoff were also infiltrated into the bioswale during the test.

Detailed field notes with timing of all injection test actions are found in Appendix B.

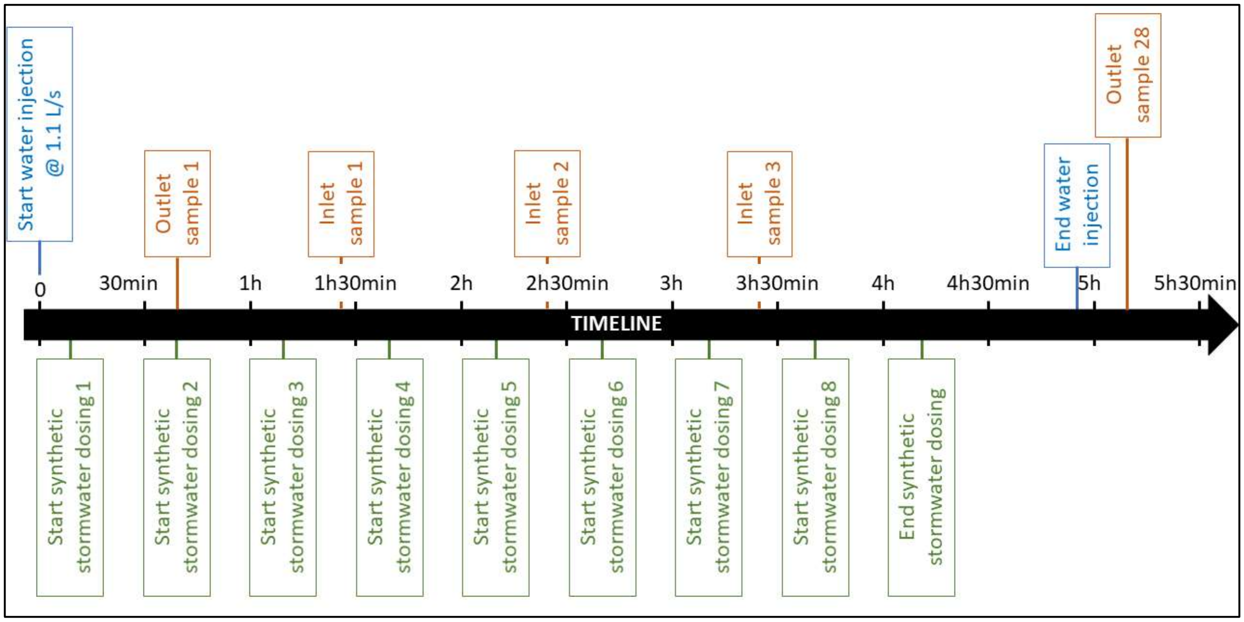


Figure 2-1: Approximate Timeline of Synthetic Stormwater Injection Test Actions

2.5 Water Quality Monitoring

Sample Collection

Inlet Water Quality Samples

A sample was collected from the fire hose to investigate the baseline quality of the tap water used in the injection tests. In addition, three replicates were collected from the synthetic stormwater concentrate used in the injection test, referred to as 'inlet samples'. The samples were collected from different batches of the mixed synthetic stormwater concentrate, as shown in Table 2-1 as well as Figure 2-1.

Outlet Water Quality Samples

One outlet grab sample was collected from the underdrain during the pre-test performed on 2021-10-19, to investigate outlet water quality when clean water, i.e., no sediment, is infiltrated through the bioswale. The sample was collected approximately 3 h after the start of the tap water injection. The pump of an ISCO 3700 automatic sampler was used to pump water from the monitoring manhole into sample collection bottles. The tubing was rinsed with sample water before sample collection began.

In total, 28 discrete outlet samples were collected every 10 min during the synthetic stormwater injection test. Analysis of water quality in discrete samples allows for generation of pollutographs (i.e., a plot of pollutant concentration variation over time) for analyzed parameters as well as calculation of pollutant loads. The first outlet sample was collected 30 min after the start of the first synthetic stormwater injection and the last sample was collected approximately 30 min after the last stormwater injection ended and 15 min after the tap water injection was stopped. The approximate timeline of the injection test and collected outlet samples are shown in Figure 2-1. Samples were collected by pumping water from the monitoring manhole into sample collection bottles.

Parameters

Water quality was determined for both *in situ* and laboratory parameters. These included:

- *In situ*: pH, dissolved oxygen (mg/L, DO), turbidity (NTU), conductivity (μS/cm), and water temperature (°C);
- Nutrients:
  - Total nitrogen, Total Kjeldahl Nitrogen (TKN), nitrate, nitrite (all in mg/L); and
  - Total phoshorous (mg/L);
- Total Suspended Solids (mg/L, TSS);
- *E.coli* (MPN/100 mL);
- Hardness (mg/L); and
- Total metals (μg/L).

The full suite of parameters was not analyzed in all collected samples; analyses performed on each sample are found Table 2-1.

Table 2-1: Water Quality Parameters Analyzed in Samples Collected During the Water Injection Pre-test and the Synthetic Stormwater Injection Tests

Sample Collected	Parameter Analyzed
Inlet	
Tap Water	Full suite of laboratory parameters: • Nutrients; • TSS; • *E.coli* • Hardness; • Total metals.
Inlet Sample #1	Full suite of laboratory parameters
Inlet Sample #2	Full suite of laboratory parameters
Inlet Sample #3	Full suite of laboratory parameters
Outlet	
Outlet Clean Water[1]	• Nutrients; • TSS; • Hardness; • Total metals.
Outlet Samples #1 through #28	TSS
Outlet Samples #12, 18, and 24	Full suite of laboratory parameters

Sample Collected	Parameter Analyzed
Outlet Samples #7 and 9	*In situ* parameters: • pH; • Water temperature; • Dissolved oxygen; • Conductivity; • Turbidity.
1. The Outlet Clean Water sample was collected during the water injection pre-test on 2021-10-19. All other samples were collected during the synthetic stormwater injection test on 2021-10-20.	

For analysis of laboratory parameters, samples were submitted to CARO Analytical Services, a CALA-accredited lab.

In situ parameters were analyzed using a ProDSS Multiparameter Digital Water Quality Meter.

2.6 Bioswale Assessment Approach

Comparison with Previously Collected Data and Water Quality Guidelines

Water quality data from the synthetic stormwater injection test were compared to data collected during previous studies at the same site and reported in the 2020 *Green Infrastructure Asset Effectiveness Monitoring Program – Final Report*.

Outlet water quality was also evaluated against regional (Metro Vancouver Monitoring and Adaptive Management Framework for Stormwater[4]), provincial (British Columbia Approved and Working Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture[5]), and federal guidelines (CCME Water Quality Guidelines of the Protection of Aquatic Life[6]). Guidelines values applicable to the studied parameters are summarized in Table 2-2.

Flows and Pollutant Loads

Known flows (approximately 0.7 L/s) and volumes (approximately 12,600 L or 12.6 m^3) of water were applied to the bioswale during the synthetic stormwater injection tests, and outflow data (L/s) were collected using automated monitoring equipment. Collected flow data were used to generate inflow and outflow hydrographs and determine the reduction of volumes and flows. Flow data were also used, together with TSS concentrations measured in the 28 outlet water samples, to estimate the outlet TSS load (g).

[4] Metro Vancouver (2014): Monitoring and Adaptive Management Framework for Stormwater. http://www.metrovancouver.org/services/liquid-waste/LiquidWastePublications/Monitoring_Adaptive_Management_Framework_for_Stormwater.pdf
[5] Government of British Columbia (2022): Ambient Water Quality Guidelines. https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-quality/water-quality-guidelines
[6] Canadian Council of Ministers of the Environment (2022): Canadian Water Quality Guidelines for the Protection of Aquatic Life. https://ccme.ca/en/summary-table

To estimate the TSS removal efficiency for the injection test, logged flows (L/s) were first converted to L/min. An outlet volume was estimated for every outlet water sample by adding together the flows (L/min) recorded 5 min before and 5 min after each outlet sample was collected (outlet samples were collected every 10 min). The estimated outlet volumes (L) were then multiplied with the TSS concentration (mg/L) in corresponding outlet sample to generate a TSS load (g). The TSS load in each outlet sample was then added together to a total outlet load for the synthetic stormwater injection test. The injected load of TSS was known (approximately 1,600 g).

The TSS removal efficiency (RE) was calculated for the synthetic stormwater injection test using:

$$RE\ (\%) = 100 \times \frac{Injected\ Load\ (g) - Outlet\ Load(g)}{Injected\ Load\ (g)}$$

Loads of other pollutants were estimated in a similar way in the outlet samples, only fewer samples were collected. Inlet loads were estimated from parameter concentrations in tap water and the total volume of applied tap water, as well as the average parameter concentrations measured in the three inlet samples and the total volume of applied synthetic stormwater. The tap water loads, and synthetic stormwater loads were then added to achieve a total applied load of nitrogen, phosphorous, and specific metals.

The loads of TSS and other pollutants contributed with road runoff during the injection tests are assumed to be negligible compared to injected loads and not included in the load estimations.

Table 2-2: Classification of Water Quality Results According to the Metro Vancouver Monitoring and Adaptive Management Framework for Stormwater, British Columbia Approved Water Quality Guidelines for Aquatic Life and Canadian Environmental Quality Guidelines for Aquatic Life

Parameter (Unit)	AMF Classification[1]			BC Freshwater WQG[2]		Canadian Freshwater WQG[3]	
	Good	Satisfactory	Need Attention	Short Term	Long Term	Short Term	Long Term
Physical Parameters							
pH	6.5-9.0	6.0-6.5 or 9.0-9.5	<6 or >9.5	6.5-9.0		N/A	6.5-9.0
Dissolved Oxygen (mg/L)	≥11	6.5-11	≤6.5	Lowest Instantaneous Minimum: 9	Lowest Chronic: 11	Lowest acceptable concentration: for warm water biota = 6.0 for cold water biota = 9.5	
Conductivity (µS/cm)	<50	50-200	>200	N/A		N/A	
Turbidity (NTU)	≤5	5-25	>25	Change from background of 8 NTU at any one time for a duration of 24 h in all waters during clear flows or in clear waters		Maximum increase of 8 NTUs from background levels for a short-term exposure (e.g., 24-h period)	
Water Temperature (°C, wet season)	7-12	5-7 or 12-14	<5 or >14	±1 change from ambient background		Thermal additions to receiving waters should be such that the maximum weekly average temperature is not exceeded	
Total Suspended Solids (mg/L)	N/A[4]	N/A	N/A	Change from background of 25 mg/L at any one time for a duration of 24 h in all waters during clear flows or in clear waters		Maximum increase of 25 mg/L from background levels for any short-term exposure (e.g., 24-h period)	

Parameter (Unit)	AMF Classification[1]			BC Freshwater WQG[2]		Canadian Freshwater WQG[3]	
	Good	Satisfactory	Need Attention	Short Term	Long Term	Short Term	Long Term
Nutrients							
Nitrate (mg/L)	<2	2-5	>5	32.8	3	550	13
Nitrite (mg/L)	N/A			0.06	0.02	N/A	0.060
Total Phosphorous (µg/L)	N/A			Not applicable (for lakes)		N/A	
Metals (total concentration unless otherwise stated)							
Cadmium (µg/L)	<0.06	0.06-0.34	>0.34	Calculated: 0.141 [5] (dissolved)	Calculated: 0.076 [5] (dissolved)	0.51	0.05
Copper (µg/L)	<3	3-11	>11	Calculated: 0.9 [5] (dissolved)	Calculated: 0.2 [5] (dissolved)	N/A	2
Iron (µg/L)	<800	800-5,000	>5,000	1,000	N/A	N/A	300
Lead (µg/L)	<5	5-30	>30	Calculated: 14 [5]	Calculated: 3.86 [5]	N/A	1
Zinc (µg/L)	<6	6-40	>40	33	7.5	Calculated: 21 [5,6] (dissolved)	Calculated: 18 [5,6] (dissolved)

1. Metro Vancouver (2014) Monitoring and Adaptive Management Framework for Stormwater
2. British Columbia Approved Water Quality Guidelines (2019) for the Protection of Freshwater Aquatic Life
3. Canadian Council of Ministers of the Environment (2021) Water Quality Guidelines for the Protection of Freshwater Aquatic Life
4. N/A – not available
5. Calculated assuming hardness = 25 mg/L $CaCO_3$, pH = 5.5, temperature 12°C, and DOC = 3 mg/L.
6. The Canadian Water Quality Guideline is for the dissolved concentration of the metal. When guideline users only have total metal concentrations for their site, it is recommended that they first compare their total metal concentration to dissolved metal guideline, and where there is an exceedance, re-sample the waterbody for the dissolved metal.

3. Results

3.1 Bioswale Hydraulics

The main hydraulic-related outcomes of the injection tests are summarized in Table 3-1 and described further below.

Table 3-1: Injection Test Summary Hydraulics

Variable	Value
Infiltration Lag Time	
From 2018/2019 studies (h)	2
From water injection pre-test (h)	2
Inflow	
Flow of injected water (L/s)	0.7
Duration of injection flow (h)	5
Injected synthetic stormwater volume (L)	12,600
Direct rainfall volume (L)	150
Infiltrated road runoff volume (L)	1,290
Total water volume applied to bioswale during test (L)	14,400
Outflow	
Maximum outflow (L/s)	0.24
Total outlet water volume (L)	2,900
Reductions	
Outlet / Inlet flow ratio (-)	0.34
Outlet / Inlet volume ratio (-)	0.20

Infiltration Lag Time

The infiltration lag time is the time needed for influent water to reach the underdrain of the bioswale. In the water injection pre-test, added rhodamine dye started to appear in the underdrain approximately 2 h after the first dye injection. At that time, approximately 5000 L (5 m^3) of water had been injected into the bioswale. The weather was dry for approximately 40 h (data from Creekside Rain Gauge) prior to water injection; hence it was assumed that the bioswale was not saturated with water when the test started. The infiltration lag time was not studied during the synthetic stormwater injection test.

Detailed analysis of rainfall and flow data collected in 2018/2019 also showed that the lag time was approximately 2 h. The analysis showed that saturated soil conditions led to shorter lag times, and dry soils could accept more stormwater before producing any outflow.

Lag time may potentially differ from 2 h if substantially different conditions prevail, such as length of the antecedent dry period and rainfall intensity.

Inlet and Outlet Flows and Volumes

The water flows applied during the synthetic stormwater injection test (manually measured) are graphed in Figure **3-1**. Approximately 12,600 L (12.6 m^3) of tap water was applied to the bioswale during the test. An additional 150 (0.15 m^3) of rainfall was estimated to have infiltrated as well as a potential runoff volume of 12,900 L (1.29 m^3). The total volume infiltrated into the bioswale during the injection test is estimated to 14,000 L (14 m^3).

Outlet flow data collected between the start of the dechlorinated tap water injection (2021-10-20 09:35) and the end of the water level logging (2021-10-20 15:10) are graphed in Figure **3-1**. Some observations include:

- A clear increase in flow is seen approximately 20 min (09:55) after the start of the water injection (09:35).
- The flow continues to steadily increase for approximately 1 h 20 min (11:15), after which the flow increase appears to slow down. At that time, approximately 4,200 L (4.2 m^3) of synthetic stormwater has been injected into the bioswale, not including rainfall and runoff from adjacent impervious areas.
- The flow continues to increase, but at a lower rate, until it reaches its peak at 0.24 L/s (13:50), 3 h after the flow started to increase and 3 h and 20 min after the water injection started. The peak flow is reached before the water injection has ended.
- When the water injection is stopped (14:30), the outlet flow decreases drastically and reaches negligible levels in less than 15 min.
- Between the start (09:35) and the end (15:10) of the water level logging, the total volume of water passed through the underdrain is estimated to 2,890 L.

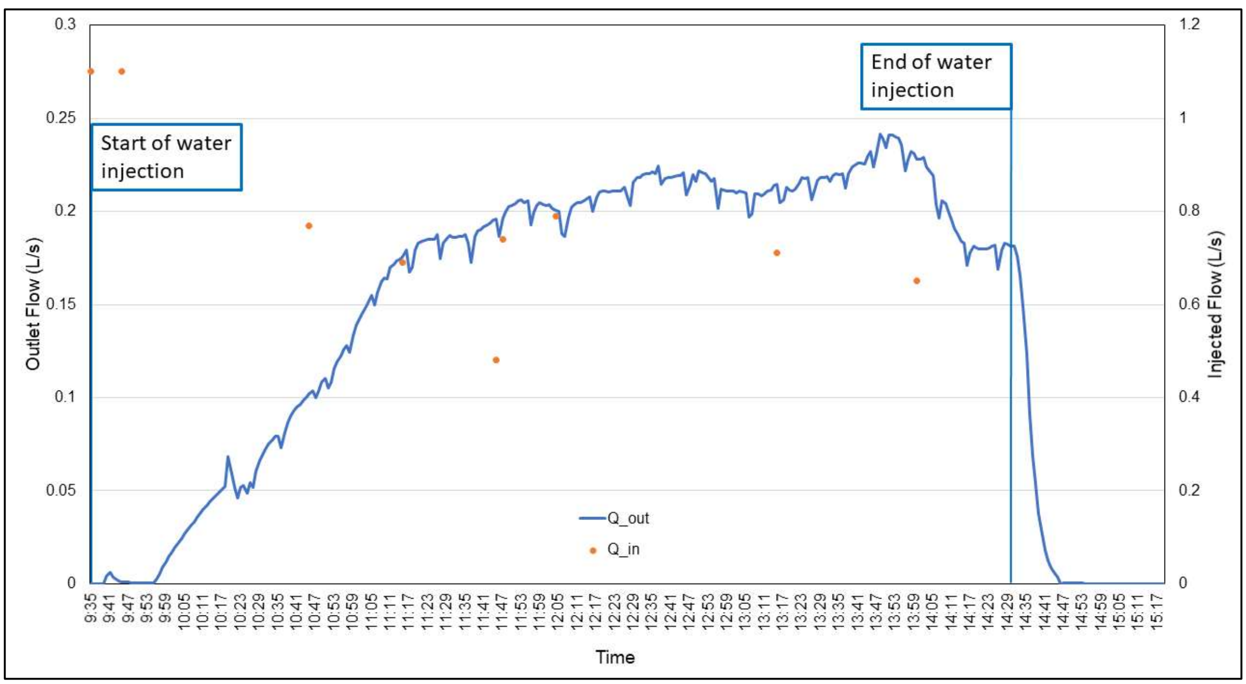


Figure 3-1: **Hydrograph of Injected (●) and Outlet (—) Flows (L/s) During the Synthetic Stormwater Injection Test**

The sharp increase in flow after 20 min of water injection (Figure **3-1**) suggests that the infiltration lag time was shorter during the synthetic stormwater injection test compared to the pre-test, when water was observed in the underdrain after 30 min. The shortened lag time is likely a result of more saturated soils at the beginning of the synthetic stormwater injection test because of the shorter antecedent dry period; 40 h dry period prior to the pre-test vs. 20 h dry period prior to the synthetic stormwater injection test.

It is not known why the flow rate peaks and starts declining before the water injection is ended. A potential explanation is that water starts to soak into a larger volume of the soil media, which leads to lower outlet flows.

The estimated inlet to outlet flows and volumes reveal that during the synthetic stormwater injection test, applied water volumes (including injected synthetic stormwater, rainfall, and runoff) were reduced by approximately 77%, from 14,000 L (14 m^3) to less than 3,000 L (3 m^3). Further, the peak flow rate was reduced by approximately 66% in the bioswale, from 0.7 to 0.24 L/s. The flow reduction may potentially be higher than 66% as the contribution from rainfall and runoff was not considered in the estimations and the inlet flow may therefore be underestimated.

3.2 Water Quality

Road-Deposited Sediments

Analyzed concentrations of nutrients and metals in the road-deposited sediment (Table 3-2) are only indicative as standard procedures for sample storage were not followed. For comparison, concentrations of metals found in other studies of street-sweeping sediment are included in Table 3-2. Nutrients were not investigated in referenced studies.

Table 3-2: Concentrations (mg/kg dry weight) of Nutrients and Total Metals in Road-Deposited Sediment (Average of Duplicate Samples), and Concentrations Reported in the Literature

Parameter	Concentration [mg/kg] This Study	Concentration [mg/kg] Virginia, US [1]	Concentration [mg/kg] Gothenburg, Sweden [2]	Concentration [mg/kg] Katowice, Poland [3]
Organic Matter (%)	3.79	N/A [4]	N/A	N/A
pH	7.0	N/A	N/A	N/A
Nitrite (as N)	<0.500	N/A	N/A	N/A
Nitrate (as N)	2.86	N/A	N/A	N/A
Total Phosphorus	465	N/A	N/A	N/A
Total Cadmium	0.613	0.83	0.15	0.35
Total Copper	83.2	0.89	16.7	240
Total Iron	16,600	50,000	N/A	N/A
Total Lead	421	7.3	4.9	430
Total Zinc	177	30	30	2,000

Parameter	Concentration [mg/kg] This Study	Concentration [mg/kg] Virginia, US [1]	Concentration [mg/kg] Gothenburg, Sweden [2]	Concentration [mg/kg] Katowice, Poland [3]
1. Virginia Transportation Research Council (2018). Characterization of Residuals Collected From Street Sweeping Operations. https://rosap.ntl.bts.gov/view/dot/35101. *Street sweeping residuals were collected from 79 locations throughout Virginia, with varying land use and average daily traffic between 1-400 and >10,000. Reported concentrations are averaged over all collected samples.*				
2. Järlskog, I., Hvitt Strömvall, A., Magnusson, K. et al (2021) Traffic-related microplastic particles, metals, and organic pollutants in an urban area under reconstruction Science of the Total Environment, 774 http://dx.doi.org/10.1016/j.scitotenv.2021.145503. *Street sweeping samples were collected from a downtown core area undergoing construction, with average daily traffic around 5,500. Reported concentrations are averaged over 7 samples.*				
3. Adamiec, E., Jarosz-Krzemińska, E. & Wieszała, R. Heavy metals from non-exhaust vehicle emissions in urban and motorway road dusts. Environ Monit Assess 188, 369 (2016). https://doi.org/10.1007/s10661-016-5377-1. *Road dust was collected from urban roads in Katowice, Poland.*				
4. N/A – not reported.				

As seen in Table 3-2, considerably larger loads of phosphorous were found in the road-deposited sediment than nitrogen species. Also, the metal concentrations varied considerably, with iron being the most abundant metal at 16.6 g/kg. Compared to the referenced studies, road-deposited sediment collected in Vancouver generally showed higher concentrations of metals than found in Virginia and Sweden, but lower than concentrations found in urban road dust in Poland. Road dust quality is generally dependent on the particle size – smaller particle sizes contain comparably higher metal content than coarser particles – and road type – road dust from urban roads is usually more contaminated with metals than dust from low traffic areas and highways.

Inlet Water Quality

Selected water quality data for tap water and replicates of the prepared synthetic stormwater concentrate (Inlet 1-3; 200 g street sweeping material in 20 L water) are found in Table 3-3.

Data in Table 3-3 suggest that tap water was a negligible source of solids, bacteria, and the metals cadmium, lead, and zinc during the injection tests. Copper and iron were detected in tap water and may originate from leaching from pipes and other water infrastructure.

It should be noted that water quality of Inlet samples 1–3 was measured on the concentrated sediment-water mix; the mix was then diluted with tap water during the injection test. For example, TSS concentrations in Inlet samples 1–3 varied between 788 and 2,400 mg/L, whereas the TSS concentration in injected water was estimated to 130 mg/L (1,600 g sediment added to 12,600 L water).

Water quality data for Inlet samples 1–3 show that the street sweeping material leached nutrients, metals, and bacteria. The inlet samples generally show high nutrient levels; much of the leached nitrogen is composed of TKN (organically bound nitrogen and ammonia), whereas nitrate is only a small portion. The difference in nitrate concentrations between tap water and Inlet samples is smaller than for other nutrients. Water quality varied in the three Inlet samples, likely because it was difficult to collect homogeneous samples of the prepared sediment-water slurry as coarser particles settled very easily and were not well distributed at the time of sampling.

Table 3-3: Water Quality of Tap Water and Prepared Synthetic Stormwater Injected into the Bioswale

Sample ID	Tap Water	Inlet 1	Inlet 2	Inlet 3
Date and Time Sampled	2021-10-20 13:15	2021-10-20 10:45	2021-10-20 12:00	2021-10-20 13:00
Nutrients (mg/L)				
Nitrite (as N)	<0.0050	<0.0050	<0.0050	<0.0050
Nitrate (as N)	0.095	0.148	0.212	0.167
Nitrate + Nitrite (as N)	0.095	0.148	0.212	0.167
Total Kjeldahl Nitrogen (TKN)	0.063	2.86	6.71	4.94
Total Nitrogen	0.158	3.0	6.92	5.11
Total Phosphorus	0.0068	0.648	2.27	0.794
Total Metals (µg/L)				
Cadmium	<0.010	0.355	0.597	0.357
Copper	0.85	81.8	139	86.6
Iron	10	4,350	7,140	4,650
Lead	<0.20	220	410	171
Zinc	<4	238	413	233
Other Parameters				
Total hardness (mg/L, as $CaCO_3$)	19.1	44.9	74.7	45.3
Total Suspended Solids (mg/L)	<2.0	788	2,410	2,380
E. coli (MPN/100 mL)	<1.8	79	79	350

1. Green cells indicate that water quality complies with the AMF 'Good' threshold, orange cells indicate that water quality exceeds the AMF 'Satisfactory' threshold and red cells indicate that water quality data exceeds the AMF 'Need Attention' threshold. No colour means that there is no AMF threshold for the parameter.

