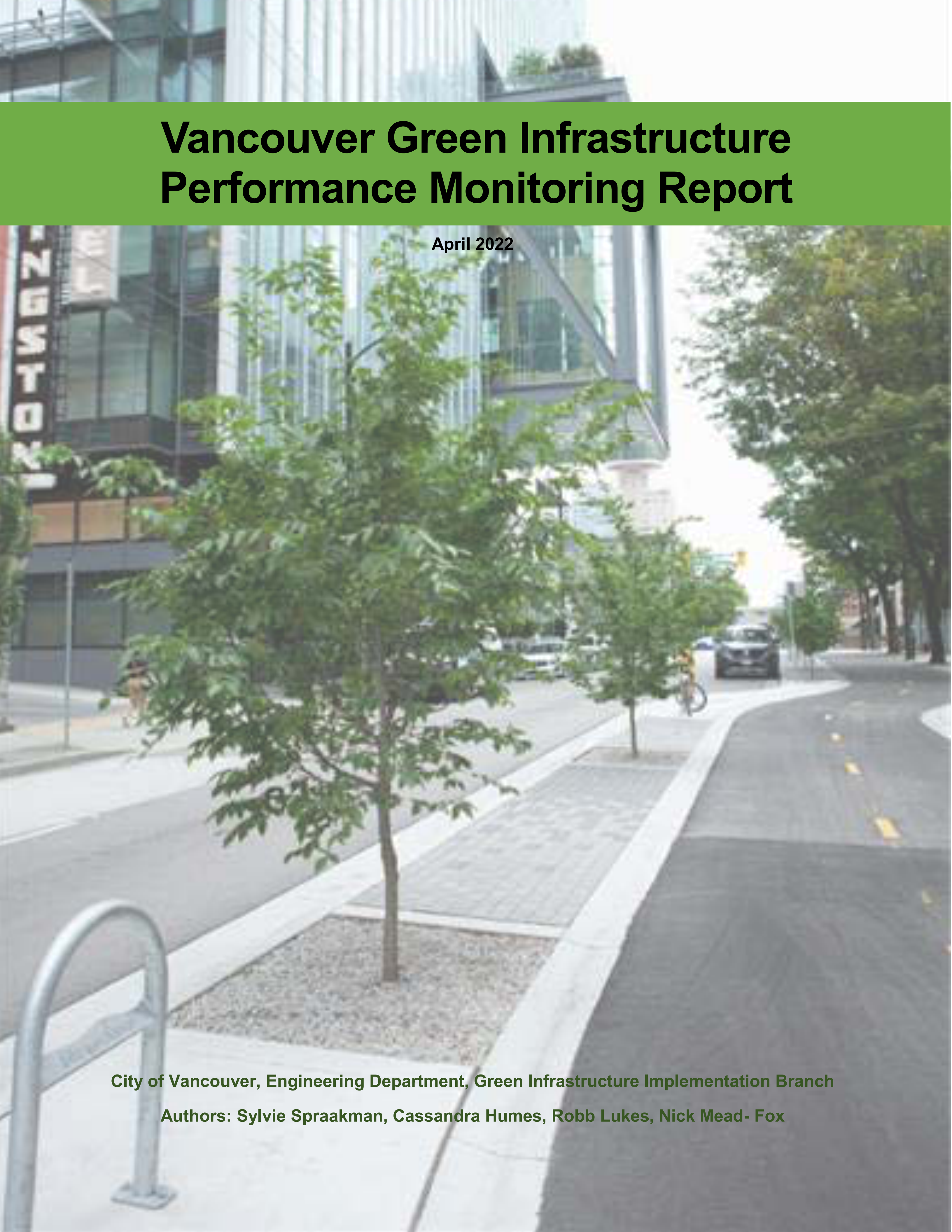
Vancouver Green Infrastructure Performance Monitoring Report

April 2022



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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 it where it lands. This results in the diversion of large amounts of water 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. Monitoring objectives falling under the categories of compliance, performance and optimization have been established in order to determine the performance of GRI systems within the Vancouver context, as well as to inform future design and construction.

During the 2018-2021 period, the Green Infrastructure Implementation Branch at the City of Vancouver conducted monitoring at six locations housing thirteen GRI systems, including bioswales, infiltration trenches, and rainwater tree trenches. **Bioswales** typically consist of a shallow depression or basin that features layers of rock, engineered soils, and resilient vegetation that can tolerate extreme rain and drought events. **Infiltration trenches** use conventional grey rainwater infrastructure to collect and convey rainwater to areas where it can be stored and infiltrated. **Rainwater Tree Trenches (RTTs)** are multifunctional GRI practices that provide both storage for rainwater and support to street trees.

Monitoring involved collection and data review from rain gauges, water level loggers in monitoring wells, soil sensors for volumetric water content at varying depths, ultrasonic sensors to measure flow in system underdrains, and visual observations during site visits. The monitoring summarized in this report is catalogued by site, and summarized by priority monitoring objectives.

The monitoring objectives are described below along with the corresponding results and conclusions from the monitoring program.

Objective 1: Evaluate surface ponding in GRI systems

Performance Target: Surface water should not be present for longer than 24 hours after a storm event. Ponding beyond 24 hours is generally unacceptable to the public. It may pose a risk to adults late at night or small children seeking puddles to splash in. While mosquito hatching is a commonly raised concern, mosquitoes need at least 7 days of standing water to develop and hatch.

Result: Ponding after 24 hours was not observed in any of the 13 systems that were monitored via visual assessments for this study. Surface ponding often only lasted for the duration of rainfall, and so drainage through the GRI systems occurred very rapidly.

Conclusion: The surface ponding performance target is being met by all monitored systems.

Objective 2: Evaluate subsurface storage drawdown

Performance Target: Subsurface storage should be empty within 72 hours of a storm event. This is a design requirement for the City of Vancouver, and relates to the average period between storm events. The water within the system should be fully drained before the next rain event to ensure that storage space is available in the system.

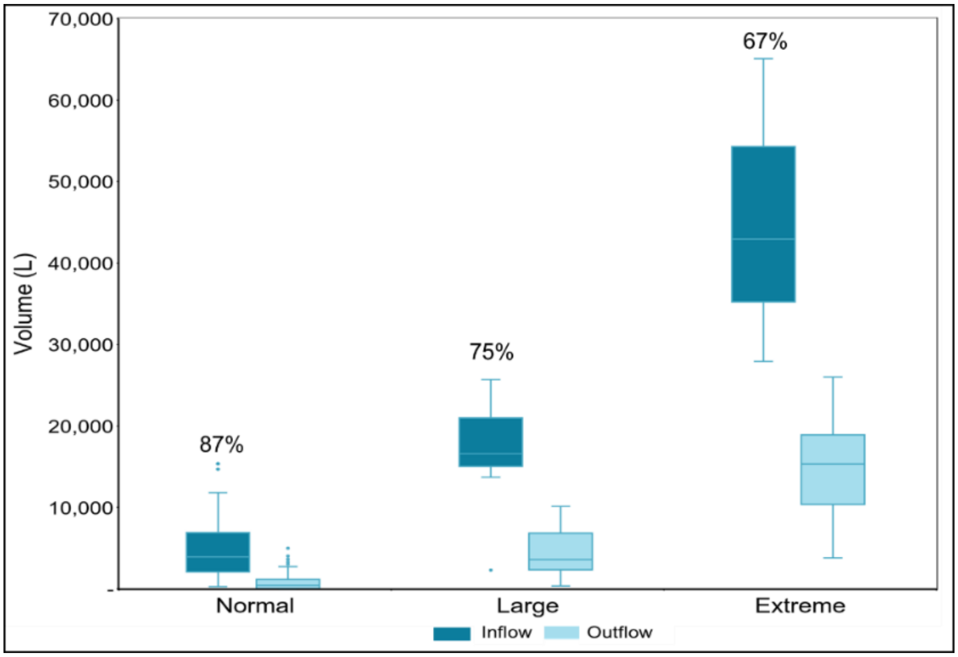
Result: Monitored drawdown times are between 0.4-28.5 hours with an average of 14.5 hours across 7 sites with water level loggers monitored between 2018 and 2021.

Conclusion: Subsurface storage generally drained faster than infiltration testing would suggest, indicating that a larger drainage area and more runoff could have been accommodated.

Objective 3: Determine if retention/filtration targets are being met

Performance Target: GRI systems are designed to retain or filter 90% of annual runoff volume, which is comparable to capturing 48 mm over 24 hours. Filtration refers to water that is filtered through the soil medium of a GRI system, providing water quality improvements and delaying the peak flow into connected sewers. Retention refers to the water that is permanently stored in the GRI system.