Outlet Water Quality

In situ Measurements

In situ measurements of outlet water quality during the synthetic stormwater tests are presented in Table 3-4. pH was low in the first outlet sample (Outlet A) but was a suspected measurement error and for the second sample other equipment was used, which showed higher and close to neutral pH.

Table 3-4: *In Situ* Water Quality of Samples Collected from the Bioswale Underdrain During the Synthetic Stormwater Injection Test

Parameter	Outlet A	Outlet B
Date and Time Sampled	2021-10-20 11:16	2021-10-20 11:36
Water temperature (°C)	12.0	11.8
Dissolved oxygen (mg/L)	10.2	No data
Conductivity (µS/cm)	131	107
pH	5.3	7.7
Turbidity (NTU)	4.8	4.9

Green cells indicate that water quality complies with the AMF 'Good' threshold, orange cells indicate that water quality exceeds the AMF 'Satisfactory' threshold and red cells indicate that water quality data exceeds the AMF 'Need Attention' threshold.

Nutrients and Metals in Outlet Water Samples

Selected water quality data for the Outlet Clean Water sample collected from the underdrain during the pre-test are found in Table 3-5. Data for Outlet samples 6, 12, 18, and 25, collected at different times during the synthetic stormwater injection test, are also found in Table 3-5. Remaining outlet samples are not presented in Table 3-5, as they were only analyzed for TSS concentrations. Analyses of solids is presented in Section 0.

Data in Table 3-5 indicate that the bioswale is releasing nutrients, metals, and bacteria into stormwater when clean water is flushed through the soil. Other studies have also noted that soil-based bioretention can leach pollutants from the soil media, specifically dissolved compounds[7]. Numerous studies have seen that bioretention practices may leach nitrogen, mainly in the dissolved forms such as ammonia (NH_4^+) and nitrate (NO_3^-). Nitrogen is released from bioretention soils due to mineralization of organic matter in soil media, decomposition of dead plants, and accumulation of organic matter transported with stormwater[8]. In addition, phosphorus removal in bioretention systems has proven inconsistent, with some systems removing phosphorous while others are leaching. Leaching of phosphorous is often observed when compost is used as a soil amendment and the soil media contains high organic matter content[9].

[7] LeFevre et al. Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells, *Journal of Environmental Engineering*, 2015, 141(1).
[8] Osman et al. A Review of Nitrogen Removal for Urban Stormwater Runoff in Bioretention System, *Sustainability*, 2019, 11(19), 5415; https://doi.org/10.3390/su11195415
[9] The Water Research Foundation (2020): International Stormwater BMP Database 2020 Summary Statistics. https://www.waterrf.org/resource/international-stormwater-bmp-database-2020-summary-statistics

The outlet samples collected during the synthetic stormwater injection tests show lower concentrations of all analyzed parameters, except iron, compared to the Outlet Clean Water sample (Table 3-5). In addition, concentrations in the outlet samples decline as the injection test proceeds; Outlet sample 24 shows the lowest parameter concentrations of all collected outlet samples. It is not known why this trend in water quality is observed. One potential explanation could be that the injection of water has led to leaching of dissolved pollutants from the bioswale soil, and the available load of leachable pollutants has decreased over time as the injection tests have proceeded, or that flows increased during the procedure which led to diluted pollutant concentrations.

Table 3-5: Water Quality of Samples Collected from the Bioswale Underdrain During the Water Injection Pre-Test (Outlet Clean Water) and the Synthetic Stormwater Injection Test (Outlet Samples 6, 12, 18, and 24)

Sample ID	Outlet Clean Water	Outlet 6	Outlet 12	Outlet 18	Outlet 24
Date and Time Sampled	2021-10-19 12:17	2021-10-20 11:06	2021-10-20 12:06	2021-10-20 13:06	2021-10-20 14:06
Nutrients (mg/L)					
Nitrite (as N)	0.124	N/A	0.0512	0.0301	0.0211
Nitrate (as N)	2.92	N/A	0.812	0.746	0.669
Nitrate + Nitrite (as N)	3.04	N/A	0.864	0.776	0.69
Total Kjeldahl Nitrogen (TKN)	2.47	N/A	2.46	1.59	1.06
Total Nitrogen	5.52	3.5	3.32	2.37	1.75
Total Phosphorus	2.5	N/A	1.23	0.978	0.858
Total Metals (µg/L)					
Cadmium	0.051	N/A	0.028	0.020	0.014
Copper	10.3	N/A	9.22	5.44	3.79
Iron	225	N/A	231	166	143
Lead	<0.20	N/A	<0.20	<0.20	<0.20
Zinc	14.7	N/A	9.3	4.1	<4
Other Parameters					
Total hardness (mg/L, as $CaCO_3$)	40.6	N/A	29.7	28	25.4
Total Suspended Solids (mg/L)	4.0	5.0	2.8	<2.5	<2.5
E. coli (MPN/100 mL)	N/A	3,500	33	49	79

1. Green cells indicate that water quality complies with the AMF 'Good' threshold, orange cells indicate that water quality exceeds the AMF 'Satisfactory' threshold and red cells indicate that water quality data exceeds the AMF 'Need Attention' threshold. No colour means that there is no AMF threshold for the parameter.
2. Due to a communication mistake with the lab, not all water quality parameters were analyzed in Outlet 6.

Pollutant Loads and Removal Efficiencies

Solids

Solids, expressed as mg TSS/L, were measured in all 28 outlet samples, and assessed in detail, including pollutograph, inlet and outlet loads, and estimated pollutant removal efficiency.

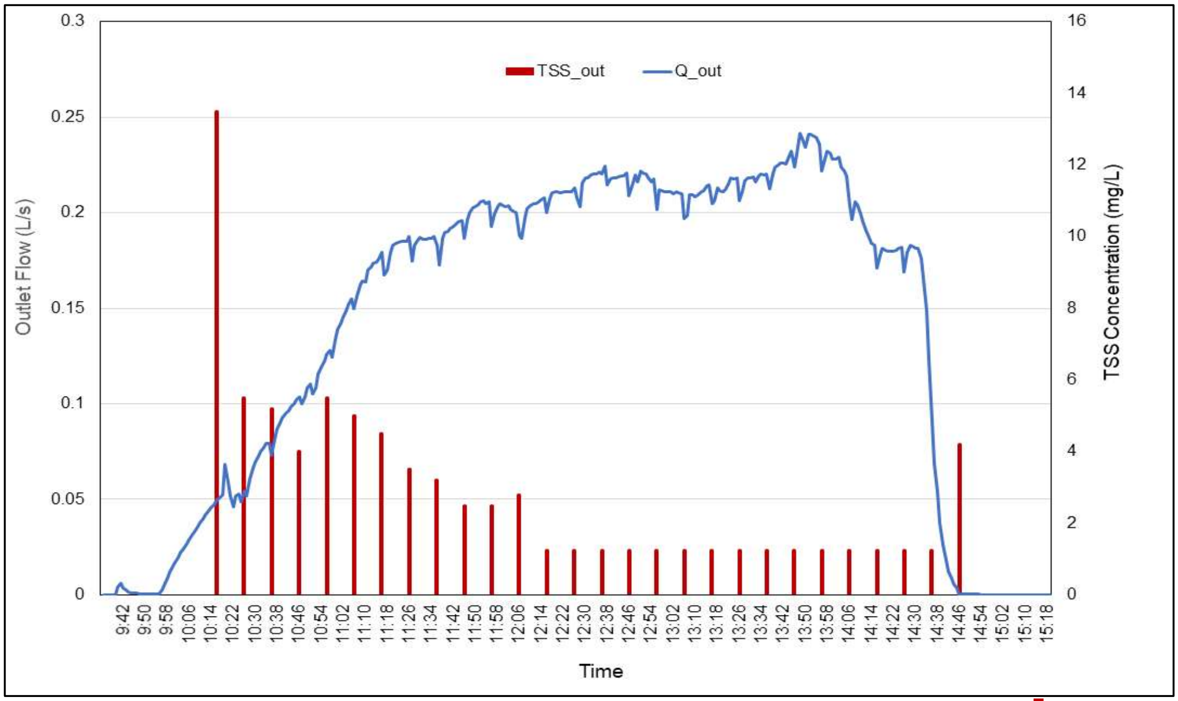


Figure 3-2: Pollutograph Showing Outlet Flows (—, L/s) and TSS Concentrations (, mg/L) During the Synthetic Stormwater Injection Test. TSS Concentrations Below Detection Limit (2.5 mg/L) have been Replaced with ½ Detection Limit.

Figure 3-2 shows that the outlet TSS concentration reached its peak at an early stage of the injection test. The outlet TSS concentration decreased considerably within short time, likely because of increasing flows diluting the TSS concentration, and approximately 2 h 30 min after the first injection of synthetic stormwater (12:16), outlet TSS was reduced to concentrations below detection limit (<2.5 mg/L, replaced with ½ detection limit in Figure 3-2), except for an increase in TSS in the final Outlet Sample 28. The TSS concentration in outlet sample 28 may have been affected by bottom sediments in the outlet pipe as water level was very low at the time of sampling.

The injected TSS concentration was estimated to 130 mg/L, which is almost 10 times higher than the highest TSS concentration measured in the outlet (13.5 mg/L), equivalent to a concentration reduction of 90%.

At the end of the synthetic stormwater injection test, approximately 1,600 g of solids had been applied to the bioswale. The outlet TSS load was calculated using logged outlet flows (converted to volume) and measured TSS concentrations the 28 outlet water samples, and estimated to 6.75 g. The estimated removal efficiency of TSS loads during the injection test is >99%.

Nutrients and Metals

Loads of nutrients and metals were estimated from the average parameter concentrations measured in the three inlet samples of concentrated synthetic stormwater (Table 3-3), and the total volume of applied (concentrated) synthetic stormwater (160 L). For comparison, pollutant loads were also calculated by multiplying the nutrient and metal concentrations in the road-deposited sediment with the total applied mass (1,600 g) of sediment. As seen in Table 3-6, loads estimated from parameter concentrations in the sediment are consistently higher – metal loads are one magnitude higher – than loads estimated from the synthetic stormwater samples. The discrepancies are likely due to thesmall number of samples of the synthetic stormwater not accurately characterizing concentrations, exceeded holding time for sediment samples, as well as the occurrence of particulate/dissolved pollutant species in the synthetic stormwater. A portion of the pollutants in the road-deposited sediment are assumed to remain attached particles and not dissolve into the synthetic stormwater; pollutants attached to settled particles are generally not captured in the chemical analysis of synthetic stormwater.

The removal efficiencies in Table 3-6 are based on parameter loads in the synthetic stormwater and the outlet samples. Loads in the sediment were not used because it is assumed that a portion of the pollutants in the road-deposited sediment are attached particles and behave like solids (TSS) rather than mobile compounds in the bioswale. As parameter concentrations were measured only in three batches of the concentrated synthetic stormwater, and only in four outlet samples, the estimated inlet and outlet loads and removal efficiencies of nutrients and metals in the bioswale are uncertain. Loads were not calculated for *E. coli* as data were limited and varied considerably between samples.

Table 3-6: Estimated Inlet and Outlet Loads (g) and Removal Efficiencies (%) of Total Nitrogen, Phosphorous, and Metals during the Synthetic Stormwater Test

Load	Nitrogen	Phosphorus	Cadmium	Copper	Iron	Lead	Zinc
Tap Water Load (g) [1]	2.0	$8.6*10^{-2}$	$6.3*10^{-5}$	$1.1*10^{-2}$	0.13	$1.3*10^{-3}$	$2.5*10^{-2}$
Synthetic Stormwater Load (g) [2]	0.80	0.20	$7.0*10^{-5}$	$1.6*10^{-2}$	0.86	$4.3*10^{-2}$	$4.7*10^{-2}$
Sediment Load (g) [3]	$>5*10^{-3}$ (4)	0.74	$9.8*10^{-4}$	0.13	26	0.67	0.28
Total Injected Load (g)	2.8	0.28	$1.3*10^{-4}$	$2.7*10^{-2}$	0.99	$4.4*10^{-2}$	$7.2*10^{-2}$
Outlet Load (g) [2]	7.9	3.5	$7.2*10^{-5}$	$2.0*10^{-2}$	0.55	$2.9*10^{-3}$	$1.9*10^{-2}$
Removal Efficiency (%)	*-180*	*-1100*	*46*	*26*	*44*	*99*	*73*

1. Tap water loads of cadmium, lead, and zinc were estimated by replacing <DL with ½ DL.
2. Calculated from parameter concentrations in inlet samples of concentrated synthetic stormwater and total water volume.
3. Calculated from parameter concentrations in road-deposited sediment and total sediment mass.
4. Nitrate load only.
5. Lead concentrations were <DL in all outlet samples; outlet loads of lead were estimated by replacing <DL with ½ DL.

As seen in Table 3-6, tap water contributed a considerably portion of the injected load of nutrients and metals; although parameter concentrations were low in tap water, almost 13,000 L of tap water was applied during the injection test, compared to 160 L of synthetic stormwater concentrate. For all parameters except nitrogen, however, loads contributed by the synthetic stormwater are larger than those contributed by tap water.

The estimated removal efficiencies indicate that nitrogen and phosphorous are released from the bioswale during the injection test. These data verify the assumption that soil-based bioretention may leach dissolved nutrient species such as ammonia, nitrate, and phosphate. According to the estimated removal efficiencies, metals are removed to a varying degree in the bioswale; from 26% removal of copper to 99% removal of lead. These results are likely related to metal speciation and variation in the sorption of metals to particles as metals have varying tendencies to sorb to solids. Among the most common stormwater metals, lead has largest tendency to sorb to solids whereas cadmium has the lowest sorption potential. In the injection test, it appears that copper has the lowest sorption to particles as the estimated removal efficiency is the lowest.

Comparison to Previously Collected Water Quality Data

Compared to previous monitoring data, collected on 2018-12-13, injection test outlet water quality from Bioswale #2 is better, with lower concentrations of nutrient species and metals. Water quality measured in 2018 showed more exceedances of the AMF thresholds, with nitrate, cadmium, and copper concentrations exceeding the 'need attention' level.

The Outlet Clean Water sample exceeded the AMF 'satisfactory' thresholds for nitrate, copper, and zinc. *E.coli* levels were very high at 3,500 MPN/100 mL and exceeding the AMF 'need attention' level at the start of the injection test. Although concentrations of all measured water quality parameters decreased over time, copper and *E.coli* concentrations were above the AMF 'satisfactory' threshold in Outlet sample 24. Water quality data collected during the 2018/2019 monitoring program also showed copper concentrations exceeding the AMF 'satisfactory' and 'need attention' thresholds in outlet samples from the two bioswales and the stormwater tree trench. Noted exceedances of provincial and federal water quality guidelines (Table 2-2) include: all outlet samples exceed the provincial long-term guideline for nitrite; all samples exceed the federal long-term copper guideline; Outlet Clean Water and Outlet sample #6 exceed the provincial long-term guideline for zinc. These data indicate that GRI may not be effective at attaining applicable water quality guidelines for copper, which was also indicated by copper's lower injection test removal efficiency compared to other metals (Table 3-5).

It is difficult to draw any conclusions on whether the maturation of Bioswale #2 has led to improved pollutant reduction capacity and improved outlet water quality, as only one rainfall-runoff event was captured at the bioswale in the 2018/2019 monitoring program and the injection tests produced limited data on pollutants except TSS.

3.3 Comparison to Similar GRI Practices

Bioretention such as bioswales can be designed with different objectives in mind, for example TSS reduction or peak flow mitigation, for different climates, and for different soil conditions. Because of the many design possibilities of bioretention, together with site specific conditions, their performance can vary widely.

Previous bioretention studies have reported 24–99% peak flow rate reduction and 20–98% volume reduction. Reduction of flow rate and volumes may vary between events depending on conditions in the bioretention at the start of the event – reductions are generally higher when the basin is dry at the start of an event – and rainfall characteristics such as intensity and duration. In the injection test, the volume was reduced by 77% and peak flow rate by 66%; however, reductions during rainfall-runoff events that are, e.g., less/more intense, shorter/longer duration, or shorter/longer antecedent dry period, may be different and are currently not known.

Data summarized from over 50 studies and reported in the in the International Stormwater BMP Database 2020 Summary Statistics[10] suggest that bioretention is one of the best performing stormwater BMPs (best management practices) for solids reduction, with effluent TSS concentration ranging from 4 to 10 mg/L in the investigated studies. A comparison of TSS influent/effluent concentrations indicated significant reduction, generally above 70%. Similarly, studies reviewed in the Low Impact Development Stormwater Planning and Design Guide[11], published by the Toronto and Region Conservation Authority (TRCA) in 2010, showed TSS concentrations reduced by >60% in bioretention. Further, more recent studies of 10 bioretention practices in Ontario showed that TSS loads were reduced by 73 to 99%[12]. Manganka et al. (2015)[13] found that the reduction of TSS loads improved from 62% when dry periods between runoff events were less than 6 days, to 81% for longer dry periods. Reviewed studies show that a high reduction of TSS loads can be expected in bioretention. A TSS reduction of 99% suggest that Bioswale #2 is among the more efficient bioretention practices for removing solids from stormwater.

[10] The Water Research Foundation (2020): International Stormwater BMP Database 2020 Summary Statistics. https://www.waterrf.org/resource/international-stormwater-bmp-database-2020-summary-statistics

[11] Toronto and Region Conservation Authority (2010): Low Impact Development Stormwater Planning and Design Guide. https://sustainabletechnologies.ca/home/urban-runoff-green-infrastructure/low-impact-development/low-impact-development-stormwater-planning-and-design-guide-2017-update/

[12] Sustainable Technologies Evaluation Program (STEP): Comparative Performance Assessment of Bioretention in Ontario, Technical Brief (2019). https://sustainabletechnologies.ca/app/uploads/2019/10/STEP_Bioretention-Synthesis_Tech-Brief-New-Template-2019-Oct-10.-2019.pdf

[13] Manganka et al. Performance characterisation of a stormwater treatment bioretention basin. *Journal of Environmental Management*, 2015, 150, 173-178. https://doi.org/10.1016/j.jenvman.2014.11.007

4. Summary

Key results from the injection tests are as follows:

- The infiltration lag time is approximately 2 h when the bioswale is not saturated with water. The infiltration lag time appeared to be reduced during the synthetic stormwater injection test, when soils were assumed to be more saturated prior to the start of the injection testing.
- The peak flow rate was reduced from approximately 0.7 L/s to 0.24 L/s, which corresponds to a 66% reduction.
- The applied volume of water was reduced from approximately 14 m^3 (12.6 m^3 injected, 0.15 m^3 direct rainfall, 1.3 m^3 runoff) to 2.9 m^3, which corresponds to a 77% reduction.
- Street sweeping material used for the synthetic stormwater contributed not only TSS to the injected water, but also metals, bacteria, and nutrients. Tap water also contained low levels of nutrients, copper, and iron.
- The injected TSS concentration throughout the stormwater injection test was estimated to 130 mg/L, and the highest TSS concentration measured in the outlet was 13.5 mg/L, which corresponds to a 90% reduction.
- At the end of the synthetic stormwater injection test, approximately 1,600 g of solids had been applied to the bioswale, and from flow and water quality measurements in the underdrain, the outlet load was estimated to 6.75 g TSS. The estimated removal efficiency of TSS loads during the injection test is >99%.
- During the pre-test (injection of water), the bioswale released nutrients and metals with outlet water. Higher outlet concentrations of these compounds were found during the pre-test than during the synthetic stormwater injection test, suggesting that nutrients and metals, assumed to be attached to particles in the synthetic stormwater, were removed during the injection test, while dissolved species of these compounds were leached during the pre-test. Estimated injection test removal efficiencies of nitrogen and phosphorous were negative, suggesting release of these compounds, while all metals were removed to some degree. Other studies have also observed leaching of dissolved pollutants, specifically nitrogen and phosphorous species, from bioretention.
- Outlet water quality measured during the injection test was improved, with fewer exceedances of AMF thresholds compared to monitoring data collected in 2018. However, the limited data (mostly TSS) make it difficult to draw any conclusions on whether the maturation of Bioswale #2 has led to improved pollutant reduction capacity and improved outlet water quality.
- Water quality data collected during the injection tests and in the 2018/2019 monitoring program suggest that GRI practices such as bioswale and stormwater tree trenches are not effective at attaining water quality guidelines for copper.

5. Recommendations

The stormwater injection tests proved to be time efficient procedures for studying a bioswale in detail and generating time series of data to evaluate its efficiency to reduce runoff flows and volumes as well as applied pollutant loads. The outcomes of the injection tests reported here are only an indication of how well a bioswale may function under certain conditions. It is not known how the bioswale functions during different rainfall-runoff events, e.g., higher rainfall intensity, or whether a stormwater tree trench would be as effective as the bioswale in reducing TSS. It is recommended to evaluate the efficiency of frequently implemented GRI practices in the City, to make sure they are well designed for the intended purpose, whether it be flow rate reduction or pollution removal. Injection tests can be used for evaluating both hydraulics and pollutant removal in GRI practices.

Other recommendations and lessons learned from the performed injection tests include:

- Frequent sampling to adequately capture the concentrations of relevant water quality parameters in the outlet. The frequency of sample collection should be determined by the desired accuracy of pollutant concentration and load estimations and the total time of the injection test procedure.
- Pre-determine the content of pollutants and other characteristics, e.g., organic matter content, of the material used to “pollute” the synthetic stormwater, in this case road-deposited sediments, to get a better understanding of injected pollutants and loads.
- Aim for a large fraction of fine material in the synthetic stormwater as coarser particles settle out rapidly. In this study, the road-deposited sediments were sieved through a 600 µm mesh size, which resulted in rapid settling of particles and heterogeneous samples of the synthetic stormwater.
- Constant mixing of the synthetic stormwater is required to avoid particles settling out. Procedures for automated mixing should be investigated.

The injection tests indicated that nutrients, both nitrogen and phosphorous species, as well as some metals can leach from the bioswale. If the City is concerned about leached nutrient levels, it is recommended to perform additional research, desktop research may suffice, on available soil amendments and bioretention designs to reduce nutrient leaching.

The injection tests and monitoring studies performed in 2018/2019 suggest that although GRI practices improve stormwater quality, water quality guidelines for copper as still exceeded. To further reduce copper levels in stormwater, the City may want to look into additional pre- or post-treatment practices as well as pollution prevention measures.

Submission

KERR WOOD LEIDAL ASSOCIATES LTD.

Prepared by:

Karin Bjorklund, M.Sc., PhD
Water Quality Specialist

Tabe Johnson, P.Eng.
Project Engineer

Reviewed by:

Patrick Lilley, M.Sc., R.P.Bio., BC-CESCL
Senior Biologist and Technical Reviewer

KHB/TJ

Revision Table

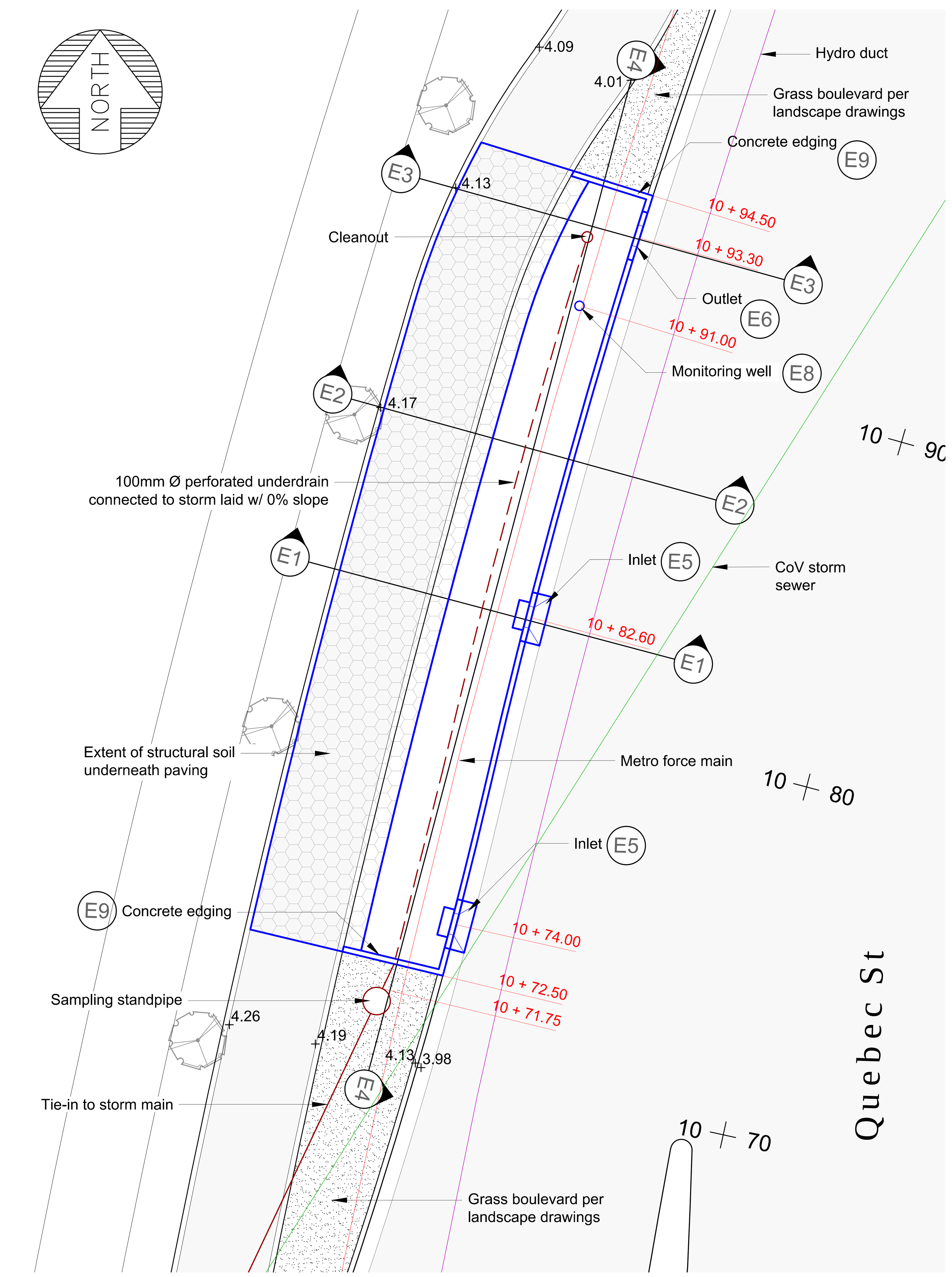
Revision #	Date	Status	Description	Author
0	April 28, 2022	FINAL		KB/TJ

Proudly certified as a leader in quality management under Engineers and Geoscientists BC's OQM Program from 2013 to 2021.

Appendix A

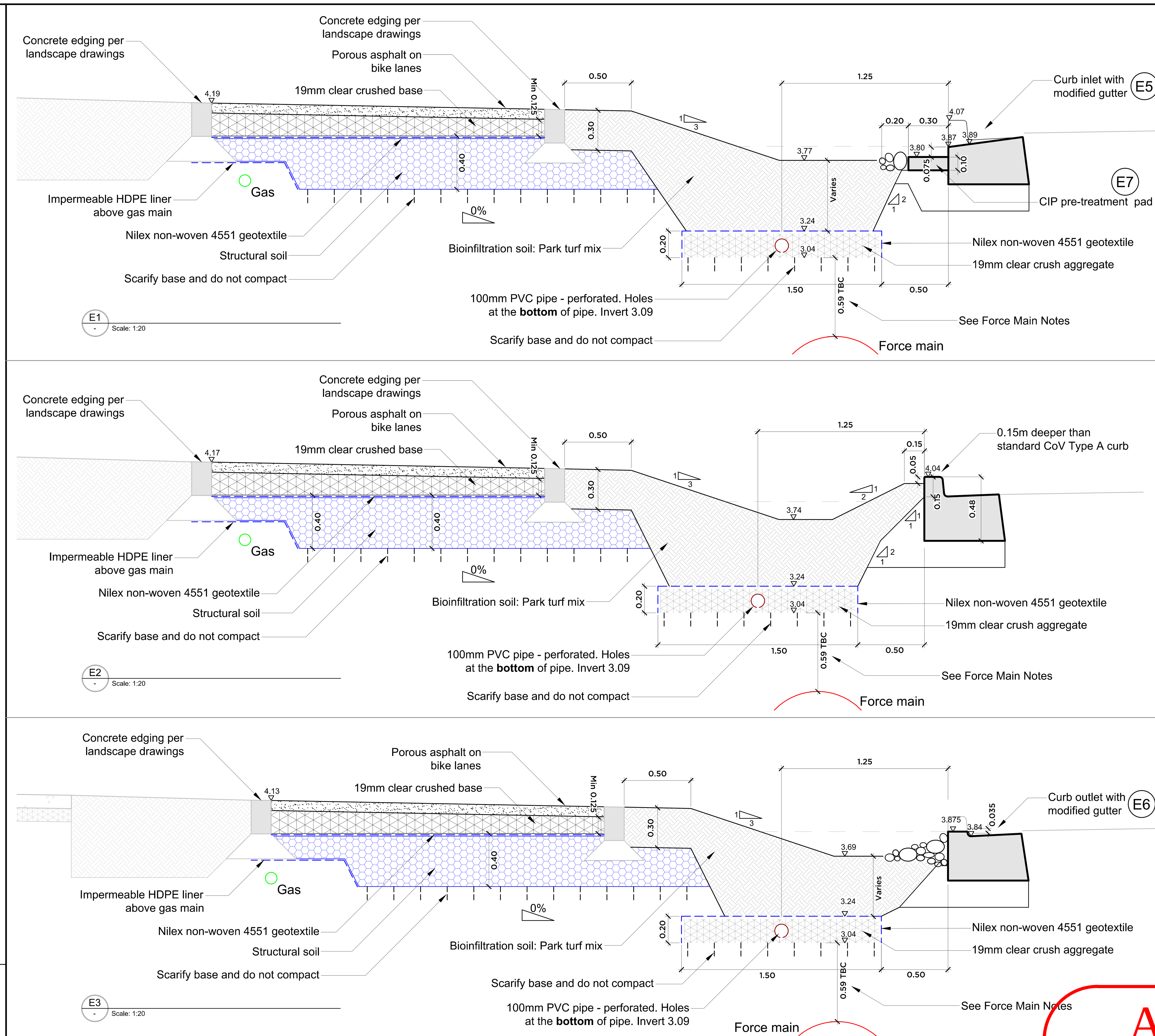
As-Built Drawings Bioswale #2

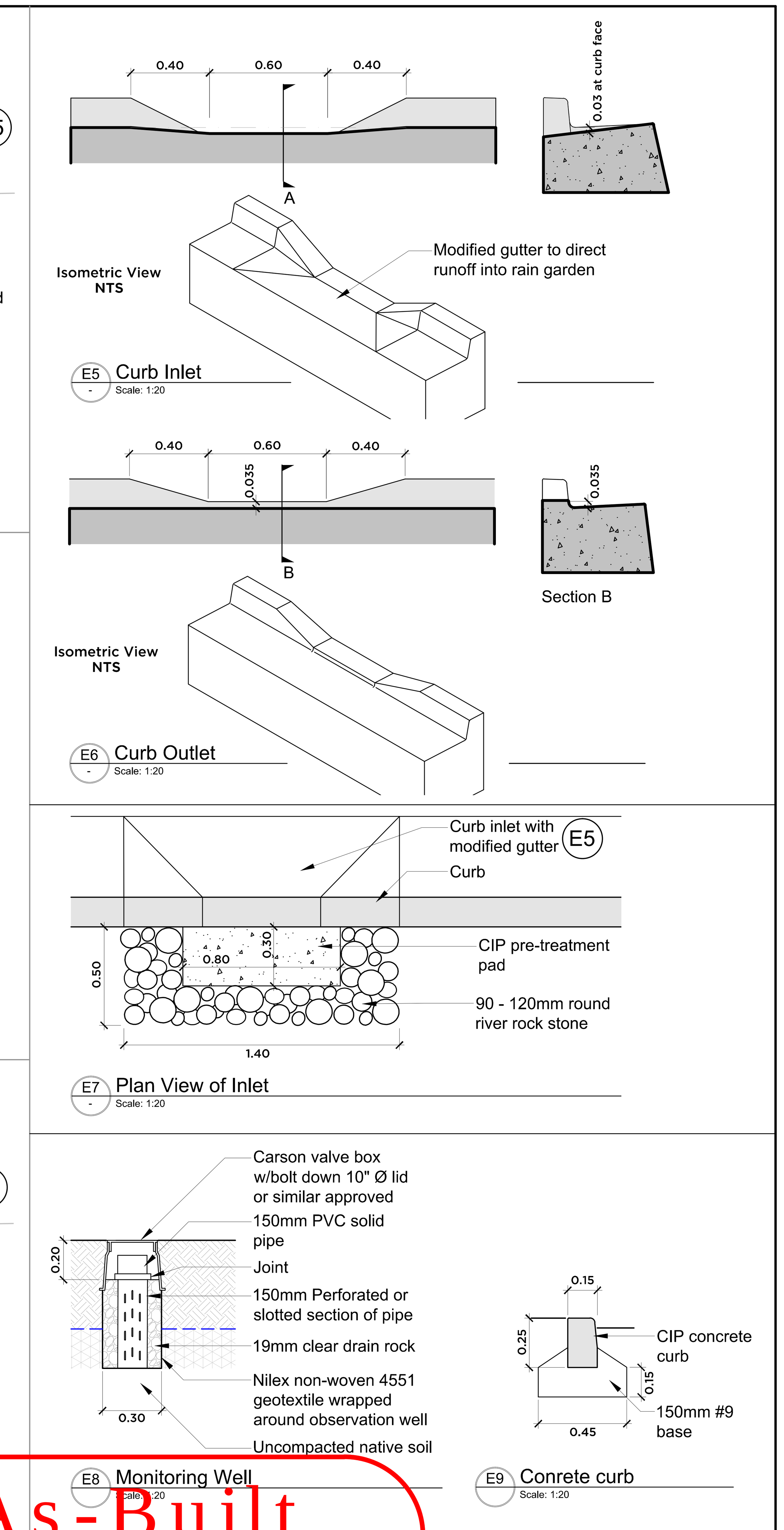
KERR WOOD LEIDAL ASSOCIATES LTD.
consulting engineers



Location Plan

Scale 1:100





Structural Soil and Growing Medium

Location E: Provide Structural Soil with Ecomedia as the growing medium component - supplied by Veratec. Contact: Larry Agnew 778.928.1606 providing 1 week's notice.
Quantity: 23m3.

Location E: Provide Ecomedia as the growing medium for the swale, supplied by Veratec. Contact: Larry Agnew 778.928. 1606 providing 1 week's notice.
Quantity: 30m3

Force Main Notes:

1. Daylight Force Main (using hydroexcavator) to confirm pipe depth at two locations. Please provide 48 hours advance notice so that Metro Vancouver staff can be on site to inspect.

CITY OF VANCOUVER

APPROVALS	INITIALS	CONTACT
LANDSCAPE ARCHITECT		604.296.2979
PROJECT ENGINEER		604.296.2975
CONSTRUCTION COORDINATOR		

REVISIONS / DESCRIPTION	INITIALS
Rev 3 Tie-in to storm main moved to south end of practice April 2018	APL
Rev 4 Structural soil/growing medium supply details/Sampling standpipe amended May 2018	APL
ACCOUNT #:	
DIRECTORY: H:\GREEN INFRASTRUCTURE\13-8100-40 - Green Infrastructure Case Files\ENG - GI - Quebec and 1st Precinct Upgrades\11 - Design\	

ENGINEERING SERVICES – CITY OF VANCOUVER – GREEN INFRASTRUCTURE

DESIGNED BY:	APL
DRAFTED BY:	APL
CHECKED BY:	RL
FILE NAME:	ENG - GI - Quebec St Reconstruction_AS-BUILT.dwg

Quebec and 1st Ave Precinct Improvements
Green Infrastructure
Location E - Plan and Sections

SCALE:	As shown
DATE:	March 2018
DWG. NO.	2008-63-D-GI3.5 AB
REV. NO.	4
SHEET:	6 OF 7

FILE: H:\GREEN INFRASTRUCTURE\13-8100-40 - Green Infrastructure Case Files\ENG - GI - Quebec and 1st Precinct Upgrades\11 - Design\ENG - GI - Quebec St Reconstruction_AS-BUILT.dwg DATE:Oct 16, 2018 - 3:32pm USER:enapl

Appendix B

KWL Field Notes Synthetic Stormwater Injection Test 2021-10-20

KERR WOOD LEIDAL ASSOCIATES LTD.
consulting engineers

Appendix B – KWL Field Notes Synthetic Stormwater Injection Test 2021-10-20

Time	Time since start of water injection	Time since start of synthetic stormwater injection	Action	Comment	Collected Sample(s)
9:15	-20 min	-30 min	Start of water level (flow) logging in underdrain		
9:35	0 min	-10 min	Start of tap water injection	Flow 1.1 L/s	
9:40	5 min	-5 min	Flow check, underdrain	No flow over weir at this time	
9:45 – 10:15	10 min	0 min	Start synthetic stormwater dosing, batch 1	Synthetic stormwater prepared by mixing 200 g dry sediment to 20 L tap water Empty bucket with synthetic stormwater into bioswale over 30 min	
9:45	10 min	0 min	Flow check, injected water	1.1 L/s (11 L bucket filled in 10 s)	
10:00	25 min	15 min	Flow check, underdrain	Flow observed over weir	
10:15 – 10:45	40 min	30 min	Start synthetic stormwater dosing, batch 2	Total of 400 g sediment added	
10:16	41 min	31 min		First outlet sample collected 30 min after first batch of synthetic stormwater was injected	Outlet sample #1 Analyze for: TSS
10:26	51 min	41 min			Outlet sample #2 Analyze for: TSS

KERR WOOD LEIDAL ASSOCIATES LTD.
consulting engineers

Time	Time since start of water injection	Time since start of synthetic stormwater injection	Action	Comment	Collected Sample(s)
10:36	1 h 1 min	51 min			Outlet sample #3 Analyze for: TSS
10:45 – 11:15	1 h 10 min	1 h	Start synthetic stormwater dosing, batch 3	Total of 600 g sediment added	
10:45	1 h 10 min	1 h	Flow check, injected water	0.77 L/s	
10:46	1 h 11 min	1 h 1 min			Outlet sample #4 Analyze for: TSS
10:56	1 h 21 min	1 h 11 min			Outlet sample #5 Analyze for: TSS
11:00	1 h 25 min	1 h 15 min			Inlet sample #1 Analyze for: Full suite of laboratory parameters
11:06	1 h 31 min	1 h 21 min			Outlet sample #6 Analyze for: TSS, total N, *E.coli*
11:15 – 11:45	1 h 40 min	1 h 30 min	Start synthetic stormwater dosing, batch 4	Total of 800 g sediment added	
11:15	1 h 40 min	1 h 30 min	Flow check, injected water	0.69 L/s	
11:16	1 h 41 min	1 h 31 min		*In situ* data measured in outlet sample: • Water temperature: 12.0 °C • Dissolved oxygen (DO): 94.5%; 10.18 mg/L	Outlet sample #7 Analyze for: TSS, *in situ* parameters

Time	Time since start of water injection	Time since start of synthetic stormwater injection	Action	Comment	Collected Sample(s)
				• Conductivity: 131.2 µS/cm • pH: 5.29 • Redox potential: 197 mV • Turbidity: 4.8 NTU	
11:26	1 h 51 min	1 h 41 min			Outlet sample #8 Analyze for: TSS
11:36	2 h 1 min	1 h 51 min		*In situ* data measured in outlet sample: • Water temperature: 11.8 °C • (DO: no data) • Conductivity: 106.7 µS/cm • pH: 5.76 • Redox potential: 232 mV • Turbidity: 4.89 NTU	Outlet sample #9 Analyze for: TSS, *in situ* parameters
11:45	2 h 10 min	2 h	Start synthetic stormwater dosing, batch 5	Total of 1,000 g sediment added	
11:45	2 h 10 min	2 h	Flow check, injected water	0.48 L/s	
11:46	2 h 11 min	2 h 1 min			Outlet sample #10 Analyze for: TSS
11:47	2 h 12 min	2 h 2 min	Flow check, injected water	0.74 L/s	
11:56	2 h 21 min	2 h 11 min			Outlet sample #11 Analyze for: TSS
11:58	2 h 23 min	2 h 13 min			Inlet sample #2

Time	Time since start of water injection	Time since start of synthetic stormwater injection	Action	Comment	Collected Sample(s)
					Analyze for: Full suite of laboratory parameters
12:04	2 h 29 min	2 h 10 min	Flow check, injected water	0.79 L/s	
12:06	2 h 31 min	2 h 21 min			Outlet sample #12 Analyze for: Full suite of laboratory parameters
12:15 – 12:45	2 h 40 min	2 h 30 min	Start synthetic stormwater dosing, batch 6	Total of 1,200 g sediment added	
12:16	2 h 41 min	2 h 31 min			Outlet sample #13 Analyze for: TSS
12:26	2 h 51 min	2 h 41 min			Outlet sample #14 Analyze for: TSS
12:36	3 h 1 min	2 h 51 min			Outlet sample #15 Analyze for: TSS
12:45 – 13:15	3 h 10 min	3 h	Start synthetic stormwater dosing, batch 7	Total of 1,400 g sediment added	
12:46	3 h 11 min	3 h 1 min			Outlet sample #16 Analyze for: TSS
12:56	3 h 21 min	3 h 11 min			Outlet sample #17 Analyze for: TSS
13:00	3 h 25 min	3 h 15 min			Inlet sample #3

Time	Time since start of water injection	Time since start of synthetic stormwater injection	Action	Comment	Collected Sample(s)
					Analyze for: Full suite of laboratory parameters
13:06	3 h 31 min	3 h 21 min			Outlet sample #18 Analyze for: Full suite of laboratory parameters
13:15 – 13:45	3 h 40 min	3 h 30 min	Start synthetic stormwater dosing, final batch 8	Total of 1,600 g sediment added	
13:15	3 h 40 min	3 h 30 min	Flow check, injected water	0.71 L/s	
13:16	3 h 41 min	3 h 31 min			Outlet sample #19 Analyze for: TSS
13:26	3 h 51 min	3 h 41 min			Outlet sample #20 Analyze for: TSS
13:36	4 h 1 min	3 h 51 min			Outlet sample #21 Analyze for: TSS
13:45	4 h 10 min	4 h	End of final synthetic stormwater dosing	Tap water injection continues until 14.30	
13:46	4 h 11 min	4 h 1 min			Outlet sample #22 Analyze for: TSS
13:47	4 h 12 min	4 h 2 min		Added last bits of sediment in cell	
13:56	4 h 21 min	4 h 11 min			Outlet sample #23

Time	Time since start of water injection	Time since start of synthetic stormwater injection	Action	Comment	Collected Sample(s)
					Analyze for: TSS
14:00	4 h 25 min	4 h 15 min	Flow check, injected water	0.65 L/s	
14:06	4 h 31 min	4 h 21 min			Outlet sample #24 Analyze for: Full suite of laboratory parameters
14:16	4 h 41 min	4 h 31 min			Outlet sample #25 Analyze for: TSS
14:26	4 h 51 min	4 h 41 min			Outlet sample #26 Analyze for: TSS
14:30	4 h 55 min	4 h 45 min	End of tap water injection	Total water injection time: 4 h 55 min, or ~ 5 h, at a flow of approx.. 0.7 L/s Total injected water volume: = 12,600 L, or ~ 13 m^3	
14:36	5 h 1 min	4 h 51 min			Outlet sample #27 Analyze for: TSS
14:46	5 h 11 min	5 h 1 min			Outlet sample #28 Analyze for: TSS
15:10	5 h 35 min	5 h 25 min	End of water level (flow) logging in underdrain		

Appendix C

Laboratory Reports

KERR WOOD LEIDAL ASSOCIATES LTD.
consulting engineers

CARO ANALYTICAL SERVICES

CERTIFICATE OF ANALYSIS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby) 200 - 4185A Still Creek Dr Burnaby, BC V5C 6G9		
ATTENTION	Patrick Lilley	**WORK ORDER**	21J2703
PO NUMBER		**RECEIVED / TEMP**	2021-10-20 17:00 / 10.2°C
PROJECT	42.158	**REPORTED**	2021-10-28 13:13
PROJECT INFO	Bioswale #2	**COC NUMBER**	B097650

Introduction:

CARO Analytical Services is a testing laboratory full of smart, engaged scientists driven to make the world a safer and healthier place. Through our clients' projects we become an essential element for a better world. We employ methods conducted in accordance with recognized professional standards using accepted testing methodologies and quality control efforts. CARO is accredited by the Canadian Association for Laboratories Accreditation (CALA) to ISO/IEC 17025:2017 for specific tests listed in the scope of accreditation approved by CALA.

Big Picture Sidekicks

You know that the sample you collected after snowshoeing to site, digging 5 meters, and racing to get it on a plane so you can submit it to the lab for time sensitive results needed to make important and expensive decisions (whew) is VERY important. We know that too.

We've Got Chemistry

It's simple. We figure the more you enjoy working with our fun and engaged team members; the more likely you are to give us continued opportunities to support you.

Ahead of the Curve

Through research, regulation knowledge, and instrumentation, we are your analytical centre for the technical knowledge you need, BEFORE you need it, so you can stay up to date and in the know.