Result: Measuring water retention in a GRI system requires accurate and continuous accounting of inflows and outflows. While measuring discharge into the sewer system is straightforward, measuring the surface flow into a GRI system and the subsurface infiltration out of the system is technically challenging and expensive. Consequently, flow and volume measurements were only taken at one rainwater tree trench. All runoff directed to the rainwater tree trench was filtered, and 84% of the annual runoff volume was completely captured. The rainwater tree trench performed better during normal events (87% retained) compared to extreme events (67% of events retained). Though the GRI system is designed only for the normal events, it still showed the ability to reduce the volume of stormwater entering the storm system during extreme events.



Boxplots of inflow and outflow volumes and percent volume reduction for different size storm events at Quebec & 1st Location C RTT

Conclusion: As this is only one system, it is not advisable to extrapolate these results to apply to all systems. More efficient methods for determining if the retention/filtration target method should be explored. Though this system had excellent retention (84% of inflow volume retained), the results indicate that meeting the 90% annual rainfall capture target outlined in the Rain City Strategy through retention alone may be difficult on low infiltrating sites, but that it is possible to meet the target still through filtration.

Objective 4: Compare design infiltration rates and drawdown rates

Performance Target: The process of determining in-situ infiltration capacity is challenging due to the high variability in subsoil conditions and instrumentation used. As such, engineers design quite conservatively and apply a factor of safety of between 2 and 9 to the measured infiltration capacity. By comparing measured drawdown (the real rate at which water is leaving the system), to the design infiltration rates, we can determine if safety factors are correctly applied and if the drawdown rate decreases over time. These conclusions will inform future designs to ensure that modelled performance matches actual performance over the long term. Systems receiving too much runoff may require excess maintenance, while systems that could accommodate more drainage are being under-utilized.

Result: Five of the seven sites have monitored drawdown rates greater than or equal to the design infiltration rate. Four of the seven sites monitored have monitored drawdown times 400% greater than the design infiltration rate. Drawdown rates were measured using water level loggers installed within monitoring wells within the GRI system boundary.

Conclusion: The higher than expected drawdown rates indicate that water is leaving the system faster than expected. In over half the cases, the monitored drawdown rate was 400% greater than the design infiltration rate. This would indicate that re-evaluating how factors of safety are applied is necessary. We recommend using a safety factor of between 1 and 2, instead of safety factors between 2 and 9.

Objective 5: Monitor soil moisture for plant health

Performance Target: Trees and vegetation in GRI experience a wide range of moisture conditions that impact plant health. We would like to know whether the soil moisture extends outside tolerable ranges from excessive or prolonged saturation or dryness.

Result: Both Soil cell and Structural soil rainwater tree trenches did not have moisture levels that fell below 20%. Moisture levels in the bioswale shows seasonal variation with moisture levels nearing 5% during summer drought and up to 40% during winter wet conditions. No major plant die off was noted at the bioswale.

Conclusion: The results indicate that the plants within our systems are resilient under a wide variety of conditions. The moisture variation shows that the systems are receiving sufficient water to last through droughts and not so much to cause lasting damage to the plants during major storms. More complete visual condition assessments of plants will allow a greater correlation to soil moisture and plant health in the future.

Objective 6: Assess peak flow attenuation

Performance Target: Currently there are no explicit performance targets for peak flow reductions in right-of-way GRI systems, however peak flow reductions from GRI may play an important role in the City's goal of reducing combined sewer overflows (CSO).

Green infrastructure 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 released to receiving bodies of water. For larger rainfall events, the capacity of a GRI system may be exceeded causing overflow to the sewer system. However, even during overflow a delay in time of concentration and reduced related peak flow is still typically observed compared to non-GRI conditions. Assessing peak flow attenuation will help us to improve our understanding of GRI's impact on City sewers and how GRI works under large and extreme event conditions.

Result: Measuring peak flow reduction requires accurate inflow and outflow measurements. Sewer outflow measurements were collected using an ultrasonic sensor in the systems underdrain, while inflow measurements were estimated using runoff calculations from the collected rainfall. Due to the difficulty and expense of outflow monitoring, peak flow reduction was assessed at one rainwater tree trench, and we saw an average peak flow reduction of 75% across 125 events, as shown in the table below.

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	125	17	14	156
Peak Flow Reduction	79%	63%	61%	75%

Conclusion: The monitoring data indicates that GRI systems can provide the greatest peak flow reductions for minor and normal events, but can also significantly reduce peak flows during major storm events. These results may be complicated by system bypass, which would inflate the observed reductions during extreme events due to lower than expected inflow rates. Future monitoring studies should explore opportunities for inflow monitoring to assess the accuracy of the modelled inflow values.

Next Steps

Moving forward, the monitoring program will continue to monitor existing and newly built assets. New technologies and partnerships will be implemented to further the monitoring program and address additional objectives. Monitoring reports will be published on a bi-annual basis to allow for sufficient data collection and time for analysis. In future years the GRI monitoring program will expand to include additional assets, such as porous asphalt, dry wells, laneway infiltration trenches, and more.

The monitoring program will also expand to assess design variants between GRI systems of the same typology. Bioretention cells, tree trenches, and swales all contain design variants that can impact performance, and understanding the extent of these impacts can help to optimize our designs in the future. Variants to consider include weir design, pretreatment sediment pads and basins, the inclusions of tree species, the presence of curb banding surrounding the system, and the durability of design materials such as perforated pipes, geotextiles, impermeable liners, and soil cells. An example future study might include reducing the outlet flow through capping or applying orifice plates to the underdrain to increase retention.

To overcome the challenges of measuring GRI system inflow to assess the performance objectives related to peak flow attenuation and retention, the GRI branch will use synthetic runoff tests and pre- and post-GRI sewer monitoring. Synthetic runoff tests involve discharging water into the system at a controlled rate and measuring the underdrain outflow and drawdown times. Sewer flow monitoring pre- and post-GRI installation can indicate whether the overall sewershed is impacted due to the presence of GRI.

Planting decisions and plant establishment periods are another GRI component that should be monitored in the future. While the planting and establishment recommendations currently in place are based on existing industry best practices, the recommended plant list and the time is required for these plants to establish successfully should be refined for local conditions.

Monitoring in the future may also include additional objectives, such as assessing sediment loading rates, surface heat reductions, and water quality improvements. A stormwater injection test has been planned for one or more assets to assess sediment and water quality loading, and will be included in a future report.

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. A trial with a local sensor technology company is currently underway, and the City is exploring whether a network of sensors could be connected to LoRaWAN instead of cellular data.

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.

Contents

Figures

Tables

Appendices

1 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, which decreases the volume of runoff directed to the sewer system, reducing combined sewer overflow where the sewers are combined or removing pollutants from stormwater before it is discharged to receiving waters where pipes are separated.

The Rain City Strategy outlines a volumetric target to treat and retain the first 48 mm of each rainfall event within GRI practices, which is approximately equal to 90% of annual runoff volume. By capturing this volume of runoff in each rainfall event, it is equivalent to removing 90% of annual stormwater runoff from entering the sewer system and more closely matches natural hydrology.

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:

- Regulatory Compliance: to ensure that we are improving water quality for downstream receivers, in compliance with regional, provincial and federal standards.
- 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 monitoring that has occurred at GRI assets from 2018 through to June 2021. This report includes the results of flow, water level and soil moisture monitoring at GRI systems installed by the City of Vancouver Green Infrastructure Implementation Branch. The GRI typologies monitored include bioretention systems, bioswales, rainwater tree trenches and infiltration trenches.

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 three 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.