Work Order Comments:

If you have any questions or concerns, please contact me at nyipp@caro.ca

Authorized By:

Nicole Yipp
Team Lead, Client Service

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Baseline (21J2703-01) | Matrix: Water | Sampled: 2021-10-19 12:17						
Anions						
Nitrate+Nitrite (as N)	**3.04**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	**0.124**	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						
Hardness, Total (as CaCO3)	**40.6**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**2.92**	N/A	0.0500	mg/L	N/A	
Nitrogen, Total	**5.52**	N/A	0.0500	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**2.47**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**2.50**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	**4.0**	600	2.0	mg/L	2021-10-26	
Total Metals						
Aluminum, total	**0.211**	50	0.0050	mg/L	2021-10-27	
Antimony, total	**0.00032**	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	**0.00362**	1	0.00050	mg/L	2021-10-27	
Barium, total	**0.0086**	N/A	0.0050	mg/L	2021-10-27	
Beryllium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Bismuth, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Boron, total	**0.253**	50	0.0500	mg/L	2021-10-27	
Cadmium, total	**0.000051**	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**12.7**	N/A	0.20	mg/L	2021-10-27	
Chromium, total	**0.00092**	4	0.00050	mg/L	2021-10-27	
Cobalt, total	**0.00057**	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.0103**	2	0.00040	mg/L	2021-10-27	
Iron, total	**0.225**	10	0.010	mg/L	2021-10-27	
Lead, total	< 0.00020	1	0.00020	mg/L	2021-10-27	
Lithium, total	**0.00037**	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**2.17**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.0221**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00121**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.00375**	2	0.00040	mg/L	2021-10-27	
Phosphorus, total	**2.50**	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**5.29**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**2.8**	N/A	1.0	mg/L	2021-10-27	
Silver, total	< 0.000050	1	0.000050	mg/L	2021-10-27	
Sodium, total	**2.96**	N/A	0.10	mg/L	2021-10-27	
Strontium, total	**0.0366**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	< 0.000020	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Baseline (21J2703-01) | Matrix: Water | Sampled: 2021-10-19 12:17, Continued						
Total Metals, Continued						
Tin, total	**0.00033**	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	< 0.0050	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000043**	N/A	0.000020	mg/L	2021-10-27	
Vanadium, total	**0.0053**	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	**0.0147**	3	0.0040	mg/L	2021-10-27	
Zirconium, total	**0.00024**	N/A	0.00010	mg/L	2021-10-27	
Inlet 1 (21J2703-02) | Matrix: Water | Sampled: 2021-10-20 10:45						
Anions						
Nitrate+Nitrite (as N)	**0.148**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	< 0.0050	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						
Hardness, Total (as CaCO3)	**44.9**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**0.148**	N/A	0.00500	mg/L	N/A	
Nitrogen, Total	**3.00**	N/A	0.0500	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**2.86**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**0.648**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	**788**	600	2.0	mg/L	2021-10-27	
Total Metals						
Aluminum, total	**3.94**	50	0.0050	mg/L	2021-10-27	
Antimony, total	**0.00137**	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	**0.00169**	1	0.00050	mg/L	2021-10-27	
Barium, total	**0.0731**	N/A	0.0050	mg/L	2021-10-27	
Beryllium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Bismuth, total	**0.00049**	N/A	0.00010	mg/L	2021-10-27	
Boron, total	**0.110**	50	0.0500	mg/L	2021-10-27	
Cadmium, total	**0.000355**	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**14.7**	N/A	0.20	mg/L	2021-10-27	
Chromium, total	**0.00702**	4	0.00050	mg/L	2021-10-27	
Cobalt, total	**0.00226**	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.0818**	2	0.00040	mg/L	2021-10-27	
Iron, total	**4.35**	10	0.010	mg/L	2021-10-27	
Lead, total	**0.220**	1	0.00020	mg/L	2021-10-27	
Lithium, total	**0.00154**	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**1.99**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.135**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00063**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.00598**	2	0.00040	mg/L	2021-10-27	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Inlet 1 (21J2703-02) | Matrix: Water | Sampled: 2021-10-20 10:45, Continued						
Total Metals, Continued						
Phosphorus, total	**0.614**	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**1.38**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**7.2**	N/A	1.0	mg/L	2021-10-27	
Silver, total	< 0.000050	1	0.000050	mg/L	2021-10-27	
Sodium, total	**2.97**	N/A	0.10	mg/L	2021-10-27	
Strontium, total	**0.0618**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	**0.000020**	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Tin, total	**0.00204**	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	**0.0920**	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000162**	N/A	0.000020	mg/L	2021-10-27	
Vanadium, total	**0.0077**	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	**0.238**	3	0.0040	mg/L	2021-10-27	
Zirconium, total	**0.00054**	N/A	0.00010	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	**79**	N/A	2	MPN/100 mL	2021-10-21	
Inlet 2 (21J2703-03) | Matrix: Water | Sampled: 2021-10-20 12:00						
Anions						
Nitrate+Nitrite (as N)	**0.212**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	< 0.0050	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						
Hardness, Total (as CaCO3)	**74.7**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**0.212**	N/A	0.00500	mg/L	N/A	
Nitrogen, Total	**6.92**	N/A	0.250	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**6.71**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**2.27**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	**2410**	600	2.0	mg/L	2021-10-27	
Total Metals						
Aluminum, total	**6.28**	50	0.0050	mg/L	2021-10-27	
Antimony, total	**0.00255**	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	**0.00269**	1	0.00050	mg/L	2021-10-27	
Barium, total	**0.105**	N/A	0.0050	mg/L	2021-10-27	
Beryllium, total	**0.00014**	N/A	0.00010	mg/L	2021-10-27	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Inlet 2 (21J2703-03) | Matrix: Water | Sampled: 2021-10-20 12:00, Continued						
Total Metals, Continued						
Bismuth, total	**0.00049**	N/A	0.00010	mg/L	2021-10-27	
Boron, total	**0.0770**	50	0.0500	mg/L	2021-10-27	
Cadmium, total	**0.000597**	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**24.7**	N/A	0.20	mg/L	2021-10-27	
Chromium, total	**0.0129**	4	0.00050	mg/L	2021-10-27	
Cobalt, total	**0.00393**	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.139**	2	0.00040	mg/L	2021-10-27	
Iron, total	**7.14**	10	0.010	mg/L	2021-10-27	
Lead, total	**0.410**	1	0.00020	mg/L	2021-10-27	
Lithium, total	**0.00262**	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**3.13**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.235**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00073**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.0112**	2	0.00040	mg/L	2021-10-27	
Phosphorus, total	**1.11**	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**1.67**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**9.8**	N/A	1.0	mg/L	2021-10-27	
Silver, total	**0.000057**	1	0.000050	mg/L	2021-10-27	
Sodium, total	**3.29**	N/A	0.10	mg/L	2021-10-27	
Strontium, total	**0.108**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	**0.000037**	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	**0.00016**	N/A	0.00010	mg/L	2021-10-27	
Tin, total	**0.00200**	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	**0.150**	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000277**	N/A	0.000020	mg/L	2021-10-27	
Vanadium, total	**0.0131**	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	**0.413**	3	0.0040	mg/L	2021-10-27	
Zirconium, total	**0.00065**	N/A	0.00010	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	**79**	N/A	2	MPN/100 mL	2021-10-21	
Inlet 3 (21J2703-04) | Matrix: Water | Sampled: 2021-10-20 13:00						
Anions						
Nitrate+Nitrite (as N)	**0.167**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	< 0.0050	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Inlet 3 (21J2703-04) | Matrix: Water | Sampled: 2021-10-20 13:00, Continued						
Calculated Parameters, Continued						
Hardness, Total (as CaCO3)	**45.3**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**0.167**	N/A	0.00500	mg/L	N/A	
Nitrogen, Total	**5.11**	N/A	0.100	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**4.94**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**0.794**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	**2380**	600	2.0	mg/L	2021-10-27	
Total Metals						
Aluminum, total	**4.10**	50	0.0050	mg/L	2021-10-27	
Antimony, total	**0.00157**	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	**0.00168**	1	0.00050	mg/L	2021-10-27	
Barium, total	**0.0644**	N/A	0.0050	mg/L	2021-10-27	
Beryllium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Bismuth, total	**0.00036**	N/A	0.00010	mg/L	2021-10-27	
Boron, total	**0.0602**	50	0.0500	mg/L	2021-10-27	
Cadmium, total	**0.000357**	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**14.6**	N/A	0.20	mg/L	2021-10-27	
Chromium, total	**0.00824**	4	0.00050	mg/L	2021-10-27	
Cobalt, total	**0.00240**	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.0866**	2	0.00040	mg/L	2021-10-27	
Iron, total	**4.65**	10	0.010	mg/L	2021-10-27	
Lead, total	**0.171**	1	0.00020	mg/L	2021-10-27	
Lithium, total	**0.00169**	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**2.14**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.145**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00057**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.00662**	2	0.00040	mg/L	2021-10-27	
Phosphorus, total	**0.653**	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**1.39**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**7.1**	N/A	1.0	mg/L	2021-10-27	
Silver, total	< 0.000050	1	0.000050	mg/L	2021-10-27	
Sodium, total	**2.93**	N/A	0.10	mg/L	2021-10-27	
Strontium, total	**0.0619**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	**0.000022**	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Tin, total	**0.00179**	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	**0.114**	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000179**	N/A	0.000020	mg/L	2021-10-27	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Inlet 3 (21J2703-04) | Matrix: Water | Sampled: 2021-10-20 13:00, Continued						
Total Metals, Continued						
Vanadium, total	**0.0086**	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	**0.233**	3	0.0040	mg/L	2021-10-27	
Zirconium, total	**0.00048**	N/A	0.00010	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	**350**	N/A	2	MPN/100 mL	2021-10-21	
Outlet 1 (21J2703-05) | Matrix: Water | Sampled: 2021-10-20 10:16						
General Parameters						
Solids, Total Suspended	**13.5**	600	2.0	mg/L	2021-10-27	
Outlet 2 (21J2703-06) | Matrix: Water | Sampled: 2021-10-20 10:26						
General Parameters						
Solids, Total Suspended	**5.5**	600	2.0	mg/L	2021-10-27	
Outlet 3 (21J2703-07) | Matrix: Water | Sampled: 2021-10-20 10:36						
General Parameters						
Solids, Total Suspended	**5.2**	600	2.0	mg/L	2021-10-27	
Outlet 4 (21J2703-08) | Matrix: Water | Sampled: 2021-10-20 10:46						
General Parameters						
Solids, Total Suspended	**4.0**	600	2.0	mg/L	2021-10-27	
Outlet 5 (21J2703-09) | Matrix: Water | Sampled: 2021-10-20 10:56						
General Parameters						
Solids, Total Suspended	**5.5**	600	2.0	mg/L	2021-10-27	
Outlet 6 (21J2703-10) | Matrix: Water | Sampled: 2021-10-20 11:06						
General Parameters						
Solids, Total Suspended	**5.0**	600	2.0	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	**3,500**	N/A	2	MPN/100 mL	2021-10-21	
Outlet 7 (21J2703-11) | Matrix: Water | Sampled: 2021-10-20 11:16						

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	WORK ORDER	21J2703
PROJECT	42.158	REPORTED	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Outlet 7 (21J2703-11) | Matrix: Water | Sampled: 2021-10-20 11:16, Continued						
General Parameters						
Solids, Total Suspended	**4.5**	600	2.0	mg/L	2021-10-27	
Outlet 8 (21J2703-12) | Matrix: Water | Sampled: 2021-10-20 11:26						
General Parameters						
Solids, Total Suspended	**3.5**	600	2.0	mg/L	2021-10-27	
Outlet 9 (21J2703-13) | Matrix: Water | Sampled: 2021-10-20 11:36						
General Parameters						
Solids, Total Suspended	**3.2**	600	2.0	mg/L	2021-10-27	
Outlet 10 (21J2703-14) | Matrix: Water | Sampled: 2021-10-20 11:46						
General Parameters						
Solids, Total Suspended	**2.5**	600	2.0	mg/L	2021-10-27	
Outlet 11 (21J2703-15) | Matrix: Water | Sampled: 2021-10-20 11:56						
General Parameters						
Solids, Total Suspended	**2.5**	600	2.0	mg/L	2021-10-27	
Outlet 12 (21J2703-16) | Matrix: Water | Sampled: 2021-10-20 12:06						
Anions						
Nitrate+Nitrite (as N)	**0.864**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	**0.0512**	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						
Hardness, Total (as CaCO3)	**29.7**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**0.812**	N/A	0.00500	mg/L	N/A	
Nitrogen, Total	**3.32**	N/A	0.0500	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**2.46**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**1.23**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	**2.8**	600	2.0	mg/L	2021-10-27	
Total Metals						
Aluminum, total	**0.192**	50	0.0050	mg/L	2021-10-27	
Antimony, total	**0.00025**	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	**0.00178**	1	0.00050	mg/L	2021-10-27	
Barium, total	**0.0066**	N/A	0.0050	mg/L	2021-10-27	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Outlet 12 (21J2703-16) | Matrix: Water | Sampled: 2021-10-20 12:06, Continued						
Total Metals, Continued						
Beryllium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Bismuth, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Boron, total	**0.0516**	50	0.0500	mg/L	2021-10-27	
Cadmium, total	**0.000028**	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**9.46**	N/A	0.20	mg/L	2021-10-27	
Chromium, total	**0.00085**	4	0.00050	mg/L	2021-10-27	
Cobalt, total	**0.00058**	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.00922**	2	0.00040	mg/L	2021-10-27	
Iron, total	**0.231**	10	0.010	mg/L	2021-10-27	
Lead, total	< 0.00020	1	0.00020	mg/L	2021-10-27	
Lithium, total	**0.00043**	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**1.47**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.0388**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00082**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.00338**	2	0.00040	mg/L	2021-10-27	
Phosphorus, total	**1.11**	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**3.75**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**2.1**	N/A	1.0	mg/L	2021-10-27	
Silver, total	< 0.000050	1	0.000050	mg/L	2021-10-27	
Sodium, total	**1.69**	N/A	0.10	mg/L	2021-10-27	
Strontium, total	**0.0273**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	< 0.000020	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Tin, total	< 0.00020	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	< 0.0050	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000042**	N/A	0.000020	mg/L	2021-10-27	
Vanadium, total	**0.0043**	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	**0.0093**	3	0.0040	mg/L	2021-10-27	
Zirconium, total	**0.00034**	N/A	0.00010	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	**33**	N/A	2	MPN/100 mL	2021-10-21	
Outlet 13 (21J2703-17) | Matrix: Water | Sampled: 2021-10-20 12:16						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	

Outlet 14 (21J2703-18) | Matrix: Water | Sampled: 2021-10-20 12:26

CARO ANALYTICAL SERVICES

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Outlet 14 (21J2703-18) | Matrix: Water | Sampled: 2021-10-20 12:26, Continued						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 15 (21J2703-19) | Matrix: Water | Sampled: 2021-10-20 12:36						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 16 (21J2703-20) | Matrix: Water | Sampled: 2021-10-20 12:46						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 17 (21J2703-21) | Matrix: Water | Sampled: 2021-10-20 12:56						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 18 (21J2703-22) | Matrix: Water | Sampled: 2021-10-20 13:06						
Anions						
Nitrate+Nitrite (as N)	**0.776**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	**0.0301**	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						
Hardness, Total (as CaCO3)	**28.0**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**0.746**	N/A	0.00500	mg/L	N/A	
Nitrogen, Total	**2.37**	N/A	0.0500	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**1.59**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**0.978**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Total Metals						
Aluminum, total	**0.126**	50	0.0050	mg/L	2021-10-27	
Antimony, total	< 0.00020	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	**0.00156**	1	0.00050	mg/L	2021-10-27	
Barium, total	**0.0054**	N/A	0.0050	mg/L	2021-10-27	
Beryllium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Bismuth, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Boron, total	< 0.0500	50	0.0500	mg/L	2021-10-27	
Cadmium, total	**0.000020**	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**8.78**	N/A	0.20	mg/L	2021-10-27	

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Outlet 18 (21J2703-22) | Matrix: Water | Sampled: 2021-10-20 13:06, Continued						
Total Metals, Continued						
Chromium, total	**0.00058**	4	0.00050	mg/L	2021-10-27	
Cobalt, total	**0.00037**	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.00544**	2	0.00040	mg/L	2021-10-27	
Iron, total	**0.166**	10	0.010	mg/L	2021-10-27	
Lead, total	< 0.00020	1	0.00020	mg/L	2021-10-27	
Lithium, total	**0.00037**	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**1.48**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.0182**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00060**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.00202**	2	0.00040	mg/L	2021-10-27	
Phosphorus, total	**0.929**	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**3.89**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**2.0**	N/A	1.0	mg/L	2021-10-27	
Silver, total	< 0.000050	1	0.000050	mg/L	2021-10-27	
Sodium, total	**1.78**	N/A	0.10	mg/L	2021-10-27	
Strontium, total	**0.0245**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	< 0.000020	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Tin, total	< 0.00020	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	< 0.0050	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000028**	N/A	0.000020	mg/L	2021-10-27	
Vanadium, total	**0.0037**	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	**0.0041**	3	0.0040	mg/L	2021-10-27	
Zirconium, total	**0.00024**	N/A	0.00010	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	**49**	N/A	2	MPN/100 mL	2021-10-21	
Outlet 19 (21J2703-23) | Matrix: Water | Sampled: 2021-10-20 13:16						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 20 (21J2703-24) | Matrix: Water | Sampled: 2021-10-20 13:26						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	

CARO ANALYTICAL SERVICES

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Outlet 21 (21J2703-25) | Matrix: Water | Sampled: 2021-10-20 13:36						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 22 (21J2703-26) | Matrix: Water | Sampled: 2021-10-20 13:46						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 23 (21J2703-27) | Matrix: Water | Sampled: 2021-10-20 13:56						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 24 (21J2703-28) | Matrix: Water | Sampled: 2021-10-20 14:06						
Anions						
Nitrate+Nitrite (as N)	**0.690**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	**0.0211**	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						
Hardness, Total (as CaCO3)	**25.4**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**0.669**	N/A	0.00500	mg/L	N/A	
Nitrogen, Total	**1.75**	N/A	0.0500	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**1.06**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**0.858**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Total Metals						
Aluminum, total	**0.0963**	50	0.0050	mg/L	2021-10-27	
Antimony, total	< 0.00020	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	**0.00127**	1	0.00050	mg/L	2021-10-27	
Barium, total	< 0.0050	N/A	0.0050	mg/L	2021-10-27	
Beryllium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Bismuth, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Boron, total	< 0.0500	50	0.0500	mg/L	2021-10-27	
Cadmium, total	**0.000014**	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**7.90**	N/A	0.20	mg/L	2021-10-27	
Chromium, total	< 0.00050	4	0.00050	mg/L	2021-10-27	
Cobalt, total	**0.00028**	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.00379**	2	0.00040	mg/L	2021-10-27	
Iron, total	**0.143**	10	0.010	mg/L	2021-10-27	
Lead, total	< 0.00020	1	0.00020	mg/L	2021-10-27	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Outlet 24 (21J2703-28) | Matrix: Water | Sampled: 2021-10-20 14:06, Continued						
Total Metals, Continued						
Lithium, total	**0.00030**	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**1.37**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.0124**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00049**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.00142**	2	0.00040	mg/L	2021-10-27	
Phosphorus, total	**0.752**	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**3.54**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**1.9**	N/A	1.0	mg/L	2021-10-27	
Silver, total	< 0.000050	1	0.000050	mg/L	2021-10-27	
Sodium, total	**1.74**	N/A	0.10	mg/L	2021-10-27	
Strontium, total	**0.0222**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	< 0.000020	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Tin, total	< 0.00020	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	< 0.0050	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000021**	N/A	0.000020	mg/L	2021-10-27	
Vanadium, total	**0.0034**	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	< 0.0040	3	0.0040	mg/L	2021-10-27	
Zirconium, total	**0.00016**	N/A	0.00010	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	**79**	N/A	2	MPN/100 mL	2021-10-21	
Outlet 25 (21J2703-29) | Matrix: Water | Sampled: 2021-10-20 14:16						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 26 (21J2703-30) | Matrix: Water | Sampled: 2021-10-20 14:26						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	
Outlet 27 (21J2703-31) | Matrix: Water | Sampled: 2021-10-20 14:36						
General Parameters						
Solids, Total Suspended	< 2.5	600	2.0	mg/L	2021-10-27	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Outlet 28 (21J2703-32) | Matrix: Water | Sampled: 2021-10-20 14:46						
General Parameters						
Solids, Total Suspended	**4.2**	600	2.0	mg/L	2021-10-27	
Tap Water (21J2703-33) | Matrix: Water | Sampled: 2021-10-20 13:15						
Anions						
Nitrate+Nitrite (as N)	**0.0950**	N/A	0.0050	mg/L	2021-10-28	
Nitrite (as N)	< 0.0050	N/A	0.0050	mg/L	2021-10-25	HT1
Calculated Parameters						
Hardness, Total (as CaCO3)	**19.1**	N/A	0.500	mg/L	N/A	
Nitrate (as N)	**0.0950**	N/A	0.00500	mg/L	N/A	
Nitrogen, Total	**0.158**	N/A	0.0500	mg/L	N/A	
General Parameters						
Nitrogen, Total Kjeldahl	**0.063**	N/A	0.050	mg/L	2021-10-24	
Phosphorus, Total (as P)	**0.0068**	N/A	0.0050	mg/L	2021-10-27	
Solids, Total Suspended	< 2.0	600	2.0	mg/L	2021-10-27	
Total Metals						
Aluminum, total	**0.0593**	50	0.0050	mg/L	2021-10-27	
Antimony, total	< 0.00020	N/A	0.00020	mg/L	2021-10-27	
Arsenic, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Barium, total	< 0.0050	N/A	0.0050	mg/L	2021-10-27	
Beryllium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Bismuth, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Boron, total	< 0.0500	50	0.0500	mg/L	2021-10-27	
Cadmium, total	< 0.000010	0.2	0.000010	mg/L	2021-10-27	
Calcium, total	**7.33**	N/A	0.20	mg/L	2021-10-27	
Chromium, total	< 0.00050	4	0.00050	mg/L	2021-10-27	
Cobalt, total	< 0.00010	5	0.00010	mg/L	2021-10-27	
Copper, total	**0.00085**	2	0.00040	mg/L	2021-10-27	
Iron, total	**0.010**	10	0.010	mg/L	2021-10-27	
Lead, total	< 0.00020	1	0.00020	mg/L	2021-10-27	
Lithium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Magnesium, total	**0.200**	N/A	0.010	mg/L	2021-10-27	
Manganese, total	**0.00348**	5	0.00020	mg/L	2021-10-27	
Molybdenum, total	**0.00014**	1	0.00010	mg/L	2021-10-27	
Nickel, total	**0.00094**	2	0.00040	mg/L	2021-10-27	
Phosphorus, total	< 0.050	N/A	0.050	mg/L	2021-10-27	
Potassium, total	**0.15**	N/A	0.10	mg/L	2021-10-27	
Selenium, total	< 0.00050	1	0.00050	mg/L	2021-10-27	
Silicon, total	**1.5**	N/A	1.0	mg/L	2021-10-27	
Silver, total	< 0.000050	1	0.000050	mg/L	2021-10-27	
Sodium, total	**1.57**	N/A	0.10	mg/L	2021-10-27	

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Tap Water (21J2703-33) | Matrix: Water | Sampled: 2021-10-20 13:15, Continued						
Total Metals, Continued						
Strontium, total	**0.0149**	N/A	0.0010	mg/L	2021-10-27	
Sulfur, total	< 3.0	N/A	3.0	mg/L	2021-10-27	
Tellurium, total	< 0.00050	N/A	0.00050	mg/L	2021-10-27	
Thallium, total	< 0.000020	N/A	0.000020	mg/L	2021-10-27	
Thorium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Tin, total	< 0.00020	N/A	0.00020	mg/L	2021-10-27	
Titanium, total	< 0.0050	N/A	0.0050	mg/L	2021-10-27	
Tungsten, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Uranium, total	**0.000029**	N/A	0.000020	mg/L	2021-10-27	
Vanadium, total	< 0.0010	N/A	0.0010	mg/L	2021-10-27	
Zinc, total	< 0.0040	3	0.0040	mg/L	2021-10-27	
Zirconium, total	< 0.00010	N/A	0.00010	mg/L	2021-10-27	
Microbiological Parameters						
E. coli (MPN)	<1.8	N/A	2	MPN/100 mL	2021-10-21	

Sample Qualifiers:

HT1 The sample was prepared and/or analyzed past the recommended holding time.

APPENDIX 1: SUPPORTING INFORMATION

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analysis Description	Method Ref.	Technique	Accredited	Location
E. coli in Water	SM 9221 (2017)	Multiple-Tube Fermentation		Sublet
Hardness in Water	SM 2340 B* (2017)	Calculation: 2.497 [total Ca] + 4.118 [total Mg] (Est)	✓	N/A
Nitrate+Nitrite in Water	SM 4500-NO3- F (2017)	Automated Colorimetry (Cadmium Reduction)	✓	Kelowna
Nitrite in Water	SM 4500-NO2 B (2017)	Colorimetry	✓	Richmond
Nitrogen, Total Kjeldahl in Water	SM 4500-Norg D* (2017)	Block Digestion and Flow Injection Analysis	✓	Kelowna
Phosphorus, Total in Water	SM 4500-P B.5* (2011) / SM 4500-P F (2017)	Persulfate Digestion / Automated Colorimetry (Ascorbic Acid)	✓	Kelowna
Solids, Total Suspended in Water	SM 2540 D* (2017)	Gravimetry (Dried at 103-105C)	✓	Richmond
Total Metals in Water	EPA 200.2 / EPA 6020B	HNO3+HCl Hot Block Digestion / Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS)	✓	Richmond

Note: An asterisk in the Method Reference indicates that the CARO method has been modified from the reference method

Glossary of Terms:

RL	Reporting Limit (default)
<	Less than the specified Reporting Limit (RL) - the actual RL may be higher than the default RL due to various factors
<1	Less than the specified Reporting Limit (RL) - the actual RL may be higher than the default RL due to various factors
mg/L	Milligrams per litre
MPN/100 mL	Most Probable Number per 100 millilitres
EPA	United States Environmental Protection Agency Test Methods
SM	Standard Methods for the Examination of Water and Wastewater, American Public Health Association

Guidelines Referenced in this Report:

Metro Vancouver Sewer Use Bylaw (excludes BOD)

Note: In some cases, the values displayed on the report represent the lowest guideline and are to be verified by the end user

CARO ANALYTICAL SERVICES

APPENDIX 1: SUPPORTING INFORMATION

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

General Comments:

The results in this report apply to the samples analyzed in accordance with the Chain of Custody document. This analytical report must be reproduced in its entirety. CARO is not responsible for any loss or damage resulting directly or indirectly from error or omission in the conduct of testing. Liability is limited to the cost of analysis. Samples will be disposed of 30 days after the test report has been issued or once samples expire, whichever comes first. Longer hold is possible if agreed to in writing.

Results in **Bold** indicate values that are above CARO's method reporting limits. Any results that are above regulatory limits are highlighted **red**. Please note that results will only be highlighted red if the regulatory limits are included on the CARO report. Any Bold and/or highlighted results do not take into account method uncertainty. If you would like method uncertainty or regulatory limits to be included on your report, please contact your Account Manager:nyipp@caro.ca

Please note any regulatory guidelines applied to this report are added as a convenience to the client, at their request, to help provide some initial context to analytical results obtained. Although CARO makes every effort to ensure accuracy of the associated regulatory guideline(s) applied, the guidelines applied cannot be assumed to be correct due to a variety of factors and as such CARO Analytical Services assumes no liability or responsibility for the use of those guidelines to make any decisions. The original source of the regulation should be verified and a review of the guideline(s) should be validated as correct in order to make any decisions arising from the comparison of the analytical data obtained to the relevant regulatory guideline for one's particular circumstances. Further, CARO Analytical Services assumes no liability or responsibility for any loss attributed from the use of these guidelines in any way.

CARO ANALYTICAL SERVICES

APPENDIX 2: QUALITY CONTROL RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

The following section displays the quality control (QC) data that is associated with your sample data. Groups of samples are prepared in “batches” and analyzed in conjunction with QC samples that ensure your data is of the highest quality. Common QC types include:

- **Method Blank (Blk)**: A blank sample that undergoes sample processing identical to that carried out for the test samples. Method blank results are used to assess contamination from the laboratory environment and reagents.
- **Duplicate (Dup)**: An additional or second portion of a randomly selected sample in the analytical run carried through the entire analytical process. Duplicates provide a measure of the analytical method's precision (reproducibility).
- **Blank Spike (BS)**: A sample of known concentration which undergoes processing identical to that carried out for test samples, also referred to as a laboratory control sample (LCS). Blank spikes provide a measure of the analytical method's accuracy.
- **Matrix Spike (MS)**: A second aliquot of sample is fortified with with a known concentration of target analytes and carried through the entire analytical process. Matrix spikes evaluate potential matrix effects that may affect the analyte recovery.
- **Reference Material (SRM)**: A homogenous material of similar matrix to the samples, certified for the parameter(s) listed. Reference Materials ensure that the analytical process is adequate to achieve acceptable recoveries of the parameter(s) tested.

Each QC type is analyzed at a 5-10% frequency, i.e. one blank/duplicate/spike for every 10-20 samples. For all types of QC, the specified recovery (% Rec) and relative percent difference (RPD) limits are derived from long-term method performance averages and/or prescribed by the reference method.

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
Anions, Batch B1J2665										
Blank (B1J2665-BLK1)				Prepared: 2021-10-25, Analyzed: 2021-10-25						
Nitrite (as N)	< 0.0050	0.0050	mg/L							
LCS (B1J2665-BS1)				Prepared: 2021-10-25, Analyzed: 2021-10-25						
Nitrite (as N)	0.0522	0.0050	mg/L	0.0500		104	90-110			
Duplicate (B1J2665-DUP1)		**Source: 21J2703-02**		Prepared: 2021-10-25, Analyzed: 2021-10-25						
Nitrite (as N)	< 0.0050	0.0050	mg/L		< 0.0050				10	
Matrix Spike (B1J2665-MS1)		**Source: 21J2703-33**		Prepared: 2021-10-25, Analyzed: 2021-10-25						
Nitrite (as N)	0.0275	0.0050	mg/L	0.0500	< 0.0050	55	80-120			SPK
Anions, Batch B1J2858										
Blank (B1J2858-BLK1)				Prepared: 2021-10-28, Analyzed: 2021-10-28						
Nitrate+Nitrite (as N)	< 0.0050	0.0050	mg/L							
Blank (B1J2858-BLK2)				Prepared: 2021-10-28, Analyzed: 2021-10-28						
Nitrate+Nitrite (as N)	< 0.0050	0.0050	mg/L							
LCS (B1J2858-BS1)				Prepared: 2021-10-28, Analyzed: 2021-10-28						
Nitrate+Nitrite (as N)	0.516	0.0050	mg/L	0.500		103	91-108			
LCS (B1J2858-BS2)				Prepared: 2021-10-28, Analyzed: 2021-10-28						
Nitrate+Nitrite (as N)	0.529	0.0050	mg/L	0.500		106	91-108			
General Parameters, Batch B1J2446										
Blank (B1J2446-BLK1)				Prepared: 2021-10-22, Analyzed: 2021-10-24						
Nitrogen, Total Kjeldahl	< 0.050	0.050	mg/L							
Blank (B1J2446-BLK2)				Prepared: 2021-10-22, Analyzed: 2021-10-24						
Nitrogen, Total Kjeldahl	< 0.050	0.050	mg/L							
LCS (B1J2446-BS1)				Prepared: 2021-10-22, Analyzed: 2021-10-24						
Nitrogen, Total Kjeldahl	0.986	0.050	mg/L	1.00		99	85-115			

APPENDIX 2: QUALITY CONTROL RESULTS

REPORTED TO Kerr Wood Leidal Associates Ltd. (Burnaby)
PROJECT 42.158
WORK ORDER 21J2703
REPORTED 2021-10-28 13:13

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
General Parameters, Batch B1J2446, Continued										
LCS (B1J2446-BS2)				Prepared: 2021-10-22, Analyzed: 2021-10-24						
Nitrogen, Total Kjeldahl	0.991	0.050	mg/L	1.00		99	85-115			
General Parameters, Batch B1J2736										
Blank (B1J2736-BLK1)				Prepared: 2021-10-26, Analyzed: 2021-10-26						
Solids, Total Suspended	< 2.0	2.0	mg/L							
Blank (B1J2736-BLK2)				Prepared: 2021-10-26, Analyzed: 2021-10-26						
Solids, Total Suspended	< 2.0	2.0	mg/L							
LCS (B1J2736-BS1)				Prepared: 2021-10-26, Analyzed: 2021-10-26						
Solids, Total Suspended	101	10.0	mg/L	100		101	83-107			
LCS (B1J2736-BS2)				Prepared: 2021-10-26, Analyzed: 2021-10-26						
Solids, Total Suspended	101	10.0	mg/L	100		101	83-107			
General Parameters, Batch B1J2839										
Blank (B1J2839-BLK1)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Phosphorus, Total (as P)	< 0.0050	0.0050	mg/L							
Blank (B1J2839-BLK2)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Phosphorus, Total (as P)	< 0.0050	0.0050	mg/L							
LCS (B1J2839-BS1)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Phosphorus, Total (as P)	0.107	0.0050	mg/L	0.100		107	85-115			
General Parameters, Batch B1J2857										
Blank (B1J2857-BLK1)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	< 2.0	2.0	mg/L							
Blank (B1J2857-BLK2)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	< 2.0	2.0	mg/L							
Blank (B1J2857-BLK3)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	< 2.0	2.0	mg/L							
Blank (B1J2857-BLK4)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	< 2.0	2.0	mg/L							
Blank (B1J2857-BLK5)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	< 2.0	2.0	mg/L							
Blank (B1J2857-BLK6)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	< 2.0	2.0	mg/L							
LCS (B1J2857-BS1)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	96.0	10.0	mg/L	100		96	83-107			
LCS (B1J2857-BS2)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	96.0	10.0	mg/L	100		96	83-107			
LCS (B1J2857-BS3)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	96.0	10.0	mg/L	100		96	83-107			

APPENDIX 2: QUALITY CONTROL RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
General Parameters, Batch B1J2857, Continued										
LCS (B1J2857-BS4)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	96.0	10.0	mg/L	100		96	83-107			
LCS (B1J2857-BS5)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	97.0	10.0	mg/L	100		97	83-107			
LCS (B1J2857-BS6)				Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	98.0	10.0	mg/L	100		98	83-107			
Duplicate (B1J2857-DUP1)		**Source: 21J2703-02**		Prepared: 2021-10-27, Analyzed: 2021-10-27						
Solids, Total Suspended	831	2.0	mg/L		788			5	20	
Total Metals, Batch B1J2749										
Blank (B1J2749-BLK1)				Prepared: 2021-10-26, Analyzed: 2021-10-27						
Aluminum, total	< 0.0050	0.0050	mg/L							
Antimony, total	< 0.00020	0.00020	mg/L							
Arsenic, total	< 0.00050	0.00050	mg/L							
Barium, total	< 0.0050	0.0050	mg/L							
Beryllium, total	< 0.00010	0.00010	mg/L							
Bismuth, total	< 0.00010	0.00010	mg/L							
Boron, total	< 0.0500	0.0500	mg/L							
Cadmium, total	< 0.000010	0.000010	mg/L							
Calcium, total	< 0.20	0.20	mg/L							
Chromium, total	< 0.00050	0.00050	mg/L							
Cobalt, total	< 0.00010	0.00010	mg/L							
Copper, total	< 0.00040	0.00040	mg/L							
Iron, total	< 0.010	0.010	mg/L							
Lead, total	< 0.00020	0.00020	mg/L							
Lithium, total	< 0.00010	0.00010	mg/L							
Magnesium, total	< 0.010	0.010	mg/L							
Manganese, total	< 0.00020	0.00020	mg/L							
Molybdenum, total	< 0.00010	0.00010	mg/L							
Nickel, total	< 0.00040	0.00040	mg/L							
Phosphorus, total	< 0.050	0.050	mg/L							
Potassium, total	< 0.10	0.10	mg/L							
Selenium, total	< 0.00050	0.00050	mg/L							
Silicon, total	< 1.0	1.0	mg/L							
Silver, total	< 0.000050	0.000050	mg/L							
Sodium, total	< 0.10	0.10	mg/L							
Strontium, total	< 0.0010	0.0010	mg/L							
Sulfur, total	< 3.0	3.0	mg/L							
Tellurium, total	< 0.00050	0.00050	mg/L							
Thallium, total	< 0.000020	0.000020	mg/L							
Thorium, total	< 0.00010	0.00010	mg/L							
Tin, total	< 0.00020	0.00020	mg/L							
Titanium, total	< 0.0050	0.0050	mg/L							
Tungsten, total	< 0.0010	0.0010	mg/L							
Uranium, total	< 0.000020	0.000020	mg/L							
Vanadium, total	< 0.0010	0.0010	mg/L							
Zinc, total	< 0.0040	0.0040	mg/L							
Zirconium, total	< 0.00010	0.00010	mg/L							
LCS (B1J2749-BS1)				Prepared: 2021-10-26, Analyzed: 2021-10-27						
Aluminum, total	0.0221	0.0050	mg/L	0.0200		111	80-120			
Antimony, total	0.0199	0.00020	mg/L	0.0200		99	80-120			
Arsenic, total	0.0193	0.00050	mg/L	0.0200		97	80-120			

APPENDIX 2: QUALITY CONTROL RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	WORK ORDER	21J2703
PROJECT	42.158	REPORTED	2021-10-28 13:13

Total Metals, Batch B1J2749, Continued

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
LCS (B1J2749-BS1), Continued				Prepared: 2021-10-26, Analyzed: 2021-10-27						
Barium, total	0.0188	0.0050	mg/L	0.0200		94	80-120			
Beryllium, total	0.0167	0.00010	mg/L	0.0200		83	80-120			
Bismuth, total	0.0199	0.00010	mg/L	0.0200		99	80-120			
Boron, total	< 0.0500	0.0500	mg/L	0.0200		103	80-120			
Cadmium, total	0.0188	0.000010	mg/L	0.0200		94	80-120			
Calcium, total	1.80	0.20	mg/L	2.00		90	80-120			
Chromium, total	0.0182	0.00050	mg/L	0.0200		91	80-120			
Cobalt, total	0.0178	0.00010	mg/L	0.0200		89	80-120			
Copper, total	0.0174	0.00040	mg/L	0.0200		87	80-120			
Iron, total	1.85	0.010	mg/L	2.00		93	80-120			
Lead, total	0.0208	0.00020	mg/L	0.0200		104	80-120			
Lithium, total	0.0164	0.00010	mg/L	0.0200		82	80-120			
Magnesium, total	1.99	0.010	mg/L	2.00		100	80-120			
Manganese, total	0.0167	0.00020	mg/L	0.0200		83	80-120			
Molybdenum, total	0.0183	0.00010	mg/L	0.0200		91	80-120			
Nickel, total	0.0189	0.00040	mg/L	0.0200		94	80-120			
Phosphorus, total	1.81	0.050	mg/L	2.00		90	80-120			
Potassium, total	1.86	0.10	mg/L	2.00		93	80-120			
Selenium, total	0.0221	0.00050	mg/L	0.0200		110	80-120			
Silicon, total	2.1	1.0	mg/L	2.00		104	80-120			
Silver, total	0.0185	0.000050	mg/L	0.0200		92	80-120			
Sodium, total	1.95	0.10	mg/L	2.00		97	80-120			
Strontium, total	0.0165	0.0010	mg/L	0.0200		82	80-120			
Sulfur, total	5.2	3.0	mg/L	5.00		105	80-120			
Tellurium, total	0.0202	0.00050	mg/L	0.0200		101	80-120			
Thallium, total	0.0192	0.000020	mg/L	0.0200		96	80-120			
Thorium, total	0.0190	0.00010	mg/L	0.0200		95	80-120			
Tin, total	0.0197	0.00020	mg/L	0.0200		98	80-120			
Titanium, total	0.0159	0.0050	mg/L	0.0200		80	80-120			
Tungsten, total	0.0200	0.0010	mg/L	0.0200		100	80-120			
Uranium, total	0.0194	0.000020	mg/L	0.0200		97	80-120			
Vanadium, total	0.0189	0.0010	mg/L	0.0200		94	80-120			
Zinc, total	0.0204	0.0040	mg/L	0.0200		102	80-120			
Zirconium, total	0.0190	0.00010	mg/L	0.0200		95	80-120			
Reference (B1J2749-SRM1)				Prepared: 2021-10-26, Analyzed: 2021-10-27						
Aluminum, total	0.271	0.0050	mg/L	0.299		91	70-130			
Antimony, total	0.0512	0.00020	mg/L	0.0517		99	70-130			
Arsenic, total	0.124	0.00050	mg/L	0.119		104	70-130			
Barium, total	0.677	0.0050	mg/L	0.801		85	70-130			
Beryllium, total	0.0453	0.00010	mg/L	0.0501		91	70-130			
Boron, total	3.41	0.0500	mg/L	4.11		83	70-130			
Cadmium, total	0.0496	0.000010	mg/L	0.0503		99	70-130			
Calcium, total	9.27	0.20	mg/L	10.7		87	70-130			
Chromium, total	0.240	0.00050	mg/L	0.250		96	70-130			
Cobalt, total	0.0364	0.00010	mg/L	0.0384		95	70-130			
Copper, total	0.424	0.00040	mg/L	0.487		87	70-130			
Iron, total	0.475	0.010	mg/L	0.504		94	70-130			
Lead, total	0.299	0.00020	mg/L	0.278		108	70-130			
Lithium, total	0.371	0.00010	mg/L	0.398		93	70-130			
Magnesium, total	3.89	0.010	mg/L	3.59		108	70-130			
Manganese, total	0.0964	0.00020	mg/L	0.111		87	70-130			
Molybdenum, total	0.192	0.00010	mg/L	0.196		98	70-130			
Nickel, total	0.242	0.00040	mg/L	0.248		98	70-130			
Phosphorus, total	0.222	0.050	mg/L	0.213		104	70-130			
Potassium, total	6.02	0.10	mg/L	5.89		102	70-130			

APPENDIX 2: QUALITY CONTROL RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	21J2703
PROJECT	42.158	**REPORTED**	2021-10-28 13:13

Total Metals, Batch B1J2749, Continued

Reference (B1J2749-SRM1), Continued Prepared: 2021-10-26, Analyzed: 2021-10-27

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
Selenium, total	0.132	0.00050	mg/L	0.120		110	70-130			
Sodium, total	8.58	0.10	mg/L	8.71		99	70-130			
Strontium, total	0.340	0.0010	mg/L	0.393		86	70-130			
Thallium, total	0.0799	0.000020	mg/L	0.0787		101	70-130			
Uranium, total	0.0346	0.000020	mg/L	0.0344		101	70-130			
Vanadium, total	0.369	0.0010	mg/L	0.391		94	70-130			
Zinc, total	2.63	0.0040	mg/L	2.50		105	70-130			

QC Qualifiers:

SPK The recovery of this analyte was outside of established control limits.

CARO ANALYTICAL SERVICES
Caring About Results, Obviously.

#1 ... -8846 V6V 2K9
#1 ... V1X 5C3
17 ... T5S 1H7
#1 ... V5G 4X4

* 2 1 J 2 7 0 3 *

CARO BC COC, Rev 2019-01

CHAIN OF CUSTODY RECORD

COC# B097650 PAGE 1 OF 3

RELINQUISHED BY:	DATE:	RECEIVED BY:	DATE:
Ben Vovko	OCT 20-21	MC WI	10/20
	TIME:		TIME: 1700

TURNAROUND TIME REQUESTED:
Routine: (5-7 Days) ☑
Rush: 1 Day* ☐ 2 Day* ☐ 3 Day* ☐
Other*
*Contact Lab To Confirm. Surcharge May Apply

REGULATORY APPLICATION: Show on Report ☐
Canadian Drinking Water Quality ☐ BC WQG ☐ BC HWR ☐
BC CSR Soil: WL ☐ AL ☐ PL ☐ RL-LD ☐ RL-HD ☐ CL ☐ IL ☐
BC CSR Water: AW ☐ IW ☐ LW ☐ DW ☐
CCME: Other:

PROJECT NUMBER / INFO: 42.158 / BIOSWALE #2 ~~GREEN INFRASTRUCTURE ASSET EFFECTIVENESS MONITORING PROGRAM~~

A: Biohazard D: Asbestos G: Strong Odour
B: Cyanide E: Heavy Metals H: High Contamination
C: PCBs F: Flammable I: Other (please specify*)

REPORT TO:
COMPANY: Kerr Wood Leidal
ADDRESS: 200-4185A STILL Creek Dr. Burnaby
CONTACT: BEN VOVKO
TEL/FAX: 604-721-1534
DELIVERY METHOD: EMAIL ☑ ONLINE ☐ OTHER* ☐
DATA FORMAT: EXCEL ☑ WATERTRAX ☐ ESdat ☐ EQuIS ☐ BC EMS ☐ OTHER* ☐
EMAIL 1: KBJORKLUND@KWL.CA
EMAIL 2:
EMAIL 3:

INVOICE TO: SAME AS REPORT TO ☐
COMPANY: KWL
ADDRESS:
CONTACT:
TEL/FAX:
DELIVERY METHOD: EMAIL ☑ ONLINE ☐ OTHER* ☐
EMAIL 1: MDERER@KWL.CA
EMAIL 2: KBJORKLUND@KWL.CA
EMAIL 3:
PO #:

** If you would like to sign up for ClientConnect and/or EnviroChain, CARO's online service offerings, please check here: ☐

SAMPLED BY: ~~City of Vancouver~~ CoV

ANALYSES REQUESTED:

CLIENT SAMPLE ID:	MATRIX: DRINKING WATER	OTHER WATER	SOIL	OTHER	CONTAINER QTY	SAMPLING: DATE YYYY-MM-DD	TIME HH:MM	CHLORINATED	FILTERED	PRESERVED	COMMENTS: (e.g. flow/volume media ID/notes)	BTEX ☐ VPH ☐ PHC F1 ☐	VOC ☐ VPH ☐	EPH ☐ PHC F2-F4 ☐	PAH ☐ L/HEPH ☐	PHENOLS Chlorinated ☐ Non-Chlor. ☐	PCB ☐ GLYCOLS ☐ HAA ☐ THM ☐	PESTICIDES ☐ ACID HERBICIDES ☐	METALS - WATER TOTAL Hg ☐	METALS - WATER DISSOLVED Hg ☐	METALS - SOIL (SALM) ☐ inc. pH ☐	pH ☐ EC ☐ ALK ☐ ANIONS ☐	TSS ☑ VSS ☐ TDS ☐	BOD ☐ COD ☐ TOG ☐ MOG ☐	TN ☐ NH3 ☐ TKN ☐	FECAL COLIFORMS ☐ HPC ☐	TOTAL COLIFORMS ☐ E. coli ☒	ESSENTIAL DRINKING WATER PACKAGE	ASBESTOS	NITRATE + NITRITE	TKN	TOTAL Phosphorous				HOLD	POSSIBLE SAMPLE HAZARD CODE(S)
BASELINE		X			3	2021-10-~~20~~ 19	1217												X				X							X	X	X					
INLET 1		X			4	2021-10-20	1045												X				X				X			X	X	X					
INLET 2		X			4	"	1200												X				X				X			X	X	X					
INLET 3		X			4	"	1300												X				X				X			X	X	X					
~~INLET 4~~ OUTLET 1		X			1	"	1016																X														
~~INLET 5~~ OUTLET 2		X			1	"	1026																X														
~~INLET 6~~ OUTLET 3		X			1	"	1036																X														
~~INLET 7~~ OUTLET 4		X			1	"	~~103~~ 1046																X														
~~INLET 8~~ OUTLET 5		X			1	"	1056																X														
~~INLET 9~~ OUTLET 6		X			4	"	1106																X														
OUTLET 7		X			1	"	1116																X														
OUTLET 8		X			1	"	1126																X														

SHIPPING INSTRUCTIONS: Return Cooler(s) ☐
Supplies Needed:

SAMPLE RETENTION:
30 Days (default) ☐
60 Days ☐ 90 Days ☐
Other (surcharges will apply):

*** OTHER INSTRUCTIONS:**
Please include hardness w/ METALS ANALYSIS

If you would like to talk to a real live Scientist about your project requirements, please check here: ☐

SAMPLE RECEIPT CONDITION:
COOLER 1 (°C): 10.2 ICE: Y ☑ N ☐
COOLER 2 (°C): ICE: Y ☐ N ☐
COOLER 3 (°C): ICE: Y ☐ N ☐
CUSTODY SEALS INTACT: NA ☐ Y ☐ N ☐

CARO ANALYTICAL SERVICES
Caring About Results, Obviously.

CARO.ca 1-888-311-8846
#110-4011 Viking Way, Richmond, BC V6V 2K9
#102-3677 Highway 97N, Kelowna, BC V1X 5C3
17225 109 Avenue NW, Edmonton, AB T5S 1H7
#108-4475 Wayburne Drive, Burnaby, BC V5G 4X4

CARO BC COC, Rev 2019-01

CHAIN OF CUSTODY RECORD

COC# B097651 PAGE 2 OF 3

RELINQUISHED BY: DATE: TIME:
RECEIVED BY: DATE: TIME:

REPORT TO:
COMPANY: KWL
ADDRESS:
CONTACT: Ben Vukro
TEL/FAX:
DELIVERY METHOD: EMAIL ☐ ONLINE ☐ OTHER* ☐
DATA FORMAT: EXCEL ☐ WATERTRAX ☐ ESdat ☐ EQuIS ☐ BC EMS ☐ OTHER* ☐
EMAIL 1:
EMAIL 2:
EMAIL 3:

INVOICE TO: SAME AS REPORT TO ☐
COMPANY:
ADDRESS:
CONTACT:
TEL/FAX:
DELIVERY METHOD: EMAIL ☐ ONLINE ☐ OTHER* ☐
EMAIL 1:
EMAIL 2:
EMAIL 3:
PO #:

TURNAROUND TIME REQUESTED:
Routine: (5-7 Days) ☐
Rush: 1 Day* ☐ 2 Day* ☐ 3 Day* ☐
Other*
*Contact Lab To Confirm. Surcharge May Apply

REGULATORY APPLICATION: Show on Report ☐
Canadian Drinking Water Quality ☐ BC WQG ☐ BC HWR ☐
BC CSR Soil: WL ☐ AL ☐ PL ☐ RL-LD ☐ RL-HD ☐ CL ☐ IL ☐
BC CSR Water: AW ☐ IW ☐ LW ☐ DW ☐
CCME: Other:

PROJECT NUMBER / INFO: 42.158 / Boswale #2

A: Biohazard B: Cyanide C: PCBs D: Asbestos E: Heavy Metals F: Flammable G: Strong Odour H: High Contamination I: Other (please specify*)

** If you would like to sign up for ClientConnect and/or EnviroChain, CARO's online service offerings, please check here: ☐

SAMPLED BY:

ANALYSES REQUESTED: TSS ☒ ; TOTAL COLIFORMS ☐ E. coli ☒ ; Nitrate + Nitrite ; TKN ; Total Phosphorous

CLIENT SAMPLE ID	DRINKING WATER	OTHER WATER	SOIL	OTHER	CONTAINER QTY	DATE YYYY-MM-DD	TIME HH:MM	CHLORINATED	FILTERED	PRESERVED	COMMENTS	METALS - WATER TOTAL	TSS	TOTAL COLIFORMS	Nitrate + Nitrite	TKN	Total Phosphorous	HOLD
OUTLET 9		X			1	2021-OCT-26	1136						X					
OUTLET 10		X			1	"	1146						X					
OUTLET 11		X			1	"	1156						X					
OUTLET 12		X			4	"	1206					X	X	X	X	X	X	
OUTLET 13		X			1	"	1216						X					
OUTLET 14		X			1	"	1226						X					
OUTLET 15		X			1	"	1236						X					
OUTLET 16		X			1	"	1246						X					
OUTLET 17		X			1	"	1256						X					
OUTLET 18		X			4	"	1306					X	X	X	X	X	X	
OUTLET ~~20~~19		X			1	"	1316						X					
OUTLET ~~21~~20		X			1	"	1326						X					

SHIPPING INSTRUCTIONS: Return Cooler(s) ☐
Supplies Needed:

SAMPLE RETENTION:
30 Days (default) ☐
60 Days ☐ 90 Days ☐
Other (surcharges will apply):

*** OTHER INSTRUCTIONS:**

If you would like to talk to a real live Scientist about your project requirements, please check here: ☐

SAMPLE RECEIPT CONDITION:
COOLER 1 (°C): ICE: Y ☐ N ☐
COOLER 2 (°C): ICE: Y ☐ N ☐
COOLER 3 (°C): ICE: Y ☐ N ☐
CUSTODY SEALS INTACT: NA ☐ Y ☐ N ☐

CARO ANALYTICAL SERVICES
Caring About Results, Obviously.