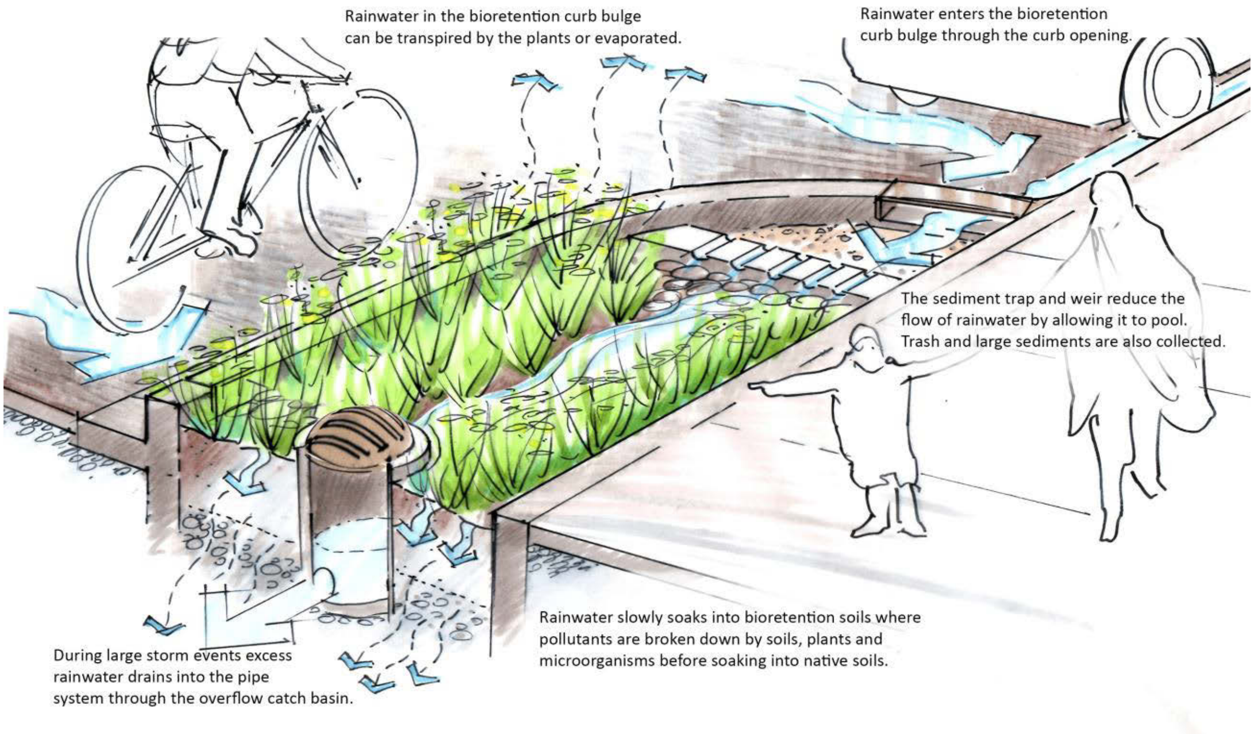


Figure 1 Bioretention schematic, from the Rain City Strategy Appendix B

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.

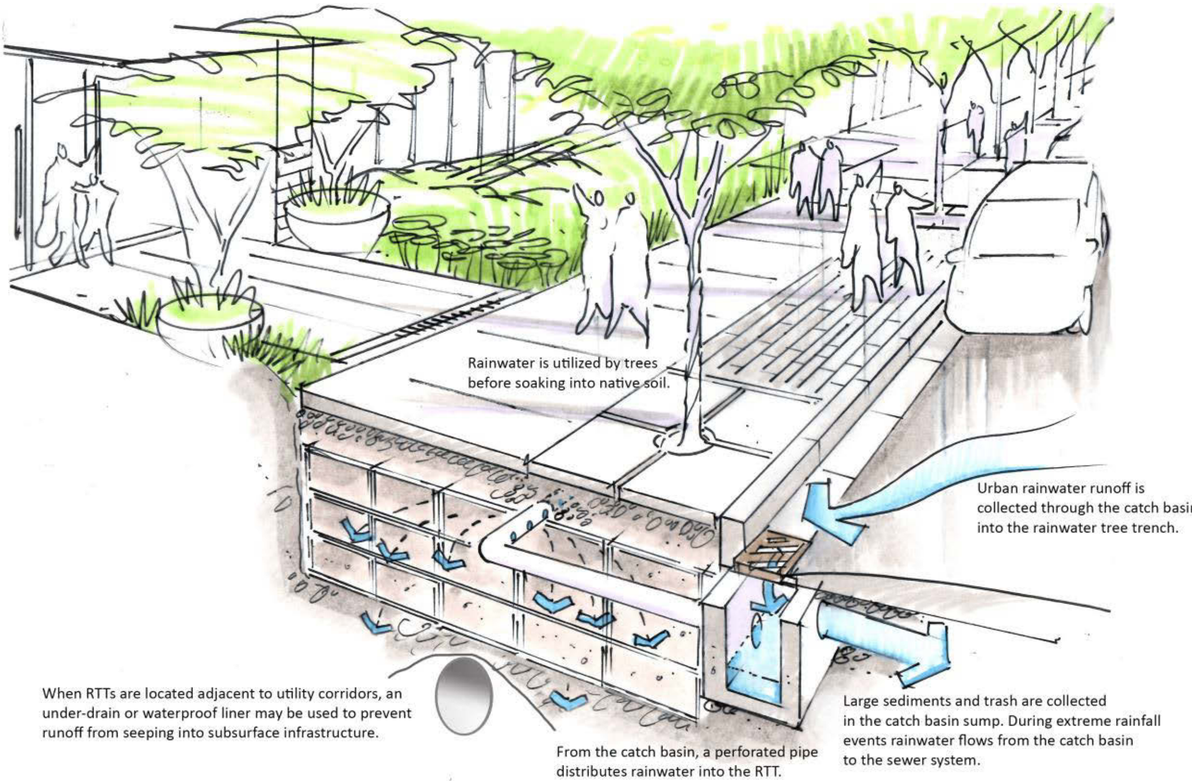


Figure 2 Rainwater tree trench schematic, from the Rain City Strategy Appendix B

Rainwater tree trench: Rainwater tree trenches (RTTs) are multifunctional GRI practices that provide both storage for rainwater and support to street trees. 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.

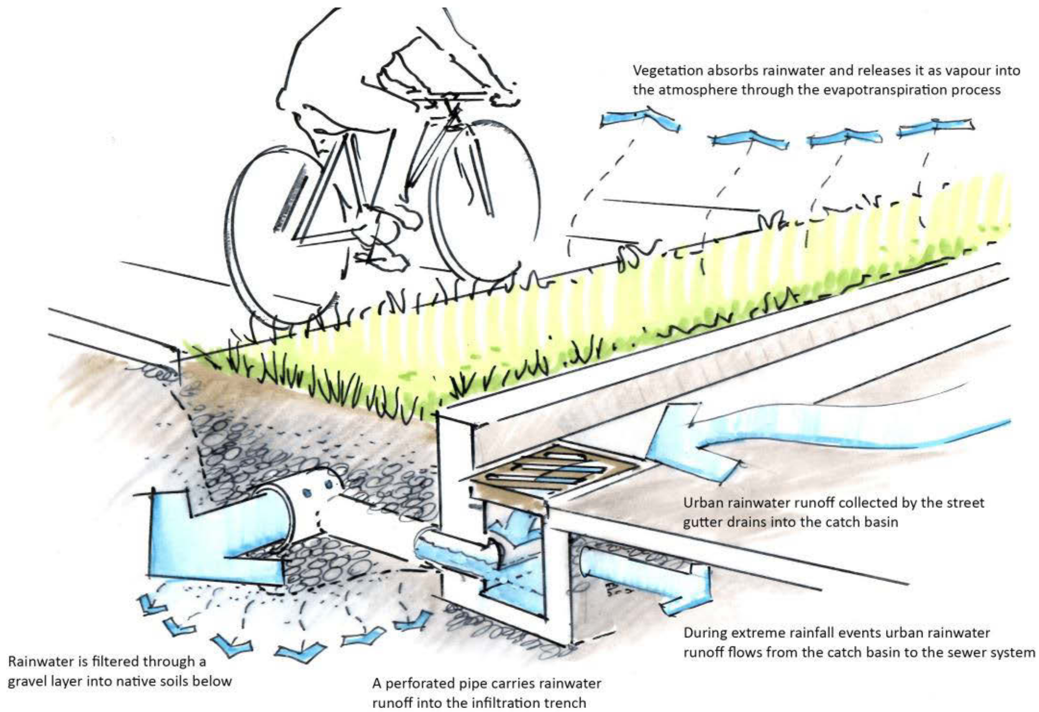


Figure 3 Infiltration trench schematic, from the Rain City Strategy Appendix B

Infiltration trench: 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.

1.2 Monitoring program objectives

The City of Vancouver's GRI monitoring is separated into three types:

Compliance Monitoring: Monitoring to assess if an existing asset is functioning properly and whether it is meeting any applicable regulatory requirements. This involves meeting Liquid Waste Management Plan (which includes implementing the Rain City Strategy goals), Metro Vancouver's Monitoring and Adaptive Management Framework for Stormwater (MAMF) and any permits or agreements (BC Hydro, Vancouver Coastal Health, etc.) that arise.

Performance Monitoring: Monitoring of assets to determine their performance against project objectives. The results will provide lessons learned on assumptions accuracy.

Optimization Monitoring: Monitoring for continuous improvement such as improving the design and materials selected for construction.

A complete list of objectives for the monitoring program are listed in Appendix A. Not all monitoring objectives were addressed in 2018-2021. Most notably, the objective related to understanding water quality and stormwater contaminant load reduction was not completely addressed. An initial study was performed in 2018 that showed water quality concentrations at the inlet and outlet, but did not completely address load reduction due to limitations in monitoring equipment. A study which builds on this is underway in fall 2021, and will be presented in the 2022 monitoring report. The objectives addressed in this monitoring report are as follows:

Compliance 1 (C1): Evaluate surface ponding: should not be ponded for longer than 24 hours. This is a City of Vancouver standard for infiltration systems. Ponding beyond 24 hours is generally unacceptable to the public. It may pose a risk to adults late at night or small children seeking puddles to splash in. While mosquito hatching is a commonly raised concern, mosquitoes need at least 7 days of standing water to develop and hatch.