CARO.ca 1-888-311-8846
#110-4011 Viking Way, Richmond, BC V6V 2K9
#102-3677 Highway 97N, Kelowna, BC V1X 5C3
17225 109 Avenue NW, Edmonton, AB T5S 1H7
#108-4475 Wayburne Drive, Burnaby, BC V5G 4X4

CHAIN OF CUSTODY RECORD

COC# B097652 PAGE 3 OF 3

CARO BC COC, Rev 2019-01

RELINQUISHED BY: DATE: TIME: RECEIVED BY: DATE: TIME:

REPORT TO:
COMPANY: KWL
ADDRESS:
CONTACT: Ben Vorko
TEL/FAX:
DELIVERY METHOD: EMAIL ☐ ONLINE ☐ OTHER* ☐
DATA FORMAT: EXCEL ☐ WATERTRAX ☐ ESdat ☐ EQuIS ☐ BC EMS ☐ OTHER* ☐
EMAIL 1:
EMAIL 2:
EMAIL 3:

INVOICE TO: SAME AS REPORT TO ☐
COMPANY:
ADDRESS:
CONTACT:
TEL/FAX:
DELIVERY METHOD: EMAIL ☐ ONLINE ☐ OTHER* ☐
EMAIL 1:
EMAIL 2:
EMAIL 3:
PO #:

TURNAROUND TIME REQUESTED:
Routine: (5-7 Days) ☐
Rush: 1 Day* ☐ 2 Day* ☐ 3 Day* ☐
Other*
*Contact Lab To Confirm. Surcharge May Apply

REGULATORY APPLICATION: Show on Report ☐
Canadian Drinking Water Quality ☐ BC WQG ☐ BC HWR ☐
BC CSR Soil: WL ☐ AL ☐ PL ☐ RL-LD ☐ RL-HD ☐ CL ☐ IL ☐
BC CSR Water: AW ☐ IW ☐ LW ☐ DW ☐
CCME: Other:

PROJECT NUMBER / INFO: 42.158 Brosmale #2

POSSIBLE SAMPLE HAZARD CODE(S): A: Biohazard B: Cyanide C: PCBs D: Asbestos E: Heavy Metals F: Flammable G: Strong Odour H: High Contamination I: Other (please specify*)

** If you would like to sign up for ClientConnect and/or EnviroChain, CARO's online service offerings, please check here: ☐

SAMPLED BY:

ANALYSES REQUESTED: BTEX ☐ VPH ☐ PHC F1 ☐; VOC ☐ VPH ☐; EPH ☐ PHC F2-F4 ☐; PAH ☐ L/HEPH ☐; PHENOLS Chlorinated ☐ Non-Chlor. ☐; PCB ☐ GLYCOLS ☐ HAA ☐ THM ☐; PESTICIDES ☐ ACID HERBICIDES ☐; METALS - WATER TOTAL Hg ☐; METALS - WATER DISSOLVED Hg ☐; METALS - SOIL (SALM) ☐ inc. pH ☐; pH ☐ EC ☐ ALK ☐ ANIONS ☐; TSS ☒ VSS ☐ TDS ☐; BOD ☐ COD ☐ TOG ☐ MOG ☐; TN ☐ NH3 ☐ TKN ☐; FECAL COLIFORMS ☐ HPC ☐; TOTAL COLIFORMS ☐ E. coli ☒; ESSENTIAL DRINKING WATER PACKAGE; ASBESTOS; NITRATE + NITRITE; TKN; TOTAL Phosphorous; HOLD

CLIENT SAMPLE ID	DRINKING WATER	OTHER WATER	SOIL	OTHER	CONTAINER QTY	DATE (YYYY-MM-DD)	TIME (HH:MM)	METALS - WATER TOTAL	TSS	TOTAL COLIFORMS / E. coli	NITRATE + NITRITE	TKN	TOTAL Phosphorous
OUTLET 22		X			1	2021-OCT-20	1346		X				
OUTLET 23		X			1	"	1356		X				
OUTLET 24		X			4	"	1406	X	X	X	X	X	X
OUTLET 25		X			1	"	1416		X				
OUTLET 26		X			1	"	1426		X				
OUTLET 27		X			1	"	1436		X				
OUTLET 28		X			1	"	1446		X				
OUTLET 21		X			1	"	1336		X				
TAP WATER	X				4	"	1315	X	X	X	X	X	X

COMMENTS: CHLORINATED, FILTERED, PRESERVED (e.g. flow/volume media ID/notes)

SHIPPING INSTRUCTIONS: Return Cooler(s) ☐
Supplies Needed:

SAMPLE RETENTION: 30 Days (default) ☐ 60 Days ☐ 90 Days ☐ Other (surcharges will apply):

* OTHER INSTRUCTIONS:

If you would like to talk to a real live Scientist about your project requirements, please check here: ☐

SAMPLE RECEIPT CONDITION:
COOLER 1 (°C): ICE: Y ☐ N ☐
COOLER 2 (°C): ICE: Y ☐ N ☐
COOLER 3 (°C): ICE: Y ☐ N ☐
CUSTODY SEALS INTACT: NA ☐ Y ☐ N ☐

CERTIFICATE OF ANALYSIS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby) 200 - 4185A Still Creek Dr Burnaby, BC V5C 6G9		
ATTENTION	Patrick Lilley	**WORK ORDER**	22C0421
PO NUMBER		**RECEIVED / TEMP**	2022-03-02 16:00 / 17.9°C
PROJECT	42.158	**REPORTED**	2022-03-10 15:17
PROJECT INFO	GI Asset Monitoring		

Introduction:

CARO Analytical Services is a testing laboratory full of smart, engaged scientists driven to make the world a safer and healthier place. Through our clients' projects we become an essential element for a better world. We employ methods conducted in accordance with recognized professional standards using accepted testing methodologies and quality control efforts. CARO is accredited by the Canadian Association for Laboratories Accreditation (CALA) to ISO/IEC 17025:2017 for specific tests listed in the scope of accreditation approved by CALA.

Big Picture Sidekicks

You know that the sample you collected after snowshoeing to site, digging 5 meters, and racing to get it on a plane so you can submit it to the lab for time sensitive results needed to make important and expensive decisions (whew) is VERY important. We know that too.

We've Got Chemistry

It's simple. We figure the more you enjoy working with our fun and engaged team members; the more likely you are to give us continued opportunities to support you.

Ahead of the Curve

Through research, regulation knowledge, and instrumentation, we are your analytical centre for the technical knowledge you need, BEFORE you need it, so you can stay up to date and in the know.

Work Order Comments:

If you have any questions or concerns, please contact me at nyipp@caro.ca

Authorized By:

Nicole Yipp
Client Service Team Lead

CARO ANALYTICAL SERVICES

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	22C0421
PROJECT	42.158	**REPORTED**	2022-03-10 15:17

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Street sweeping sand 1 (22C0421-01) | Matrix: Soil | Sampled: 2021-10-03						
Calculated Parameters						
Nitrogen, Total	**0.139**	N/A	0.0100	%	N/A	
General Parameters						
Organic Matter (LOI)	**3.79**	N/A	0.10	% dry	2022-03-08	
Moisture	< 1.0	N/A	1.0	% wet	2022-03-08	HT1
Nitrate, Water-Soluble (as N)	**2.98**	N/A	0.050	mg/kg dry	2022-03-05	
Nitrite, Water-Soluble (as N)	< 0.500	N/A	0.050	mg/kg dry	2022-03-05	
Nitrogen, Total Kjeldahl	**0.139**	N/A	0.0004	% dry	2022-03-09	HT1
pH (1:2 H2O Solution)	**7.09**	N/A	0.10	pH units	2022-03-10	
Phosphorus, Total (as P)	**465**	N/A	0.4	mg/kg dry	2022-03-10	HT1
Strong Acid Leachable Metals						
Aluminum	**5650**	N/A	40	mg/kg dry	2022-03-10	
Antimony	**5.64**	N/A	0.10	mg/kg dry	2022-03-10	
Arsenic	**2.33**	N/A	0.30	mg/kg dry	2022-03-10	
Barium	**43.1**	N/A	1.0	mg/kg dry	2022-03-10	
Beryllium	**0.11**	N/A	0.10	mg/kg dry	2022-03-10	
Boron	**3.0**	N/A	2.0	mg/kg dry	2022-03-10	
Cadmium	**0.345**	N/A	0.040	mg/kg dry	2022-03-10	
Chromium	**26.1**	N/A	1.0	mg/kg dry	2022-03-10	
Cobalt	**4.37**	N/A	0.10	mg/kg dry	2022-03-10	
Copper	**89.0**	N/A	0.40	mg/kg dry	2022-03-10	
Iron	**16200**	N/A	20	mg/kg dry	2022-03-10	
Lead	**480**	N/A	0.20	mg/kg dry	2022-03-10	
Lithium	**3.89**	N/A	0.10	mg/kg dry	2022-03-10	
Manganese	**210**	N/A	0.40	mg/kg dry	2022-03-10	
Mercury	< 0.040	N/A	0.040	mg/kg dry	2022-03-10	
Molybdenum	**1.00**	N/A	0.10	mg/kg dry	2022-03-10	
Nickel	**13.0**	N/A	0.60	mg/kg dry	2022-03-10	
Selenium	< 0.20	N/A	0.20	mg/kg dry	2022-03-10	
Silver	< 0.10	N/A	0.10	mg/kg dry	2022-03-10	
Strontium	**58.1**	N/A	0.20	mg/kg dry	2022-03-10	
Thallium	< 0.10	N/A	0.10	mg/kg dry	2022-03-10	
Tin	**7.09**	N/A	0.20	mg/kg dry	2022-03-10	
Tungsten	**0.27**	N/A	0.20	mg/kg dry	2022-03-10	
Uranium	**0.205**	N/A	0.050	mg/kg dry	2022-03-10	
Vanadium	**37.3**	N/A	1.0	mg/kg dry	2022-03-10	
Zinc	**177**	N/A	2.0	mg/kg dry	2022-03-10	
Street sweeping sand 2 (22C0421-02) | Matrix: Soil | Sampled: 2021-10-03						
Calculated Parameters						
Nitrogen, Total	**0.113**	N/A	0.0100	%	N/A	

TEST RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	22C0421
PROJECT	42.158	**REPORTED**	2022-03-10 15:17

Analyte	Result	Guideline	RL	Units	Analyzed	Qualifier
Street sweeping sand 2 (22C0421-02) | Matrix: Soil | Sampled: 2021-10-03, Continued						
General Parameters						
Carbon, Total Organic	**2.27**	N/A	0.050	% dry	2022-03-08	HT1
Moisture	< 1.0	N/A	1.0	% wet	2022-03-08	
Nitrate, Water-Soluble (as N)	**2.73**	N/A	0.050	mg/kg dry	2022-03-05	
Nitrite, Water-Soluble (as N)	< 0.500	N/A	0.050	mg/kg dry	2022-03-05	
Nitrogen, Total Kjeldahl	**0.113**	N/A	0.0004	% dry	2022-03-09	HT1
pH (1:2 H2O Solution)	**6.48**	N/A	0.10	pH units	2022-03-10	HT2
Strong Acid Leachable Metals						
Aluminum	**5450**	N/A	40	mg/kg dry	2022-03-10	
Antimony	**2.01**	N/A	0.10	mg/kg dry	2022-03-10	
Arsenic	**2.37**	N/A	0.30	mg/kg dry	2022-03-10	
Barium	**38.8**	N/A	1.0	mg/kg dry	2022-03-10	
Beryllium	< 0.10	N/A	0.10	mg/kg dry	2022-03-10	
Boron	**2.9**	N/A	2.0	mg/kg dry	2022-03-10	
Cadmium	**0.881**	N/A	0.040	mg/kg dry	2022-03-10	
Chromium	**27.9**	N/A	1.0	mg/kg dry	2022-03-10	
Cobalt	**4.21**	N/A	0.10	mg/kg dry	2022-03-10	
Copper	**77.4**	N/A	0.40	mg/kg dry	2022-03-10	
Iron	**16900**	N/A	20	mg/kg dry	2022-03-10	
Lead	**361**	N/A	0.20	mg/kg dry	2022-03-10	
Lithium	**3.70**	N/A	0.10	mg/kg dry	2022-03-10	
Manganese	**212**	N/A	0.40	mg/kg dry	2022-03-10	
Mercury	< 0.040	N/A	0.040	mg/kg dry	2022-03-10	
Molybdenum	**1.16**	N/A	0.10	mg/kg dry	2022-03-10	
Nickel	**13.6**	N/A	0.60	mg/kg dry	2022-03-10	
Phosphorus	**422**	N/A	10	mg/kg dry	2022-03-10	
Selenium	< 0.20	N/A	0.20	mg/kg dry	2022-03-10	
Silver	< 0.10	N/A	0.10	mg/kg dry	2022-03-10	
Strontium	**55.1**	N/A	0.20	mg/kg dry	2022-03-10	
Thallium	< 0.10	N/A	0.10	mg/kg dry	2022-03-10	
Tin	**3.58**	N/A	0.20	mg/kg dry	2022-03-10	
Tungsten	**0.29**	N/A	0.20	mg/kg dry	2022-03-10	
Uranium	**0.204**	N/A	0.050	mg/kg dry	2022-03-10	
Vanadium	**37.6**	N/A	1.0	mg/kg dry	2022-03-10	
Zinc	**177**	N/A	2.0	mg/kg dry	2022-03-10	

Sample Qualifiers:

HT1 The sample was prepared and/or analyzed past the recommended holding time.

HT2 The 15 minute recommended holding time (from sampling to analysis) has been exceeded - field analysis is recommended.

APPENDIX 1: SUPPORTING INFORMATION

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	22C0421
PROJECT	42.158	**REPORTED**	2022-03-10 15:17

Analysis Description	Method Ref.	Technique	Accredited	Location
Anions in Soil	Carter 15.2.2 / SM 4110 B (2017)	Fixed Ratio H2O Ext (1:5) / Ion Chromatography		Kelowna
Carbon, Total Organic in Soil	Carter 21.2	Catalytic Combustion and Infrared Detection	✓	Kelowna
Moisture in Soil	ASTM D2974-87*	Gravimetry (Dried at 105C)		N/A
Nitrogen, Total Kjeldahl in Soil	SM 4500-Norg D* (2017)	Block Digestion and Flow Injection Analysis	✓	Kelowna
Organic Matter in Soil	AASHTO T267-86	Gravimetry		Richmond
pH in Soil	Carter 16.2 / SM 4500-H+ B (2017)	1:2 Soil/Water Slurry / Electrometry	✓	Richmond
Phosphorus, Total in Soil	SM 4500-P B.5* (2011) / SM 4500-P F (2017)	Persulfate Digestion / Automated Colorimetry (Ascorbic Acid)		Kelowna
SALM in Soil	BCMOE SALM V.2 / EPA 6020B	HNO3+HCl Hot Block Digestion / Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS)	✓	Richmond

Note: An asterisk in the Method Reference indicates that the CARO method has been modified from the reference method

Glossary of Terms:

RL	Reporting Limit (default)
%	Percent
% dry	Percent (dry weight basis)
% wet	Percent (as received basis)
<	Less than the specified Reporting Limit (RL) - the actual RL may be higher than the default RL due to various factors
mg/kg dry	Milligrams per kilogram (dry weight basis)
pH units	pH < 7 = acidic, ph > 7 = basic
AASHTO	American Association of State Highway and Transportation Officials, Methods of Sampling and Testing
ASTM	ASTM International Test Methods
Carter	Soil Sampling and Methods of Analysis, 2nd Edition (2007), Carter/Gregorich
EPA	United States Environmental Protection Agency Test Methods
SM	Standard Methods for the Examination of Water and Wastewater, American Public Health Association

Guidelines Referenced in this Report:

Metro Vancouver Sewer Use Bylaw (excludes BOD)

Note: In some cases, the values displayed on the report represent the lowest guideline and are to be verified by the end user

APPENDIX 1: SUPPORTING INFORMATION

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	22C0421
PROJECT	42.158	**REPORTED**	2022-03-10 15:17

General Comments:

The results in this report apply to the samples analyzed in accordance with the Chain of Custody document. This analytical report must be reproduced in its entirety. CARO is not responsible for any loss or damage resulting directly or indirectly from error or omission in the conduct of testing. Liability is limited to the cost of analysis. Samples will be disposed of 30 days after the test report has been issued or once samples expire, whichever comes first. Longer hold is possible if agreed to in writing.

Results in **Bold** indicate values that are above CARO's method reporting limits. Any results that are above regulatory limits are highlighted **red**. Please note that results will only be highlighted red if the regulatory limits are included on the CARO report. Any Bold and/or highlighted results do not take into account method uncertainty. If you would like method uncertainty or regulatory limits to be included on your report, please contact your Account Manager:nyipp@caro.ca

Please note any regulatory guidelines applied to this report are added as a convenience to the client, at their request, to help provide some initial context to analytical results obtained. Although CARO makes every effort to ensure accuracy of the associated regulatory guideline(s) applied, the guidelines applied cannot be assumed to be correct due to a variety of factors and as such CARO Analytical Services assumes no liability or responsibility for the use of those guidelines to make any decisions. The original source of the regulation should be verified and a review of the guideline(s) should be validated as correct in order to make any decisions arising from the comparison of the analytical data obtained to the relevant regulatory guideline for one's particular circumstances. Further, CARO Analytical Services assumes no liability or responsibility for any loss attributed from the use of these guidelines in any way.

APPENDIX 2: QUALITY CONTROL RESULTS

The following section displays the quality control (QC) data that is associated with your sample data. Groups of samples are prepared in “batches” and analyzed in conjunction with QC samples that ensure your data is of the highest quality. Common QC types include:

- **Method Blank (Blk)**: A blank sample that undergoes sample processing identical to that carried out for the test samples. Method blank results are used to assess contamination from the laboratory environment and reagents.
- **Duplicate (Dup)**: An additional or second portion of a randomly selected sample in the analytical run carried through the entire analytical process. Duplicates provide a measure of the analytical method's precision (reproducibility).
- **Blank Spike (BS)**: A sample of known concentration which undergoes processing identical to that carried out for test samples, also referred to as a laboratory control sample (LCS). Blank spikes provide a measure of the analytical method's accuracy.
- **Matrix Spike (MS)**: A second aliquot of sample is fortified with a known concentration of target analytes and carried through the entire analytical process. Matrix spikes evaluate potential matrix effects that may affect the analyte recovery.
- **Reference Material (SRM)**: A homogenous material of similar matrix to the samples, certified for the parameter(s) listed. Reference Materials ensure that the analytical process is adequate to achieve acceptable recoveries of the parameter(s) tested.

Each QC type is analyzed at a 5-10% frequency, i.e. one blank/duplicate/spike for every 10-20 samples. For all types of QC, the specified recovery (% Rec) and relative percent difference (RPD) limits are derived from long-term method performance averages and/or prescribed by the reference method.

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
General Parameters, Batch B2C0518										
Blank (B2C0518-BLK1)				Prepared: 2022-03-04, Analyzed: 2022-03-05						
Nitrate, Water-Soluble (as N)	< 0.050	0.050	mg/kg dry							
Nitrite, Water-Soluble (as N)	< 0.050	0.050	mg/kg dry							
LCS (B2C0518-BS1)				Prepared: 2022-03-04, Analyzed: 2022-03-05						
Nitrate, Water-Soluble (as N)	4.06	0.050	mg/kg dry	4.00		101	90-110			
Nitrite, Water-Soluble (as N)	2.08	0.050	mg/kg dry	2.00		104	85-115			
Duplicate (B2C0518-DUP1)		**Source: 22C0421-01**		Prepared: 2022-03-04, Analyzed: 2022-03-05						
Nitrate, Water-Soluble (as N)	2.68	0.050	mg/kg dry		2.98			11	25	
Nitrite, Water-Soluble (as N)	< 0.500	0.050	mg/kg dry		< 0.500				15	
General Parameters, Batch B2C0596										
Blank (B2C0596-BLK1)				Prepared: 2022-03-08, Analyzed: 2022-03-08						
Organic Matter (LOI)	< 0.10	0.10	% dry							
Reference (B2C0596-SRM1)				Prepared: 2022-03-08, Analyzed: 2022-03-08						
Organic Matter (LOI)	6.38	0.10	% dry	5.23		122	75-125			
General Parameters, Batch B2C0686										
Blank (B2C0686-BLK1)				Prepared: 2022-03-10, Analyzed: 2022-03-10						
Carbon, Total Organic	< 0.050	0.050	% dry							
Duplicate (B2C0686-DUP1)		**Source: 22C0421-02**		Prepared: 2022-03-10, Analyzed: 2022-03-10						
Carbon, Total Organic	2.47	0.050	% dry		2.27			8	20	
Reference (B2C0686-SRM1)				Prepared: 2022-03-10, Analyzed: 2022-03-10						
Carbon, Total Organic	0.606	0.050	% dry	0.645		94	80-120			
General Parameters, Batch B2C0900										
Reference (B2C0900-SRM1)				Prepared: 2022-03-08, Analyzed: 2022-03-08						
Moisture	7.1	1.0	% wet	6.5		99	80-120			

APPENDIX 2: QUALITY CONTROL RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	22C0421
PROJECT	42.158	**REPORTED**	2022-03-10 15:17

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
General Parameters, Batch B2C1014										
Blank (B2C1014-BLK1)				Prepared: 2022-03-09, Analyzed: 2022-03-09						
Nitrogen, Total Kjeldahl	< 0.010	0.010	% wet							
Reference (B2C1014-SRM1)				Prepared: 2022-03-09, Analyzed: 2022-03-09						
Nitrogen, Total Kjeldahl	0.277	0.010	% wet	0.281		98	58.8-150			
General Parameters, Batch B2C1088										
General Parameters, Batch B2C1130										
Blank (B2C1130-BLK1)				Prepared: 2022-03-10, Analyzed: 2022-03-10						
Phosphorus, Total (as P)	< 0.4	0.4	mg/kg wet							
Duplicate (B2C1130-DUP1)		**Source: 22C0421-01**		Prepared: 2022-03-10, Analyzed: 2022-03-10						
Phosphorus, Total (as P)	443	0.4	mg/kg dry		465			5	24	
Reference (B2C1130-SRM1)				Prepared: 2022-03-10, Analyzed: 2022-03-10						
Phosphorus, Total (as P)	1790	10.8	mg/kg wet	1830		98	27.5-154			
Strong Acid Leachable Metals, Batch B2C1058										
Blank (B2C1058-BLK1)				Prepared: 2022-03-09, Analyzed: 2022-03-10						
Aluminum	< 40	40	mg/kg dry							
Antimony	< 0.10	0.10	mg/kg dry							
Arsenic	< 0.30	0.30	mg/kg dry							
Barium	< 1.0	1.0	mg/kg dry							
Beryllium	< 0.10	0.10	mg/kg dry							
Boron	< 2.0	2.0	mg/kg dry							
Cadmium	< 0.040	0.040	mg/kg dry							
Chromium	< 1.0	1.0	mg/kg dry							
Cobalt	< 0.10	0.10	mg/kg dry							
Copper	< 0.40	0.40	mg/kg dry							
Iron	< 20	20	mg/kg dry							
Lead	< 0.20	0.20	mg/kg dry							
Lithium	< 0.10	0.10	mg/kg dry							
Manganese	< 0.40	0.40	mg/kg dry							
Mercury	< 0.040	0.040	mg/kg dry							
Molybdenum	< 0.10	0.10	mg/kg dry							
Nickel	< 0.60	0.60	mg/kg dry							
Phosphorus	< 10	10	mg/kg dry							
Selenium	< 0.20	0.20	mg/kg dry							
Silver	< 0.10	0.10	mg/kg dry							
Strontium	< 0.20	0.20	mg/kg dry							
Thallium	< 0.10	0.10	mg/kg dry							
Tin	< 0.20	0.20	mg/kg dry							
Tungsten	< 0.20	0.20	mg/kg dry							
Uranium	< 0.050	0.050	mg/kg dry							
Vanadium	< 1.0	1.0	mg/kg dry							
Zinc	< 2.0	2.0	mg/kg dry							
LCS (B2C1058-BS1)				Prepared: 2022-03-09, Analyzed: 2022-03-10						
Antimony	1.96	0.10	mg/kg dry	2.00		98	80-120			
Arsenic	1.68	0.30	mg/kg dry	2.00		84	80-120			
Barium	2.0	1.0	mg/kg dry	2.00		100	80-120			
Beryllium	1.87	0.10	mg/kg dry	2.00		93	80-120			
Boron	< 2.0	2.0	mg/kg dry	2.00		95	80-120			

APPENDIX 2: QUALITY CONTROL RESULTS

REPORTED TO	Kerr Wood Leidal Associates Ltd. (Burnaby)	**WORK ORDER**	22C0421
PROJECT	42.158	**REPORTED**	2022-03-10 15:17

Strong Acid Leachable Metals, Batch B2C1058, Continued

LCS (B2C1058-BS1), Continued — Prepared: 2022-03-09, Analyzed: 2022-03-10

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
Cadmium	1.85	0.040	mg/kg dry	2.00		93	80-120			
Chromium	1.7	1.0	mg/kg dry	2.00		84	80-120			
Cobalt	1.78	0.10	mg/kg dry	2.00		89	80-120			
Copper	2.03	0.40	mg/kg dry	2.00		101	80-120			
Iron	172	20	mg/kg dry	200		86	80-120			
Lead	1.96	0.20	mg/kg dry	2.00		98	80-120			
Lithium	1.92	0.10	mg/kg dry	2.00		96	80-120			
Manganese	1.85	0.40	mg/kg dry	2.00		92	80-120			
Mercury	0.094	0.040	mg/kg dry	0.101		94	80-120			
Molybdenum	2.03	0.10	mg/kg dry	2.00		102	80-120			
Nickel	1.85	0.60	mg/kg dry	2.00		92	80-120			
Phosphorus	164	10	mg/kg dry	200		82	80-120			
Selenium	1.83	0.20	mg/kg dry	2.00		91	80-120			
Silver	1.93	0.10	mg/kg dry	2.00		97	80-120			
Strontium	1.79	0.20	mg/kg dry	2.00		89	80-120			
Thallium	1.94	0.10	mg/kg dry	2.00		97	80-120			
Tin	1.92	0.20	mg/kg dry	2.00		96	80-120			
Tungsten	1.87	0.20	mg/kg dry	2.00		93	80-120			
Uranium	1.85	0.050	mg/kg dry	2.00		93	80-120			
Vanadium	2.2	1.0	mg/kg dry	2.00		111	80-120			
Zinc	2.1	2.0	mg/kg dry	2.00		104	80-120			

Reference (B2C1058-SRM1) — Prepared: 2022-03-09, Analyzed: 2022-03-10

Analyte	Result	RL	Units	Spike Level	Source Result	% REC	REC Limit	% RPD	RPD Limit	Qualifier
Aluminum	10500	40	mg/kg dry	11500		91	70-130			
Antimony	0.62	0.10	mg/kg dry	0.724		86	70-130			
Arsenic	75.7	0.30	mg/kg dry	82.1		92	70-130			
Barium	40.0	1.0	mg/kg dry	40.0		100	70-130			
Beryllium	0.39	0.10	mg/kg dry	0.369		107	70-130			
Chromium	57.2	1.0	mg/kg dry	63.1		91	70-130			
Cobalt	9.84	0.10	mg/kg dry	10.4		95	70-130			
Copper	20.3	0.40	mg/kg dry	19.8		102	70-130			
Iron	17400	20	mg/kg dry	20200		86	70-130			
Lead	17.3	0.20	mg/kg dry	17.3		100	70-130			
Manganese	299	0.40	mg/kg dry	315		95	70-130			
Mercury	0.105	0.040	mg/kg dry	0.110		95	70-130			
Molybdenum	0.64	0.10	mg/kg dry	0.619		103	70-130			
Nickel	31.5	0.60	mg/kg dry	31.7		99	70-130			
Phosphorus	340	10	mg/kg dry	420		81	70-130			
Silver	1.65	0.10	mg/kg dry	1.75		94	70-130			
Strontium	20.6	0.20	mg/kg dry	20.3		101	70-130			
Uranium	1.22	0.050	mg/kg dry	1.18		103	70-130			
Vanadium	33.7	1.0	mg/kg dry	33.5		101	70-130			
Zinc	40.9	2.0	mg/kg dry	40.2		102	70-130			

CARO ANALYTICAL SERVICES

☑ 11(~TE
☐ 10 TE
☐ 17 TEL. (...