Compliance 2 (C2): 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.

Compliance 3 (C3): Determine if retention/filtration target is being met. GRI systems are designed to retain or filter 90% of annual runoff volume, equivalent to the 48 mm 24-hr event, to the greatest extent practical.

Performance 1 (P1): Evaluate whether design infiltration rates are matching drawdown rates. The process of determining in-situ infiltration capacity is prone to errors due to the high variability in subsoil conditions and instrumentation used. As such, engineers design conservatively and apply a factor of safety of between 2 and 9 to the measured 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.

Performance 2 (P2): 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.

Performance 3 (P3): Assess peak flow attenuation. Green infrastructure 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 released to receiving bodies of water. For larger rainfall events, the capacity of a GRI system may be exceeded, causing overflow to the sewer system, though a delay in time of concentration and reduced related peak flow is typically observed compared to non-GRI conditions. Assessing the peak flow attenuation will help us to improve our understanding of how GRI works under large and extreme event conditions.

2 Methods

This section describes the sites monitored and the monitoring equipment used for this performance report. Monitoring equipment was installed at six different locations (13 individual systems in total) between 2018 and 2020. The monitoring equipment installation, setup, data collection and analysis procedures are described below. The monitoring equipment types are listed in Table 1.

Table 1 Monitoring equipment type and location of install

Measurement Type	Monitoring Equipment	Location
Water Level	HOBO U-20-001-01	Inside monitoring well
Soil – VWC, EC, Temperature	Teros 12 Moisture Sensor	Sensors in contact with soil
	EM50 Data Logger	Inside pelican box within secure valve box
	ZL6 Data Logger	
Flow	Senix Toughsonic 14 Sensor	Manhole accessing underdrain
	HOBO U22 Logger	

2.1 Rainfall data collection

The City of Vancouver has a tipping bucket rain gauge network set-up across the city (Figure 4). Raw rainfall data is available at 5-minute intervals from the nearest rain gauge to each site and is downloaded through FlowWorks. 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: ≤24mm;
- Large Event >24mm & ≤ 48mm; and
- Extreme Event >48mm

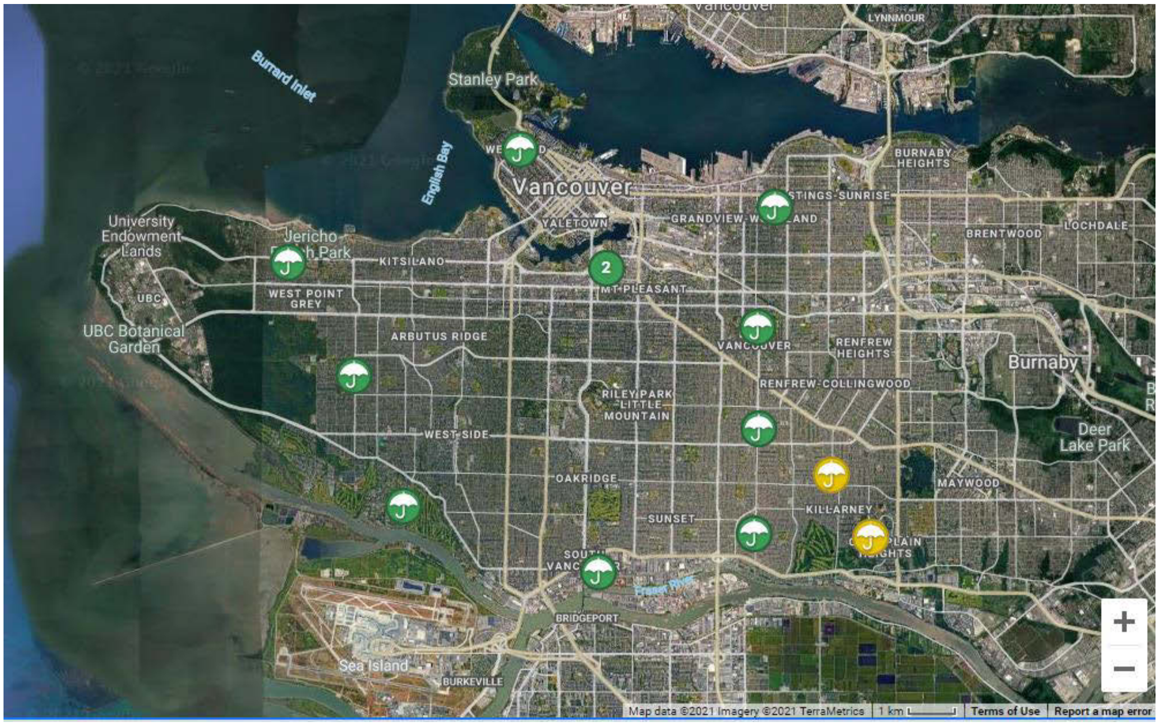


Figure 4 City of Vancouver Rain Gauge network (FlowWorks, 2021)

2.2 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 were 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 were wrapped in a geotextile to prevent any sediment from entering from the nearby media. A cap covered the well, and the entire structure is surrounded by a valve box with a bolted lid to prevent any theft or vandalism.

Onset HOBO U20-001-01 water level loggers are the only style of pressure transducer that have been used to date for water level measurements. The loggers were installed in the monitoring well post-construction by suspending the logger in the well with a non-stretch rope. The logger was not placed directly on 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. The loggers are set to record pressure measurements at 5-minute intervals, which allows the logger to hold 75 days of data before overwriting existing data occurs.

The loggers that are currently used 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 was installed inside the well (Figure 5). Data was offloaded from the loggers manually using an optic USB Base station and coupler every 4-6 weeks. Data was offloaded from the shuttle using HOBOware Pro software, which also performs the barometric compensation. The data was then exported to Excel where it is plotted with rainfall to determine where water level changes occurred and locate any outliers in the data set.

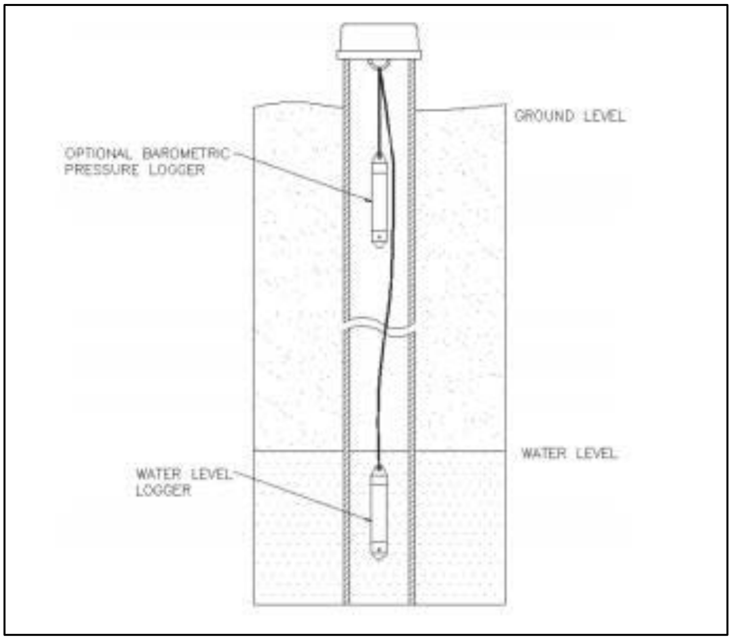


Figure 5 Schematic of HOBO water level logger installation inside a monitoring well (Onset, 2012)

Each individual storm event and water level change was analyzed to determine the well flood duration, drawdown rate and drawdown time. Well flood duration is the total time of rainfall response within the monitoring well. Drawdown duration is the time between peak water level and the return to the water level before the rainfall event (Figure 6). Drawdown rate is defined as the rate at which water exits the bioretention system duration 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.

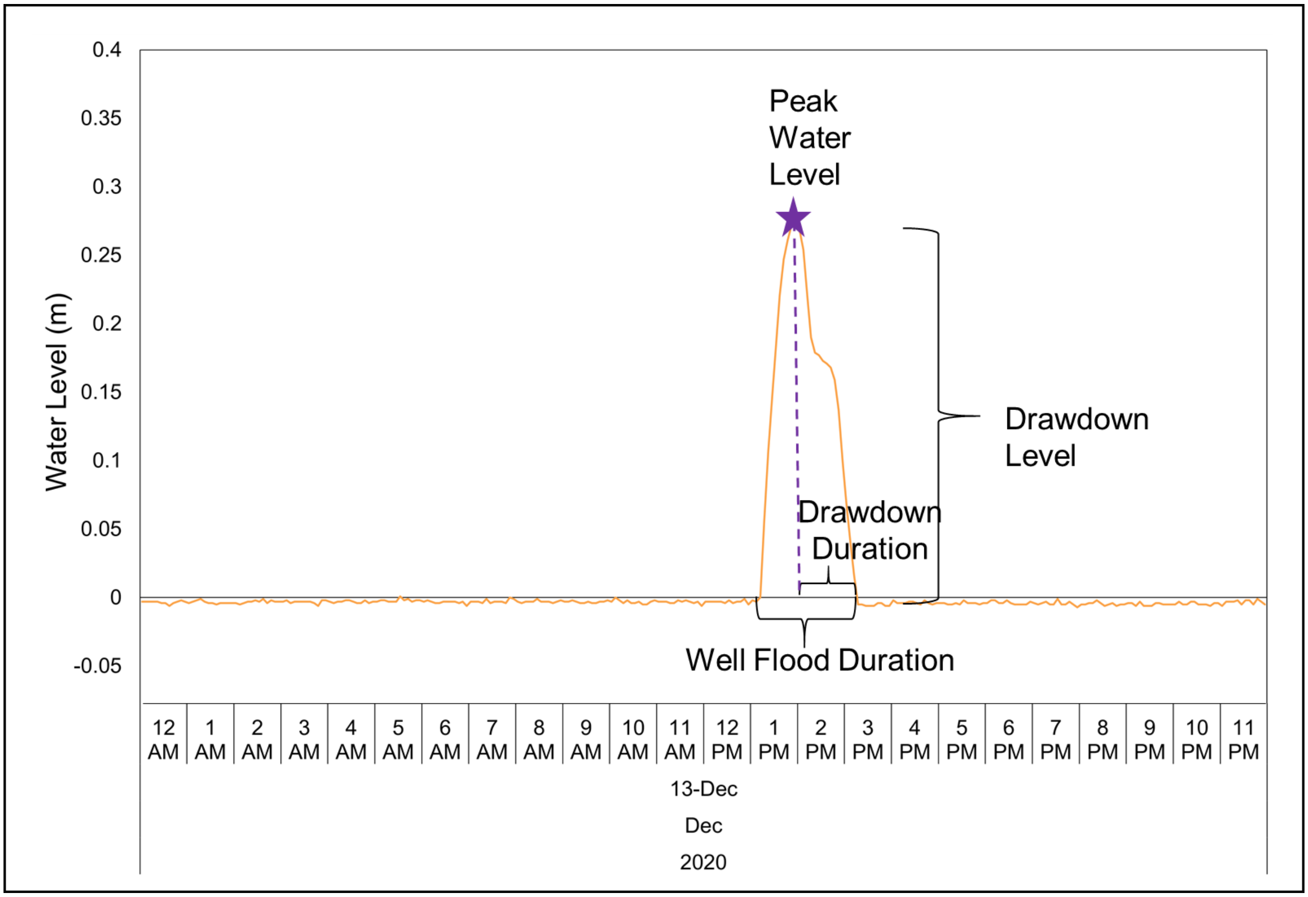


Figure 6 Example of water level response to show calculation of well flood duration, drawdown duration and drawdown rate.

2.3 Soil monitoring

To monitor the soil moisture, temperature and electrical conductivity, TEROS 12 soil sensors were used. They consist of three prongs that were inserted into the soil and 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 lead 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 to prevent any damages from occurring and the entire system is locked inside the valve box. The data logger was 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 was collected approximately every 12-16 weeks and regular maintenance of batteries were performed. Upon collection, each parameter is plotted with rainfall to determine any trends or locate any outliers in the data set.

2.4 Flow monitoring

Due to the nature of the design of GRI practices, there are many constraints such as the varying size and shape of inlets and the security of equipment in an urban landscape that make measuring inflow extremely difficult. As such, inflow was modelled using PCSWMM, catchment parameters for the drainage area, and rainfall data as described in Section 2.1. This method however does come with limitations, as the model assumes no bypass and can lead to an overestimation of inflows into the systems. Outflow was monitored in the underdrain of the system using an ultrasonic sensor. The sensor was connected to a data logger and set to record measurements at 5-minute intervals. Experimental rating curves of the flow in the underdrain relating the sensor measurements to discharge were developed prior to installation of equipment to use in the analysis of flow volume, peak reduction and lag time to the sewer system. For a detailed description of the rating curve experiment, refer to “Green infrastructure in the City of Vancouver: performance monitoring of stormwater tree trenches and bioswales” by Osvaldo Vega.

2.5 Water quality monitoring

Several opportunistic samples were taken at sites with flow monitoring equipment installed in the winter of 2018-2019, though due to the difficulty of timing sample collection and actual flow from outlet underdrains, only five samples from three sites were collected. A second attempt at sample collection occurred in the winter of 2020-2021, and no samples were able to be collected due lack of outflow. The methodology and results of the limited water quality monitoring are presented in Appendix B.

2.6 Observational monitoring

Through condition and visual assessments that track items such as clogging at the inlet, settlement of media, areal coverage of plants, number or percentage of plants alive/dead, etc., we can compile information from all installed assets to inform the GRI design team and local engineers/designers on best practices and methods.

Visual assessments were performed during monitoring equipment checkups, during occasional very heavy wet events, and 24 hours after an event greater than 48 mm, when possible.

2.7 Monitoring sites

13 sites were monitored between 2018 and 2021 and presented within this report. A summary of the equipment, monitoring type, monitoring sites, length of time for monitoring, and the location of the nearest rain gauge are presented in Table 2. Full site descriptions are included with the results in Section 3.

Table 2 Monitoring methodology summary

Site Location	Typology	Managed Impervious Area (m^2)	Design Infiltration Rate (mm/h)	Monitoring Type: Water Level	Monitoring Type: Soil (depth)	Monitoring Type: Flow	Monitoring Length	Rain Gauge Location
Yukon St. & 63rd Ave.								
North	Bioswale	442	39	x			July 2018-Present	Manitoba Yards Rain Gauge, 585 m south of site
East	Bioretention Cell	732	39	x			July 2018-Present	
Quebec St. & 1st Ave.								
Location C	RTT- Structural Soil	415	10		20 cm, 40 cm, 60 cm	x	September 2018-Present	Creekside Rain Gauge, 260 m NW of site
Location D	Bioswale	630	10	x	20 cm, 40 cm		September 2018-Present	
Location E	Bioswale	270	10	x			September 2018-Present	
Quebec St. & 2nd Ave.								
	RTT - Soil Cell	610	10	x	60 cm		March 2020-Present	Creekside Rain Gauge, 380 m NW of site
Expo Blvd. & Smithe St.								
	RTT - Soil Cell				20 cm, 40 cm		September 2020-Present	Creekside Rain Gauge 800 m SE of site
Richards St.								
Block A	RTT - Soil Cell	1409	3	x	90 cm		November 2020-Present	Creekside Rain Gauge 1.3 - 1.35 km SE of all blocks
Block B	RTT - Structural Soil	1482	10	x	90 cm		November 2020-Present	
Block C	RTT - Soil Cell	1386	10	x	90 cm		November 2020-Present	
Block D	RTT - Soil Cell	1332	10	x	90 cm		December 2020-Present	

Table 2 (Continued)

Site Location	Typology	Managed Impervious Area (m^2)	Design Infiltration Rate (mm/h)	Monitoring Type			Monitoring Length	Rain Gauge Location
				Water Level	Soil (depth)	Flow		
Burrard St. & Cornwall Ave.								
North	Infiltration Trench	663	5	x			March 2018-May 2019	Vancity Rain Gauge, 2.5 km SE of sites
South	Infiltration Trench	396	5	x			February 2018-May 2019	

3 Results by Monitoring Site

3.1 Yukon St. & 63rd Ave.

The bioretention practice located at West 63rd Avenue and Yukon Street is a City of Vancouver Green Infrastructure led and designed project constructed in 2018. The location was highlighted in the Marpole Community Plan and features a rain garden and bioswale to manage rainwater run-off, 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. 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.

The design of the practice includes two monitoring wells; one located in the North bioswale and one located in the East bioretention practice. Water level loggers were installed in the monitoring wells in July 2018. After collecting data for several months, in-situ barometric loggers were added in each well in November 2018 to improve the accuracy of the readings. Monitoring in the North practice is on-going and monitoring in the East practice ceased in July 2021.

The North bioretention monitoring well is functional and collects regular data on drawdown rate, time and water level. The East bioretention monitoring well did not see any water level response, as verified by field reports during rain events that showed no ponding inside or around the monitoring well. We anticipate that the lack of water level response is due to the location of the monitoring well within the East bioretention system. The East bioretention consists of three terraced sections separated by weir walls, and the monitoring well is located in the most-downstream terrace, furthest from the inlet. The drawdown rate at the East cell may be so fast that water does not overflow from the top terrace into the two terraces downstream. Results for the East cell are therefore not presented here.