22C0421

CHAIN-OF-CUSTODY RECORD

COC#

RELINQUISHED BY:	DATE: 2022/03/02	RECEIVED BY:	DATE:
BEN VOVKO	TIME:	SM · WI	TIME:
RELINQUISHED BY:	DATE:	RECEIVED BY: SM-WI	DATE: 3/2
	TIME:		TIME: 1600

REPORT TO:		INVOICE TO:	SAME AS REPORT TO ☐
COMPANY:	Kerr Wood Leidal	COMPANY:	Kerr Wood Leidal
ADDRESS:	200-4185A Still Creek Dr.	ADDRESS:	200-4185A Still Creek Dr.
	Burnaby, BC V5C 6G9		Burnaby, BC V5C 6G9
CONTACT:	Patrick Lilley	CONTACT:	Patrick Lilley
TEL / FAX:	604 293 3121	TEL / FAX:	604 293 3121
EMAIL PDF ☑ EDD ☐	Please email Excel file.	EMAIL PDF ☐	
EMAIL 1:	plilley@kwl.ca / yparkinson@kwl.	EMAIL 1:	plilley@kwl.ca
EMAIL 2:	kbjorklund@kwl.ca / sjonkman@	EMAIL 2:	mderer@kwl.ca
MAIL HARDCOPY ☐	HOLD FOR P/U ☐ FAX ☐	MAIL HARDCOPY ☐	HOLD FOR P/U ☐

PROJECT:	PROJECT INFO:	PO #:
42.158	GI Asset Monitoring	
SAMPLED BY:	SHIPPING INSTRUCTIONS:	RETURN COOLER(S) ☐
COV	SHIP SUPPLIES (PLEASE SPECIFY IN OTHER INSTRUCTIONS SECTION)	☐

TURNAROUND Routine (4-7 days) ☑ Other:

TIME REQUESTED: Rush:* 1 Day ☐ 2 Day ☐ 3 Day ☐ * Contact the lab to confirm, surcharges may apply

ANALYSES REQUESTED:

CLIENT SAMPLE ID:	MATRIX: DRINKING WATER	OTHER WATER	SOIL	OTHER	# CONTAINERS	SAMPLING: DATE DD-MMM-YY	TIME HH:MM	COMMENTS: CHLORINATED	FILTERED	PRESERVED	(i.e. flow/volume media ID/notes)	METALS (all)	pH	ORGANIC CONTENT / ORGANIC MATTER	TOTAL NITROGEN	TOTAL PHOSPHOROUS	HOLD
Street sweeping sand 1	☐	☐	☑	☐	2	3-OCT-21		☐	☐	☐		☑	☑	☑	☑	☑	☐
Street sweeping sand 2	☐	☐	☑	☐	2	3-OCT-21		☐	☐	☐		☑	☑	☑	☑	☑	☐

APPLICABLE REGULATORY LIMITS:
Canadian Drinking Water Quality Guidelines ☐
BC Drinking Water Protection Act/Reg. ☐
BC CSR: AL ☐ RL ☐ CL ☐ IL ☐ AW ☐
CCME ☐ Alberta Tier 1 ☐
OTHER:

SAMPLE RETENTION INSTRUCTIONS (Discarded 30 days after Report unless otherwise specified):
60 Days ☐ 90 Days ☐ Longer Date (Surcharges will apply):

OTHER INSTRUCTIONS:
Please include the scanned COC with report.
SAMPLES STORED IN FRIDGE

PAYMENT: Cheque ☐ Credit ☐ Debit ☐ Cash ☐ Invoice ☐

SAMPLE RECEIPT TEMP (°C): 17.9
Work Order #
CUSTODY SEALS INTACT: ☐Y ☐N ☐NA

Required Fields Recommended Fields SHADED AREAS: LAB USE ONLY

Appendix C –

Rodgers et al. (2023, 10). Bioretention Cells Provide a 10-fold reduction in 6PPD-Quinone Mass Loadings to Receiving Waters: Evidence from a Field Experiment and Modeling. *Environmental Science and Technologies Letters*, pp. 582-588.

Environmental Science & Technology Letters

pubs.acs.org/journal/estlcu

Letter

Bioretention Cells Provide a 10-Fold Reduction in 6PPD-Quinone Mass Loadings to Receiving Waters: Evidence from a Field Experiment and Modeling

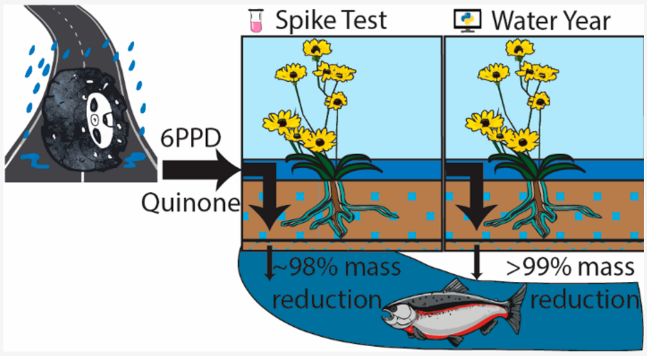
Timothy F. M. Rodgers,[†] Yanru Wang,[†] Cassandra Humes, Matthew Jeronimo, Cassandra Johannessen, Sylvie Spraakman, Amanda Giang, and Rachel C. Scholes*

Cite This: *Environ. Sci. Technol. Lett.* 2023, 10, 582−588

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Road runoff to streams and rivers exposes aquatic organisms to complex mixtures of chemical contaminants. In particular, the tire-derived chemical 6PPD-quinone (*N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine-quinone) is acutely toxic to several species of salmonids, which are critical to fisheries, ecosystems, and Indigenous cultures. We therefore urgently require interventions that can reduce loadings of 6PPD-quinone to salmonid habitats. Herein, we conducted a spike and recovery experiment on a full-scale, mature bioretention cell to assess the efficacy of stormwater green infrastructure technologies in reducing 6PPD-quinone loadings to receiving waters. We then interpreted and extended the results of our experiment using an improved version of the "Bioretention Blues" contaminant transport and fate model. Overall, our results showed that stormwater bioretention systems can effectively mitigate >∼90% of 6PPD-quinone loadings to streams under most "typical" storm conditions (i.e., < 2-year return period). We therefore recommend that stormwater managers and other environmental stewards redirect stormwater away from receiving waters and into engineered green infrastructure systems such as bioretention cells.



KEYWORDS: *bioretention, stormwater, 6PPD-quinone, trace organic contaminants, fate models, green infrastructure, salmonids*

INTRODUCTION

Road runoff to creeks, streams, and rivers exposes aquatic organisms to complex mixtures of chemical contaminants. Salmonids are anadromous or freshwater fish species that are frequently found in waters that receive road runoff. Wild or farmed salmonids are found in temperate waters around the globe and make up ∼18% of global fisheries and aquaculture trade.[1] Salmonids are particularly important along the Pacific coast of North America, where they are keystone species of critical importance to many ecosystems[2] and Indigenous cultures.[3,4]

This cultural, ecological, and economic importance means that in many areas managing threats to salmonid populations is important to maintaining socio-ecologically healthy aquatic environments. In streams in the U.S. Pacific Northwest, exposure to road runoff has been linked to the prespawn mortality of 40−90% of returning coho salmon (*Oncorhynchus kisutch*).[5] For coho salmon, the primary toxicant in road runoff was recently discovered to be the compound 6PPD-quinone (*N*-(1,3-dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine-quinone), which is produced as a transformation product when atmospheric ozone reacts with 6PPD, an antiozonant tire additive.[6] 6PPD-quinone has been found at toxicologically relevant levels in many urban streams across North America,[7−9] and in road dust in Japan,[10] and further research has shown that a number of other salmonid species are impacted at environmentally relevant concentrations of 6PPD-quinone.[11−13] 6PPD-quinone toxicity is an area of evolving research, with results indicating that juvenile salmon are also very sensitive to 6PPD-quinone exposure,[14] that toxicity is not consistent among aquatic organisms, and that the modes of toxicity are not fully understood.[15]

We therefore urgently require interventions that can reduce loadings of 6PPD-quinone to salmonid habitats, particularly in urban areas along the Pacific coast of North America where sensitive populations and high loadings coincide. Regulators are currently assessing alternatives to 6PPD in car tires, but the

Received: March 17, 2023
Revised: May 26, 2023
Accepted: May 30, 2023
Published: June 16, 2023

https://doi.org/10.1021/acs.estlett.3c00203
Environ. Sci. Technol. Lett. 2023, 10, 582−588

development and adoption of alternatives, including the replacement of the current in-use stock of tires, will likely take many years.[16] For instance, the California (USA) Department of Toxic Substances Control has proposed listing motor vehicle tires containing 6PPD as a "priority product", which would require labeling and alternatives assessments by manufacturers, but would not ban its use. The Washington State (USA) Department of Ecology investigated alternatives to 6PPD, but concluded that it was difficult to determine if any alternative would be safer than 6PPD.[17]

Previous research suggests that bioretention systems or "rain gardens",[18,19] a type of "green infrastructure", or "low impact development"[20,21] technology, could be effective at reducing 6PPD-quinone loadings to urban streams. First, the physicochemical properties of 6PPD-quinone indicate that it could be partially captured by soil sorption.[22] Further, in studies conducted before 6PPD-quinone was discovered as the primary causal toxicant in stormwater runoff, McIntyre et al.[23] and Spromberg et al.[24] found that stormwater filtered through laboratory-scale bioretention columns protected coho salmon from the acutely lethal effects of stormwater runoff. However, in a field-scale bioretention system preferential flow paths, differing loading patterns, and other factors can substantially impact bioretention system performance.[25,26]

Herein, we conducted a 6PPD-quinone spike and recovery test on a full-scale bioretention cell in Vancouver, Canada. We interpreted and extended our analysis using the Bioretention Blues model of organic contaminant fate in bioretention systems.[22] The goals of our study were to (A) Experimentally assess the effectiveness of mature bioretention systems for reducing the discharge of 6PPD-quinone, (B) model the performance of bioretention systems for removing 6PPD-quinone under different hydrological conditions, and (C) model dominant processes in 6PPD-quinone fate in bioretention systems and determine gaps in our understanding of those processes.

■ METHODS

Study Site. The studied bioretention system is located on the northeast corner of Pine and eighth Streets in Vancouver, Canada. It was constructed in summer 2021 and planted in fall 2021. The system area is 22 m^2, the contributing drainage area is 694 m^2, ponding depth is 15 cm, media depth is 45 cm with a layer of mulch on the surface, and the unlined bottom contains an underdrain wrapped in clear crush gravel and geotextile. Figures S1 and S2 show engineering drawings of the system, and SI section S1.1 gives additional site details.

Experimental Protocol. Our spike and recovery experiment was designed to represent the largest rainfall event that did not cause the system to overflow. We followed the experimental framework of Gu et al.[27] with some modifications. First, we conducted a "spike" test where chemicals (including 6PPD-quinone, bromide and rhodamine-WT) were added to the system while water was pumped from a water truck on July 28th, 2022. To assess whether 6PPD-quinone would be remobilized by rain events with small antecedent dry periods, we conducted a "flushing" test, where ~13m^3 of water but no chemicals were added (Figure 1C) on August third, 2022. We took effluent samples from the system's underdrain at a frequency of ~5−20 min for a total of 28 effluent and triplicate spike mixture samples during the spike test and 17 effluent samples during the flushing test. Further details are available in SI S1.2. Measured concentrations for 6PPD-quinone, rhodamine-WT, and bromide, measured flow rates and other water quality parameters (temperature, pH, and conductivity), the version of the Bioretention Blues model used here, and all input model parametrization files (including an EPA-SWMM model of the catchment) can be found in our data repository[28] and from the cofirst author's GitHub page.[29]

Sample Extraction and Analysis. We quantified 6PPD-quinone by extracting the water samples using off-line solid-phase extraction (SPE), and analyzed 1 mL of well-mixed extract using an Agilent 1200 series high-performance liquid chromatography (HPLC) system and a 6410 triple quadrupole mass spectrometer (Agilent Technologies, CA, USA). Full details on the sample extraction and analysis are discussed in the SI (Section S1.3 and Table S1). We measured the concentrations of the bromide and rhodamine-WT tracers using ion chromatography (Dionex Aquion, Thermo Scientific, Ontario, Canada) and UV/vis spectroscopy (Unicam UV 300, Thermo Spectronic, USA), respectively.

Quality Assurance and Quality Control. We collected six field blanks, four background samples from the water truck, and two field duplicate samples. We created three additional duplicates by subsampling the volumes collected in the field. When analyzing our results, we replaced values below the MDL with half the MDL. We defined the method detection limit (MDL) as the mean field blank level plus either the 99 or the 98% confidence interval from the field blanks (Table S2).

Model Development, Parametrization, and Calibration. We developed an updated version of the Bioretention Blues[22] model (Figure 1C) to help interpret the spike and recovery experiment and to extend our results to conditions and design configurations beyond those observed during the experiment (see SI S1.4 for full details).

We parametrized the updated Bioretention Blues model to represent the bioretention system at Pine and eighth St. in Vancouver, Canada. We calibrated the model hydrology using the Kling-Gupta efficiency (KGE)[30] between the measured and modeled outflows, and contaminant behavior using the conservative bromide and the sorptive rhodamine-WT tracers (full details in SI S1.4). We did not calibrate any parameters for 6PPD-quinone. We estimated the partition coefficients for 6PPD-quinone using BIOVIA COSMOtherm (version 21.0),[31−34] the estimated values for log K_{OC} of 3.14 and the octanol−water partition coefficient (log K_{OW}) of 4.12 are both close to experimental values of 3.2−3.5, for log K_{OC} in road dust,[10] and 4.3 for log K_{OW}.[35] We linearly interpolated the concentrations and flow rates between observations to generate a higher temporal resolution data set to use as inputs to the model (see additional parametrization details in SI S1.4).

Model Application. First, we modeled the spike and recovery experiment, using the fit between the measured and modeled values to evaluate the model, and the model outputs to help interpret the experimental results. Then, we used the model to extend our analysis and evaluate how a "typical" bioretention cell,[18] represented by our system, would perform in reducing loadings of 6PPD-quinone to receiving bodies. We simulated single event time-series for 28 design storms across the intensity-duration-frequency (IDF) curves used by the City of Vancouver, and for a continuous simulation across a synthetic "average" water year used by the City of Vancouver that contains less intense events (see SI Section S1.5 for full details, Table S3 shows the rainfall intensities for the IDF events and our data repository[28] contains the complete time-series used as inputs to the model).

We defined the "performance" of the system as its ability to reduce mass loadings and effluent concentrations of 6PPD-quinone. We assessed the "direct effluent" as the proportion of the influent mass that was released to the sewer network, through the underdrain or by overflowing. We defined the flow-weighted mean effluent concentration (MEC, ng L^{-1}) as the direct effluent mass of 6PPD-quinone divided by the total water volume entering the sewer network. We also calculated the acute risk quotient (RQ)[36] using the LC_{50} for adult coho salmon of 95 ng L^{-1}.[9] We note that an LC_{50} of 41 ng L^{-1} was recently reported by Lo et al.[14] for juvenile Coho salmon, using this value would increase all of the reported RQs by 2.3 times. We used the RQ to calculate an average (RQ_{av}) based on the MEC. An $RQ_{av} > 0.5$ indicates a "high" risk, $0.1 \leq RQ_{av} \leq 0.5$ the potential for acute risk, and $0.05 \leq RQ_{av} \leq 0.1$ the potential for acute risk to endangered species.[36]

■ RESULTS AND DISCUSSION

Our results indicate that bioretention systems can effectively reduce 6PPD-quinone loadings in urban runoff. Despite the short hydraulic residence time (peak effluent concentrations were observed ~3−11 min after injection), our experimental results showed substantial mass and concentration reductions to the effluent for 6PPD-quinone. The observed flow rates (Figure 1a) indicated that water infiltrated rapidly into the studied system and then exfiltrated to the surrounding soil.

The bromide tracer (Figure 1b, orange) peaked within ~5 min and was flushed from the system in under an hour, exhibiting a right-skewed distribution. By contrast, the sorptive rhodamine-WT tracer peaked after ~3 min (Figure 1b, blue), but then had a long tail of continued detectable concentrations. This indicates that rhodamine-WT sorbed to the soil during the initial spike and then desorbed back into the flowing water. For 6PPD-quinone (Figure 1c), the experimental results indicated a mass reduction of ~95% to the underdrain. The peak effluent concentration of ~150 ng L^{-1} was substantially lower than the influent spike mixture concentration of ~4300 ng L^{-1}, partially because the spike mixture was immediately diluted with injection water. Notably, there was a 7 min period where the concentration of 6PPD-quinone was above the LC_{50} of coho salmon (95 ng/L), but the concentration fell below the MDL (14−16 ng L^{-1}) within half an hour after spiking.

Model Evaluation and Results. The fit between measured and modeled data indicated that the Bioretention Blues model reproduced the processes involved in contaminant transport and fate in the bioretention cell during the spike and recovery experiment (Figure 1, see SI Section S2.1). The model showed adequate performance (defined as KGE values ≥0.5, 1 indicates an ideal fit)[22,37] for the calibrated flows (Figure 1a) and for the tracer compounds bromide and rhodamine-WT (Figure 1b). For 6PPD-quinone, the KGE modified to ignore bias in variances was 0.64 (Figure 1c, see SI Section S2.2).

Encouragingly, our results indicated that once captured 6PPD-quinone is unlikely to leach out of the bioretention system, at least over short interevent time scales. First, during our initial experiment we only saw detectable levels of 6PPD-quinone immediately following the spike injection. By contrast, concentrations of rhodamine-WT remained elevated throughout the experiment. This difference in fate was captured by our model, which predicted substantial remobilization of rhod-

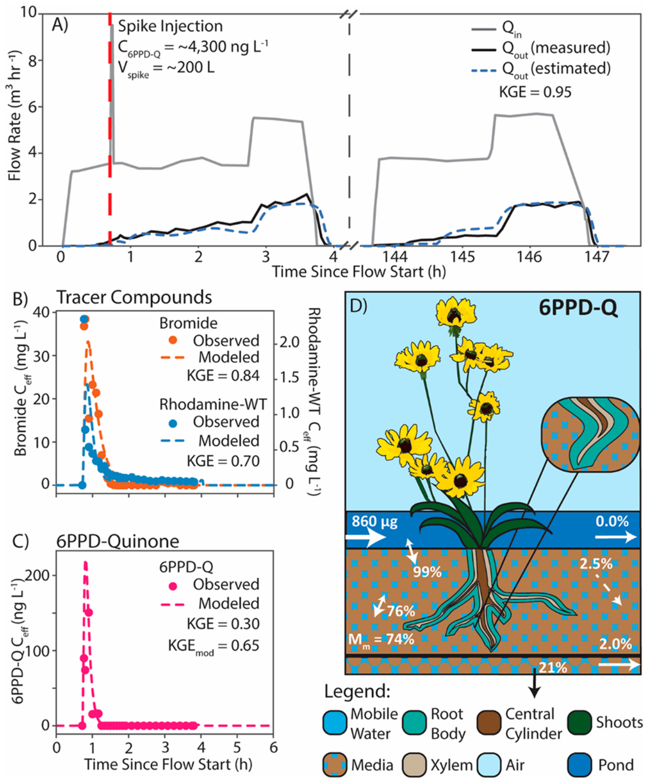


Figure 1. Overview of the results from the 6PPD-quinone (6PPD-Q) spike test. (A) Hydrology of the spike and recovery and flushing experiment, showing the measured influent and effluent flow rates, the modeled effluent flow rate (dashed line), and the timing of the spike injection. (B, C) Modeled (dashed lines) and measured (dots) effluent underdrain concentrations of the (B) calibrated tracer compounds and (C) uncalibrated 6PPD-quinone for the initial spike and recovery test period. (D) Modeled fate of 6PPD-quinone across the entire spike and flush test time period. Solid arrows represent mass transfers between compartments or into and out of the system, as a percentage of the influent mass (shown entering the ponding zone with units in µg); double-headed arrows indicate two-way processes with the larger arrowhead showing the dominant direction of exchange (e.g., 76% transfer from mobile water to media). Dashed lines represent primary transformation. M_m shows the percentage of influent mass retained by the soil.

amine-WT with the influx of clean water but predicted that 6PPD-quinone would mostly remain sorbed to the soil. Supporting this contention, during the flushing experiment, where we introduced ~13m^3 of clean water approximately 1 week after the initial spike experiment, we did not observe detectable effluent concentrations of 6PPD-quinone. For this event, the model predicted that ~2% of the influent mass would be remobilized to either the underdrain or to the surrounding soil. Although this lack of detection could have been caused by transformation or plant uptake of the 6PPD-quinone (given the uncertainty in the model parameters for those processes), it still showed that remobilization and leaching of 6PPD-quinone from fresh influent was not a substantial mass transport process, even given a very short interval (of <1 week) between large events. Overall, across the modeled period the model estimated that ~75% of the influent 6PPD-quinone was retained by the soil, with <5% released through the underdrain and ~20% exfiltrated to the surrounding soil (Figure 1d), with 2.5% predicted trans-

https://doi.org/10.1021/acs.estlett.3c00203
Environ. Sci. Technol. Lett. 2023, 10, 582−588