Sustained rainfall amounts and rainfall intensity above 5 mm/h would generate a water level response at the Yukon St & 63rd Ave system. The north monitoring well generally demonstrated drawdown within a few hours and drawdown rates above 300 mm/h. The water level monitoring results from the 2020-2021 wet season are shown on Figure 7. The system was monitored throughout 2018-2021 as well, however there are with intermittent data outages and the whole monitoring period is not shown in graph format. Between 2018 and 2021, 52 rainfall events produced a water level change for which the well flood duration, drawdown time and drawdown rate were calculated and compared to the design infiltration rate, as shown in Table 3.

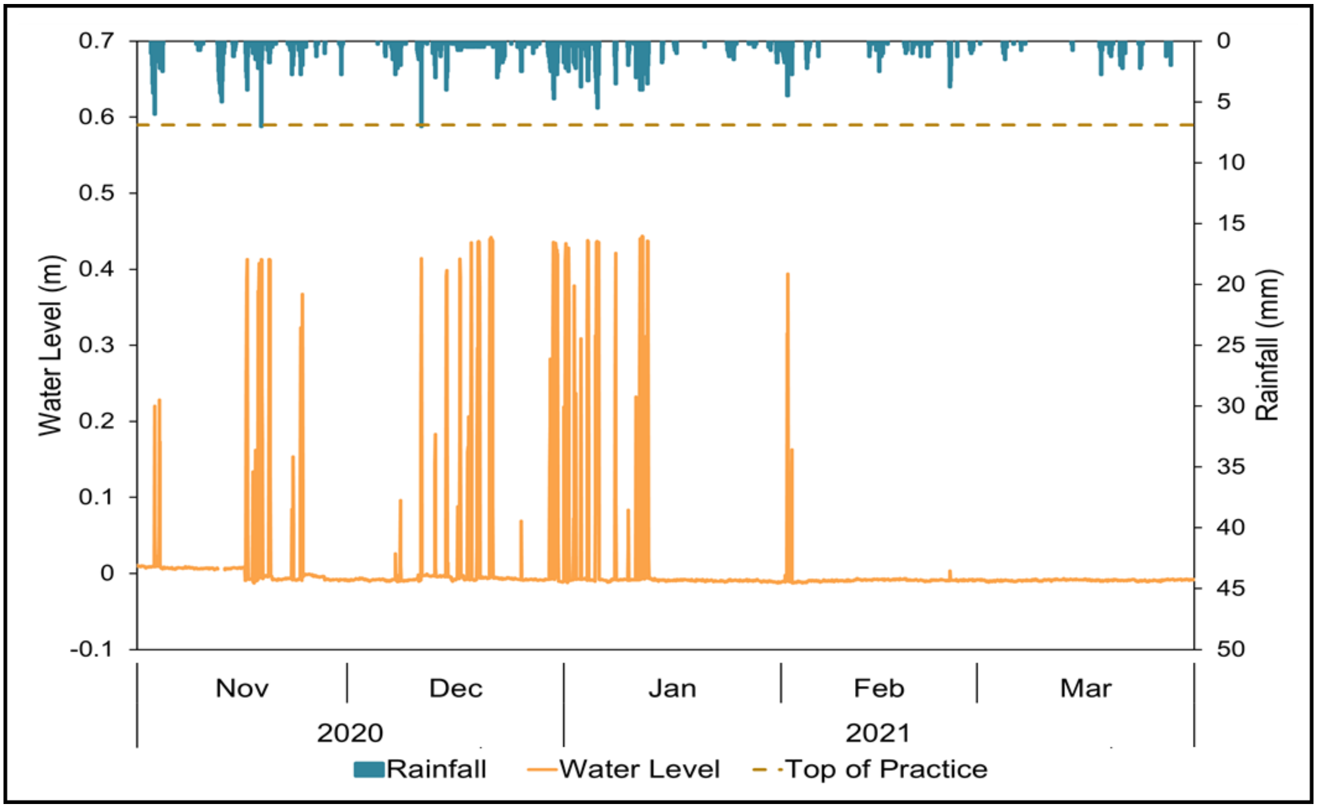


Figure 7 Yukon & 63rd hourly average rainfall and water level response.

Table 3 Yukon & 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	31	12	9	52
Storm Duration (h)	13.2	28.8	51.0	23.3
Antecedent Dry Period (hr)	23.6	33.8	15.4	24.5
Well Flood Duration (h)	2.9	5.2	7.6	4.2
Drawdown Duration (h)	1.0	1.3	3.9	1.6
Drawdown Rate (mm/h)	374	389	316	367
Design Infiltration Rate (mm/h)	39			
% change	859%	897%	710%	841%

During rainfall events, we observed that runoff from the contributing drainage area (63rd Ave, Yukon St) was completely captured by the bioretention system. The system draws down quickly so that ponding does not stay at the surface for longer than the duration of the rainfall event, and surface ponding only occurs during large events. The vegetation at this site has established well, though maintenance was required frequently following installation due to an excessive amount of ‘Morning Glory’ and local asters growing larger than 0.6 m tall. Maintenance is done four times per year and includes vegetation cutback and clearing inlets. An extra round of maintenance was required in August in response to a resident complaint about the excessive growth of ‘Morning Glory’. The system was also inspected following a large rain events, and 24 hours after a rain event had stopped and ponding at the surface was not observed, which meets our objectives. Photos from wet and dry weather inspections are shown below.

Dry weather inspections at Yukon & 63rd bioretention system, July 2021

Wet weather inspections at Yukon & 63rd bioretention system, September 2021

3.2 Quebec St. & 1st Ave.

As part of the Quebec St. precinct upgrades, 6 new GRI practices were constructed along Quebec St in the Southeast False Creek neighbourhood in 2018 (Figure 8). Monitoring is occurring at three of the six practices – 2 bioswales (Location D and Location E) and one structural soil rainwater tree trench (RTT) (Location C).

Location C, a RTT, include soil moisture monitoring and flow monitoring. Location D has soil moisture and water level monitoring, but did not have any water level response during the monitoring period (likely due to poor siting of the well within the bioswale). Location E had only water level monitoring, and, similar to Location D, water level response in the monitoring well was not observed. Installation and initial monitoring were performed as part of a Master's Thesis entitled: "Green infrastructure in the City of Vancouver: performance monitoring of stormwater tree trenches and bioswales" by Osvaldo Vega.

The 5 bioswales (Locations A, B,D, E, and F) are under maintenance contracts, which involves plant replacement when necessary, watering plants during extended dry periods, and clearing of sediment at inlets. Sediment buildup at these sites is quite heavy, and so clearing inlets was required at the three maintenance visits. The inlets at these sites were an early design that has since been revised to ensure that sediment clearing is easier for maintenance crews.

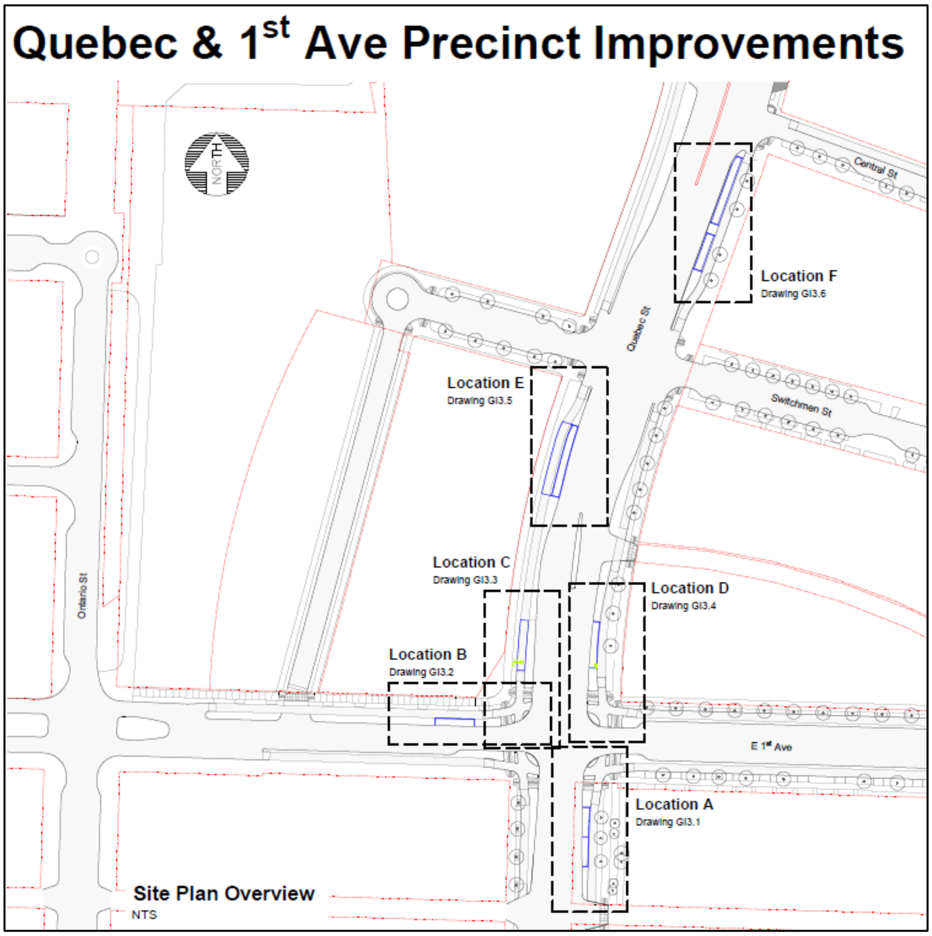


Figure 8 Monitoring locations at Quebec St. & 1st Ave.

3.2.1 Location C

Location C RTTs manages stormwater runoff from a drainage area of 415 m^2 and was sized with a design infiltration rate of 10 mm/h. 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. Flow monitoring was also installed at this location in the manhole connected to the underdrain of the tree trench in November 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 27%-40%, and the 20-cm depth varies between 28-33%. Generally, the 60-cm sensor displays a slightly higher moisture content, except over the 2020-2021 wet season in which they reversed. 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 volumetric water content for the entire monitoring period along with several data gaps are shown in Figure 9.

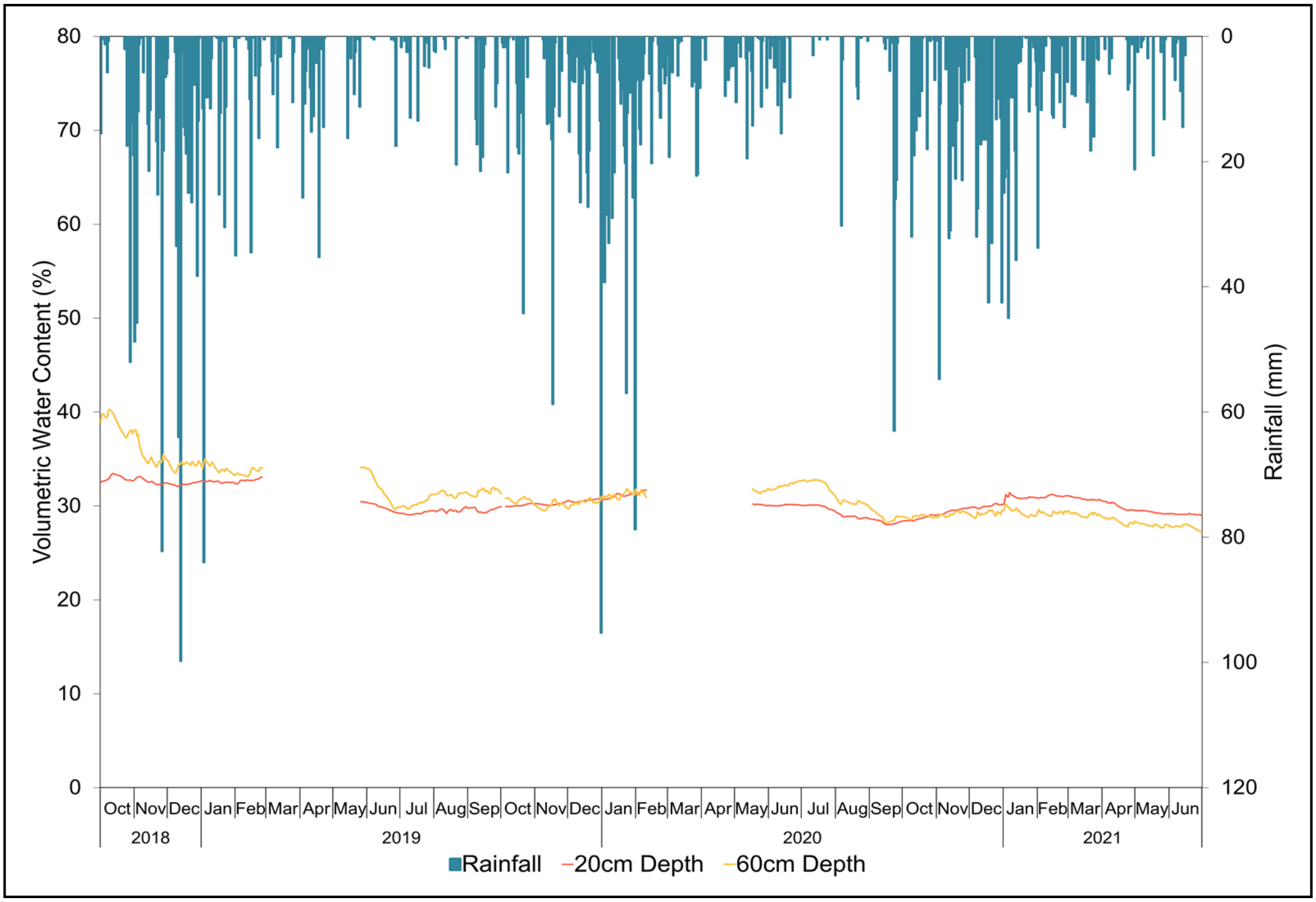


Figure 9 Daily average of rainfall and volumetric water content at 20-cm and 40-cm depth at Quebec & 1st Location C

Location C is the only RTT installation with flow monitoring equipment. Flow monitoring occurred between November 2018 and June 2021, with a data outage due to sensor error between October 2020 – March 2021. A total of 156 events were monitored, with results for normal, large and extreme events shown in Figure 10 and Table 4. Events with low intensity did not produce outflow, and during the monitoring period 13 events with average intensity less than 8.75 mm/h did not have any outflow. This RTT was able to retain (infiltrate or evapotranspirate) more than 1,000,000 L of stormwater runoff during the monitoring period.

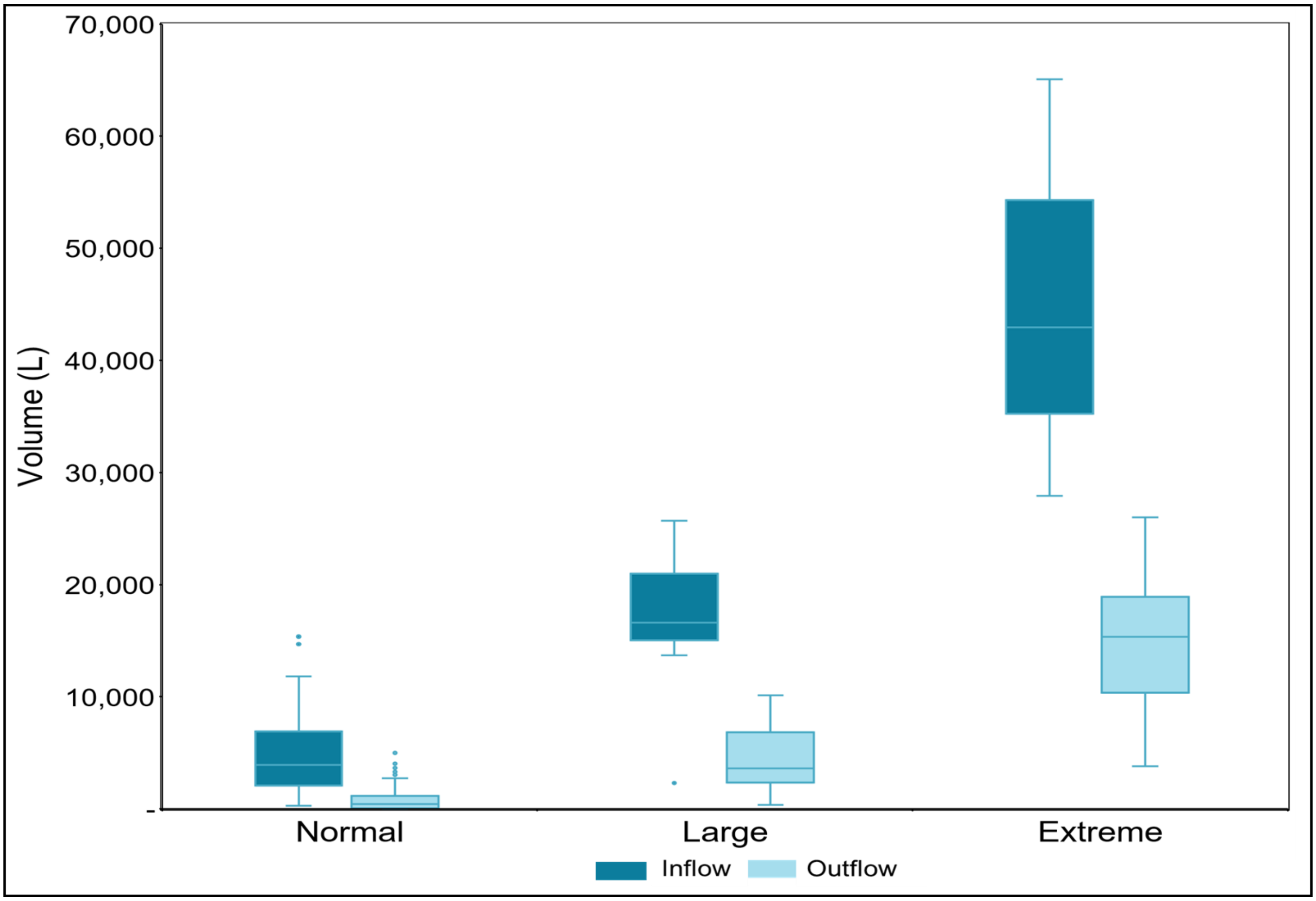


Figure 10 Boxplots of inflow and outflow volumes for different size storm events at Quebec & 1st Location C RTT