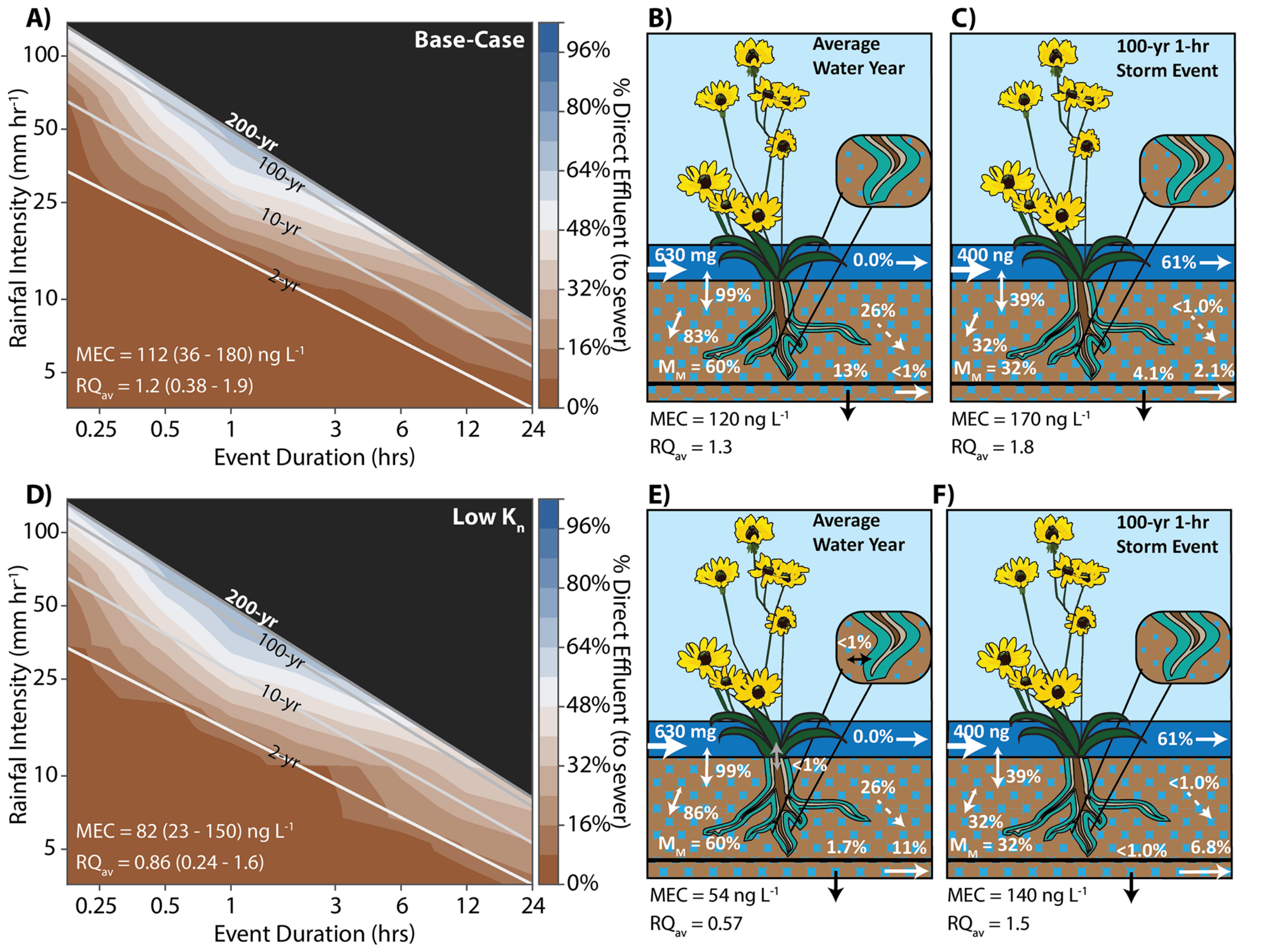


Figure 2. (A, D) Fate of 6PPD-quinone through the (A) studied and (D) low-K_n bioretention cell across the storm events defined by the City of Vancouver intensity-frequency-duration (IDF) curves. The contour colors (interpolated between the 28 simulated events) show the proportion of the influent mass that was advected through the bioretention cell to the sewer system, with brown colors representing less than 50% released and blue more than 50% released. The mean and range of the effluent concentrations (MEC) and the average risk quotients (RQ_{av}) are shown on the IDF figure. (B, E, C, F) Fate of 6PPD-quinone across (B, E) a synthetic "average" water year and (C, F) the City of Vancouver 100 year 1 h design storm event, respectively; E and F represent the low-K_n scenario. Solid arrows represent mass transfers between compartments or into and out of the system, as a percentage of the influent mass (shown entering the ponding zone with units in mg or ng); double-headed arrows indicate two-way processes with the larger arrowhead showing the dominant direction of exchange. Dashed lines represent primary transformation. M_m shows the percentage of influent mass retained by the soil.

formation in the soil compartment. SI Section S2.3 discusses limitations of our model and results.

Performance of Bioretention for 6PPD-Quinone. We ran the calibrated model for 28 events across the City of Vancouver intensity-duration-frequency (IDF) curves, assuming a constant 1000 ng L^{-1} influent concentration to represent a "worst-case" scenario, such as a system receiving effluent from a large highway (see SI section S1.5 for more details). Under these conditions, we predict that the as-built bioretention system would reduce mass-loadings of 6PPD-quinone to receiving systems by >90% for all events with a recurrence period of ≤2 years (Figure 2a). In an "average" water year, we predicted a reduction in annual mass loadings of >95%, with 26% of the influent mass predicted to transform (Figure 2b), although we note that little is known about how quickly 6PPD-quinone is transformed in soil. Some uptake by plants may occur,[38] although this is likely minor in a fast-draining bioretention system such as this one.[22] The system's RQ_{av} ranged from 0.38 for the 2 year, 10 min event to 1.9 for the 200 year, 1 h event. For larger events, there were substantial periods with an RQ > 1, indicating sustained effluent concentrations well above the LC_{50} for coho salmon.

The study system had a high exfiltration rate due to the high calibrated permeability (~125 mm h^{-1}) of the surrounding soil. To broaden the applicability of our results, we simulated the performance of a "low permeability" scenario consisting of an identical system situated in a soil with an infiltration rate of 3.3 mm h^{-1}, representing clayey or silty soils.[39] In this scenario, the system performed similarly to the as-built high permeability system, with more mass released to the sewer (e.g., 11% vs <1% for the studied system across the average water year), but a lower RQ_{av} of 0.24−1.6 across the 28 events due to the larger volume of underdrain flow diluting the effluent concentrations (Figure 2d). We note that since the Bioretention Blues model relies on system-specific calibrated parameters the uncertainty surrounding this simulated system is larger than for the as-built system.

For both the as-built and the low-permeability scenarios, this relatively high RQ_{av} (well above the US Environmental Protection Agency (EPA) threshold of >0.5 for a "high" risk) across all events was particularly driven by overflow of the

https://doi.org/10.1021/acs.estlett.3c00203
Environ. Sci. Technol. Lett. 2023, 10, 582−588

system during larger events (Figure 2c); water that overflowed the system received only minimal treatment due to settling and diffusion, leading to high combined effluent concentrations. On entering a stream, concentrations would be reduced through dilution. However, depending on the size of the stream, localized high concentrations would still be possible. Tire-derived chemicals such as 6PPD-quinone are believed to be rapidly mobilized by the first flush of a rainfall event,[40] meaning that the excellent performance for both the as-built and low permeability scenarios for smaller events and across an "average" water year could substantially reduce the risks to salmon. Larger events still present a risk, however, as in many catchments 6PPD-quinone is believed to exhibit an additional "middle flush"[40] of elevated concentrations of 6PPD-Q throughout the hydrograph.[7] Design or management interventions could therefore improve the ability of bioretention systems to protect salmon from 6PPD-quinone during extreme events.

Environmental Implications. Overall, our results showed that mature, field-scale bioretention systems can effectively capture 6PPD-quinone in stormwater. Although finding safer alternatives to 6PPD will provide the most complete protection for salmonids and other potentially sensitive aquatic organisms, the efficacy of bioretention systems means that in the short term, stormwater managers can protect sensitive populations by redirecting runoff away from streams and toward engineered systems such as bioretention. Our modeling results indicate that under most "typical" storm conditions (e.g., <2 year return period) bioretention will greatly reduce the mass and concentration of 6PPD-quinone being directly released. Even during larger events, almost 50% of 6PPD-quinone may be captured, with the lower performance for the largest events driven mainly by overflow from the ponding zone. Although knowledge gaps remain regarding the transformation rates of 6PPD-quinone in soil, and the potential for transport through interflow and shallow groundwater flow, our results indicate that 6PPD-quinone is not likely to be remobilized from soil. Therefore, redirection to riparian zones or other vegetated areas may provide protection as well. By directing road runoff toward bioretention systems, stormwater managers and other environmental stewards can help protect salmonids and any other sensitive aquatic organisms from toxic road runoff and support socio-ecologically healthy aquatic environments.

■ ASSOCIATED CONTENT

Data Availability Statement

The data used in this paper, along with an archived version of the Bioretention Blues model code, is available from our data repository.[28] Current and future versions of the model are also available with an interactive tutorial from one of the lead authors' GitHub pages.[29]

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.3c00203.

> Additional methodological details, including further information on the study site, experimental design, sample processing and analysis, and the model parametrization and calibration; additional results and discussion, including the calibrated model parameters, additional model evaluation details, and a discussion of limitations (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Rachel C. Scholes − *Department of Civil Engineering, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada;* orcid.org/0000-0001-5450-8377; Phone: 604-822-1987; Email: rachel.scholes@ubc.ca

Authors

Timothy F. M. Rodgers − *Institute of Resources, Environment and Sustainability, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada;* orcid.org/0000-0003-1850-404X

Yanru Wang − *Department of Civil Engineering, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada*

Cassandra Humes − *Green Infrastructure Design Team, City of Vancouver Engineering Services, Vancouver V5Z 0B4, Canada*

Matthew Jeronimo − *School of Population and Public Health, University of British Columbia, Vancouver, British Columbia V6T 1Z9, Canada;* orcid.org/0000-0001-8188-8993

Cassandra Johannessen − *Department of Chemistry and Biochemistry, Concordia University, Montreal, Quebec H4B 1R6, Canada;* orcid.org/0000-0001-8763-4994

Sylvie Spraakman − *Green Infrastructure Design Team, City of Vancouver Engineering Services, Vancouver V5Z 0B4, Canada*

Amanda Giang − *Institute of Resources, Environment and Sustainability and Department of Mechanical Engineering, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada;* orcid.org/0000-0002-0146-7038

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.estlett.3c00203

Author Contributions

T.F.M.R.: Conception, investigation, data curation, methodology, software, writing (original draft), and visualization; Y.W.: Investigation, data curation, methodology, writing (original draft); C.H.—Investigation, methodology, writing (review and editing); M.J.: Investigation, methodology, writing (review and editing); C.J.: software (COSMOtherm), writing (review and editing); S.S.: Conception, investigation, data curation, methodology, writing (review and editing), supervision; A.G.: Conception, writing (review and editing), supervision; R.C.S.: Conception, investigation, methodology, writing (review and editing) and supervision.

Author Contributions

[†]T.F.M.R. and Y.W. contributed equally to this project.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Many thanks to Sal Fuda and Colin Taylor for helping with sampling during the experiments; to Antonio Dias and Cayla Anderson for helping process samples for analysis; to Nick-Mead Fox for providing the SWMM model of the catchment and discussions around SWMM modeling; and to Prof. Elodie Passeport (University of Toronto) for helpful discussions regarding our experimental design. Computations were performed using infrastructure supported by CFI Innovation Fund to the Rapid Air Improvement Network (RAIN, grant number 39971). We would like to thank the Natural Sciences and Engineering Research Council (NSERC) of Canada for an NSERC postdoctoral fellowship to T.F.M.R. and NSERC Discovery Grants to A.G. (RGPIN-2018-04893) and R.C.S (RGPIN-2022-03115). We would also like to acknowledge that this research was conceptualized and implemented on the traditional, ancestral, and unceded territory of the Musqueam, Squamish, and Tsleil-Waututh peoples. As settler scholars, we are grateful to live, work, and learn as uninvited guests on these lands and we support the efforts of these communities, including their roles in stewarding, protecting, and restoring aquatic ecosystems.

REFERENCES

(1) Food and Agriculture Organization of the United Nations (FAO). FISHSTAT, 2022. https://www.fao.org/fishery/statistics-query/en/trade (accessed 2023-01-19).

(2) Walsh, J. C.; Pendray, J. E.; Godwin, S. C.; Artelle, K. A.; Kindsvater, H. K.; Field, R. D.; Harding, J. N.; Swain, N. R.; Reynolds, J. D. Relationships between Pacific Salmon and Aquatic and Terrestrial Ecosystems: Implications for Ecosystem-based Management. *Ecology* **2020**, *101* (9), e03060.

(3) Carothers, C.; Black, J.; Langdon, S. J.; Donkersloot, R.; Ringer, D.; Coleman, J.; Gavenus, E. R.; Justin, W.; Williams, M.; Christiansen, F.; Samuelson, J.; Stevens, C.; Woods, B.; Clark, S. J.; Clay, P. M.; Mack, L.; Raymond-Yakoubian, J.; Sanders, A. A.; Stevens, B. L.; Whiting, A. Indigenous Peoples and Salmon Stewardship: A Critical Relationship. *E&S* **2021**, *26* (1), art16.

(4) Campbell, S. K.; Butler, V. L. Archaeological Evidence for Resilience of Pacific Northwest Salmon Populations and the Socioecological System over the Last ~7,500 Years. *E&S* **2010**, *15* (1), art17.

(5) Scholz, N. L.; Myers, M. S.; McCarthy, S. G.; Labenia, J. S.; McIntyre, J. K.; Ylitalo, G. M.; Rhodes, L. D.; Laetz, C. A.; Stehr, C. M.; French, B. L.; McMillan, B.; Wilson, D.; Reed, L.; Lynch, K. D.; Damm, S.; Davis, J. W.; Collier, T. K. Recurrent Die-Offs of Adult Coho Salmon Returning to Spawn in Puget Sound Lowland Urban Streams. *PLoS One* **2011**, *6* (12), e28013.

(6) Tian, Z.; Zhao, H.; Peter, K. T.; Gonzalez, M.; Wetzel, J.; Wu, C.; Hu, X.; Prat, J.; Mudrock, E.; Hettinger, R.; Cortina, A. E.; Biswas, R. G.; Kock, F. V. C.; Soong, R.; Jenne, A.; Du, B.; Hou, F.; He, H.; Lundeen, R.; Gilbreath, A.; Sutton, R.; Scholz, N. L.; Davis, J. W.; Dodd, M. C.; Simpson, A.; McIntyre, J. K.; Kolodziej, E. P. A Ubiquitous Tire Rubber−Derived Chemical Induces Acute Mortality in Coho Salmon. *Science* **2021**, *371* (6525), 185−189.

(7) Johannessen, C.; Helm, P.; Lashuk, B.; Yargeau, V.; Metcalfe, C. D. The Tire Wear Compounds 6PPD-Quinone and 1,3-Diphenylguanidine in an Urban Watershed. *Arch. Environ. Contam. Toxicol.* **2022**, *82*, 171−179.

(8) Challis, J. K.; Popick, H.; Prajapati, S.; Harder, P.; Giesy, J. P.; McPhedran, K.; Brinkmann, M. Occurrences of Tire Rubber-Derived Contaminants in Cold-Climate Urban Runoff. *Environ. Sci. Technol. Lett.* **2021**, *8* (11), 961−967.

(9) Tian, Z.; Gonzalez, M.; Rideout, C. A.; Zhao, H. N.; Hu, X.; Wetzel, J.; Mudrock, E.; James, C. A.; McIntyre, J. K.; Kolodziej, E. P. 6PPD-Quinone: Revised Toxicity Assessment and Quantification with a Commercial Standard. *Environ. Sci. Technol. Lett.* **2022**, *9* (2), 140−146.

(10) Hiki, K.; Yamamoto, H. Concentration and Leachability of N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine (6PPD) and Its Quinone Transformation Product (6PPD-Q) in Road Dust Collected in Tokyo, Japan. *Environ. Pollut.* **2022**, *302*, 119082.

(11) Hiki, K.; Yamamoto, H. The Tire-Derived Chemical 6PPD-Quinone Is Lethally Toxic to the White-Spotted Char *Salvelinus Leucomaenis Pluvius* but Not to Two Other Salmonid Species. *Environ. Sci. Technol. Lett.* **2022**, *9* (12), 1050−1055.

(12) French, B. F.; Baldwin, D. H.; Cameron, J.; Prat, J.; King, K.; Davis, J. W.; McIntyre, J. K.; Scholz, N. L. Urban Roadway Runoff Is Lethal to Juvenile Coho, Steelhead, and Chinook Salmonids, But Not Congeneric Sockeye. *Environ. Sci. Technol. Lett.* **2022**, *9* (9), 733−738.

(13) Brinkmann, M.; Montgomery, D.; Selinger, S.; Miller, J. G. P.; Stock, E.; Alcaraz, A. J.; Challis, J. K.; Weber, L.; Janz, D.; Hecker, M.; Wiseman, S. Acute Toxicity of the Tire Rubber-Derived Chemical 6PPD-Quinone to Four Fishes of Commercial, Cultural, and Ecological Importance. *Environ. Sci. Technol. Lett.* **2022**, *9*, 333.

(14) Lo, B. P.; Marlatt, V. L.; Liao, X.; Reger, S.; Gallilee, C.; Brown, T. M. Acute Toxicity of 6PPD-quinone to Early Life Stage Juvenile Chinook (*Oncorhynchus Tshawytscha*) and Coho (*Oncorhynchus Kisutch*) Salmon. *Environ. Toxicol. Chem.* **2023**, *42* (4), 815−822.

(15) Hiki, K.; Asahina, K.; Kato, K.; Yamagishi, T.; Omagari, R.; Iwasaki, Y.; Watanabe, H.; Yamamoto, H. Acute Toxicity of a Tire Rubber-Derived Chemical, 6PPD Quinone, to Freshwater Fish and Crustacean Species. *Environ. Sci. Technol. Lett.* **2021**, *8* (9), 779−784.

(16) Dixon, S.; Goh, C.-Y. Tire-driven stormwater toxicity and salmon mortality from 6PPD-quinone. *Trends*, Aug 28, 2022.https://www.americanbar.org/groups/environment_energy_resources/publications/trends/2022-2023/september-october-2022/tire-driven-stormwater-toxicity/.

(17) State of Washington Department of Ecology. Hazardous Waste and Toxics Reduction Program Technical Memo. https://www.ezview.wa.gov/Portals/_1962/Documents/6ppd/6PPD%20Alternatives%20Technical%20Memo.pdf.

(18) Spraakman, S.; Rodgers, T. F. M.; Monri-Fung, H.; Nowicki, A.; Diamond, M. L.; Passeport, E.; Thuna, M.; Drake, J. A Need for Standardized Reporting: A Scoping Review of Bioretention Research 2000−2019. *Water (Switzerland)* **2020**, *12* (11), 3122.

(19) Roy-Poirier, A.; Champagne, P.; Filion, Y. Review of Bioretention System Research and Design: Past, Present, and Future. *J. Environ. Eng.* **2010**, *136* (9), 878−889.

(20) Ahiablame, L. M.; Engel, B. A.; Chaubey, I. Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. *Water, Air, and Soil Pollution* **2012**, *223* (7), 4253−4273.

(21) Wang, J.; Banzhaf, E. Towards a Better Understanding of Green Infrastructure: A Critical Review. *Ecological Indicators* **2018**, *85*, 758−772.

(22) Rodgers, T. F. M.; Wu, L.; Gu, X.; Spraakman, S.; Passeport, E.; Diamond, M. L. Stormwater Bioretention Cells Are Not an Effective Treatment for Persistent and Mobile Organic Compounds (PMOCs). *Environ. Sci. Technol.* **2022**, *56*, 6349.

(23) McIntyre, J. K.; Davis, J. W.; Hinman, C.; Macneale, K. H.; Anulacion, B. F.; Scholz, N. L.; Stark, J. D. Soil Bioretention Protects Juvenile Salmon and Their Prey from the Toxic Impacts of Urban Stormwater Runoff. *Chemosphere* **2015**, *132*, 213−219.

(24) Spromberg, J. A.; Baldwin, D. H.; Damm, S. E.; McIntyre, J. K.; Huff, M.; Sloan, C. A.; Anulacion, B. F.; Davis, J. W.; Scholz, N. L. Coho Salmon Spawner Mortality in Western US Urban Watersheds: Bioinfiltration Prevents Lethal Storm Water Impacts. *J. Appl. Ecol* **2016**, *53* (2), 398−407.

(25) de Macedo, M. B. de; do Lago, C. A. F. do; Mendiondo, E. M.; de Souza, V. C. B. Performance of Bioretention Experimental Devices: Contrasting Laboratory and Field Scales through Controlled Experiments. *RBRH* **2018**, *23*, DOI: 10.1590/2318-0331.0318170038.

(26) Marvin, J. T.; Passeport, E.; Drake, J. State-of-the-Art Review of Phosphorus Sorption Amendments in Bioretention Media: A Systematic Literature Review. *Journal of Sustainable Water in the Built Environment* **2020**, *6* (1), DOI: 10.1061/JSWBAY.0000893.

(27) Gu, X.; Rodgers, T. F. M.; Spraakman, S.; Van Seters, T.; Flick, R.; Diamond, M. L.; Drake, J.; Passeport, E. Trace Organic Contaminant Transfer and Transformation in Bioretention Cells: A Field Tracer Test with Benzotriazole. *Environ. Sci. Technol.* **2021**, *55* (18), 12281−12290.

(28) Data for: Bioretention Cells Provide a Tenfold Reduction in 6PPD-Quinone Mass Loadings to Receiving Waters: Evidence from a Field Experiment and Modeling. *Hydroshare*, https://doi.org/10.4211/hs.c24df560663448aebcbba9228c4fda19.

(29) Rodgers, T. F. M. Subsurface Sinks Model. *GitHub*, 2021. https://github.com/tfmrodge/SubsurfaceSinks.
(30) Gupta, H. V.; Kling, H.; Yilmaz, K. K.; Martinez, G. F. Decomposition of the Mean Squared Error and NSE Performance Criteria: Implications for Improving Hydrological Modelling. *Journal of Hydrology* **2009**, *377* (1−2), 80−91.
(31) Eckert, F.; Klamt, A. Fast Solvent Screening via Quantum Chemistry: COSMO-RS Approach. *AIChE J.* **2002**, *48* (2), 369−385.
(32) Klamt, A. Conductor-like Screening Model for Real Solvents: A New Approach to the Quantitative Calculation of Solvation Phenomena. *J. Phys. Chem.* **1995**, *99* (7), 2224−2235.
(33) Klamt, A.; Jonas, V.; Bürger, T.; Lohrenz, J. C. W. Refinement and Parametrization of COSMO-RS. *J. Phys. Chem. A* **1998**, *102* (26), 5074−5085.
(34) *BIOVIA COSMOtherm Release*; Dassault Systèmes, 2023; http://www.3ds.com.
(35) Walsh, J. C.; Pendray, J. E.; Godwin, S. C.; Artelle, K. A.; Kindsvater, H. K.; Field, R. D.; Harding, J. N.; Swain, N. R.; Reynolds, J. D. Relationships between Pacific Salmon and Aquatic and Terrestrial Ecosystems: Implications for Ecosystem-based Management. *Ecology* **2020**, *101* (9), e03060.
(36) US EPA. *Technical Overview of Ecological Risk Assessment: Risk Characterization*; 2017. https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/technical-overview-ecological-risk-assessment-risk (accessed 2022-10-24).
(37) Randelovic, A.; Zhang, K.; Jacimovic, N.; McCarthy, D.; Deletic, A. Stormwater Biofilter Treatment Model (MPiRe) for Selected Micro-Pollutants. *Water Res.* **2016**, *89*, 180−191.
(38) Castan, S.; Sherman, A.; Peng, R.; Zumstein, M. T.; Wanek, W.; Hüffer, T.; Hofmann, T. Uptake, Metabolism, and Accumulation of Tire Wear Particle-Derived Compounds in Lettuce. *Environ. Sci. Technol.* **2023**, *57* (1), 168−178.
(39) Hill, J. Low Permeability Soils. In *Low Impact Development Stormwater Management Planning and Design Guide*. Sustainable Technologies Evaluation Program, 2017; https://wiki.sustainabletechnologies.ca/index.php?title=Low_permeability_soils&mobileaction=toggle_view_desktop.
(40) Peter, K. T.; Hou, F.; Tian, Z.; Wu, C.; Goehring, M.; Liu, F.; Kolodziej, E. P. More Than a First Flush: Urban Creek Storm Hydrographs Demonstrate Broad Contaminant Pollutographs. *Environ. Sci. Technol.* **2020**, *54* (10), 6152−6165.

https://doi.org/10.1021/acs.estlett.3c00203
Environ. Sci. Technol. Lett. 2023, 10, 582−588