Table 4 Quebec & 1st Location C RTT flow monitoring results

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	125	17	14	156
Storm Duration (h)	10.9	22.9	41.7	15.0
Antecedent Dry Period (h)	55.6	58.8	31.1	53.8
Total Inflow Volume (L)	601,437	296,595	625,169	1,523,201
Total Outflow Volume (L)	98,844	78,185	210,056	387,085
Average Retention (mm)	10	31	71	18
Volume Reduction	87%	75%	67%	84%
Peak Flow Reduction	79%	63%	61%	75%
Lag Time (hr)	2.4	3.5	2.5	2.6

Note: All parameters are average for the category of rainfall event, and weighted average is using the weight of the number of storm events per category. Average retention (mm) was calculated as the average retention (L) divided by the drainage area (415 m^2).

3.2.2 Location D

Location D bioswale manages stormwater runoff from a drainage area of 630 m^2 and was sized with a design infiltration rate of 10 mm/h. 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. 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. Flow monitoring was also installed in the manhole connected to the underdrain of the bioswale in November 2018. However, backwater issues rendered the data unusable at this location and flow monitoring was discontinued.

The monitoring well at Location D only demonstrated water level increases during five events over its monitoring period. The rainfall events required to produce a response in water level were greater than 19 mm, and had high intensities. Even with these high-intensity storm events, water level responses were minor and were generally observed to be less than 10-cm. We think the lack of response is due to the siting of the well and due to fast drawdown times within this system. The monitoring well was located far from the normal inlets, and due to rapid infiltration rates, it was hypothesized that water does not extend horizontally to include the monitoring well, and instead drains vertically beneath the system. This was verified using visual observations during large storm events. Ponding could be seen at the inlet, but ponding in the cell did not extend along the surface to near where the monitoring well was located.

Photo of inlet ponding at Quebec & 1st Location D during rain event

Both soil sensors installed in the bioswale are functional and provide data on volumetric water content, electrical conductivity and temperature since October 2018. 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 5-40% 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 2020-2021 monitoring period is an exception to this, where the moisture levels were similar to each other over the dry periods, and then the moisture at 20-cm was higher over the wet season. The pronounced seasonal variation compared to the other sites is likely influenced by the GRI typology. Being in a bioswale, the sensors 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 11.

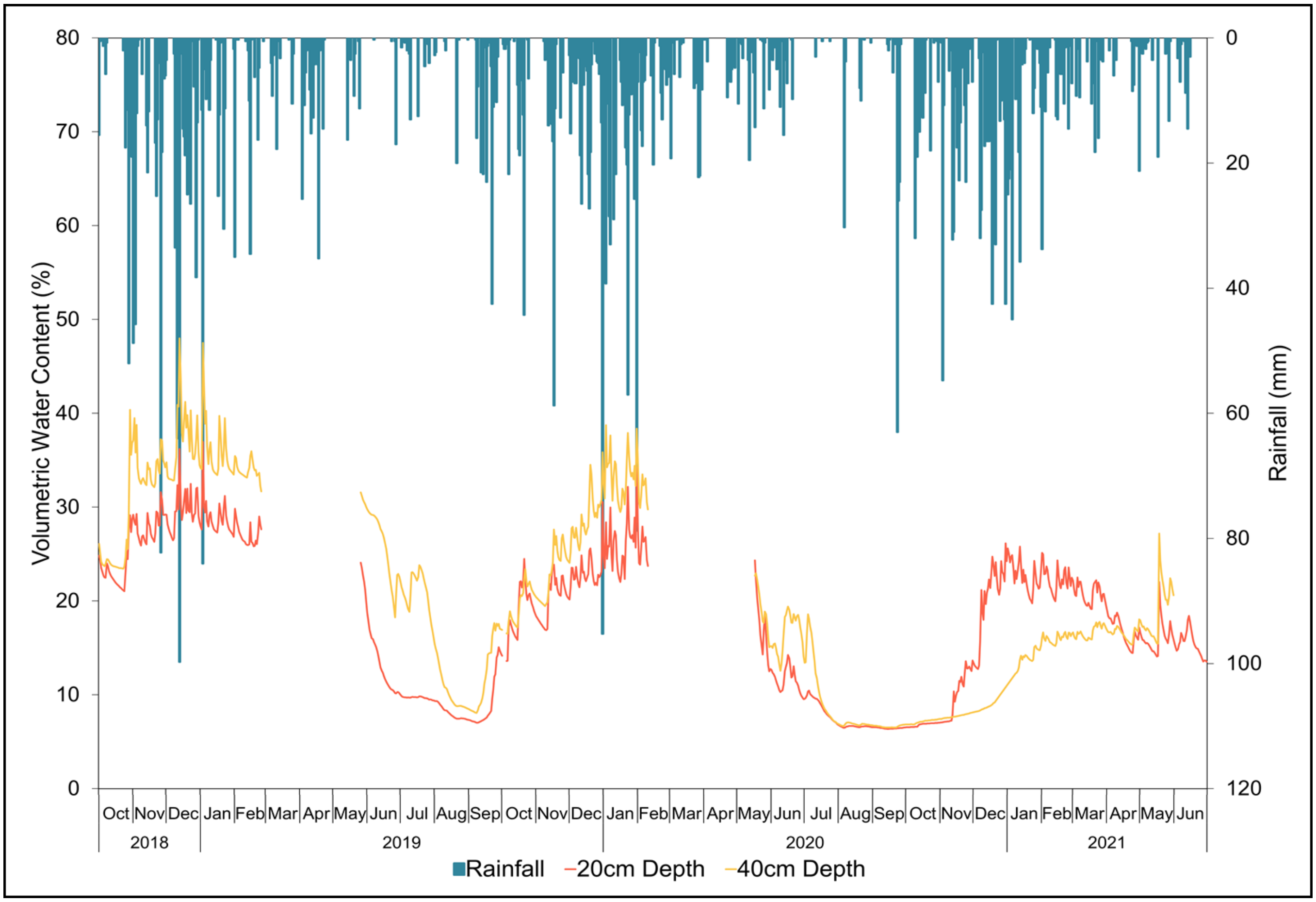


Figure 11 Daily average volumetric water content at 20-cm and 40-cm depth in Location D bioswale

3.2.3 Location E

Location E bioswale manages stormwater runoff from a drainage area of 270 m^2 and was sized with a design infiltration rate of 5 mm/h. Location E 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. Flow monitoring was also set-up at this location in the manhole connected to the underdrain of the bioswale in November 2018. However, due to a high level of background noise with the sensor, the data from this sensor has not been used.

The bioswale at Location E did not see any water level changes throughout its monitoring period as verified by no response seen in the logger data, and field observations during rain events. Location E is oversized compared to its drainage area (see Table 2), and the location of the monitoring well is at the far end of the bioswale, near the outlet. We suspect that there is not enough rainfall that reaches the monitoring well to produce a response.

3.3 Quebec St. & 2nd Ave.

The Quebec & 2nd GRI practice is part of the second phase of precinct upgrades along Quebec St constructed in 2019 . The GRI practice consists of soil cell RTTs that manages a drainage area of 610m^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 to the south of the practice each with water level loggers that were installed in March 2020. The South portion of the practice also contains a soil sensor that measured volumetric water content, electrical conductivity and temperature that was installed during construction. A data logger was connected to the soil sensors in September 2020.

3.3.1 North RTT

The North RTT monitoring well contained standing water at all times over the course of the monitoring period, however the water level has never reached the top of the well. This well displays water level changes with every rainfall event. An entire wet season has not been recorded at this location. Water levels changes for the 2020-2021 monitoring period are shown in Figure 12. 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.

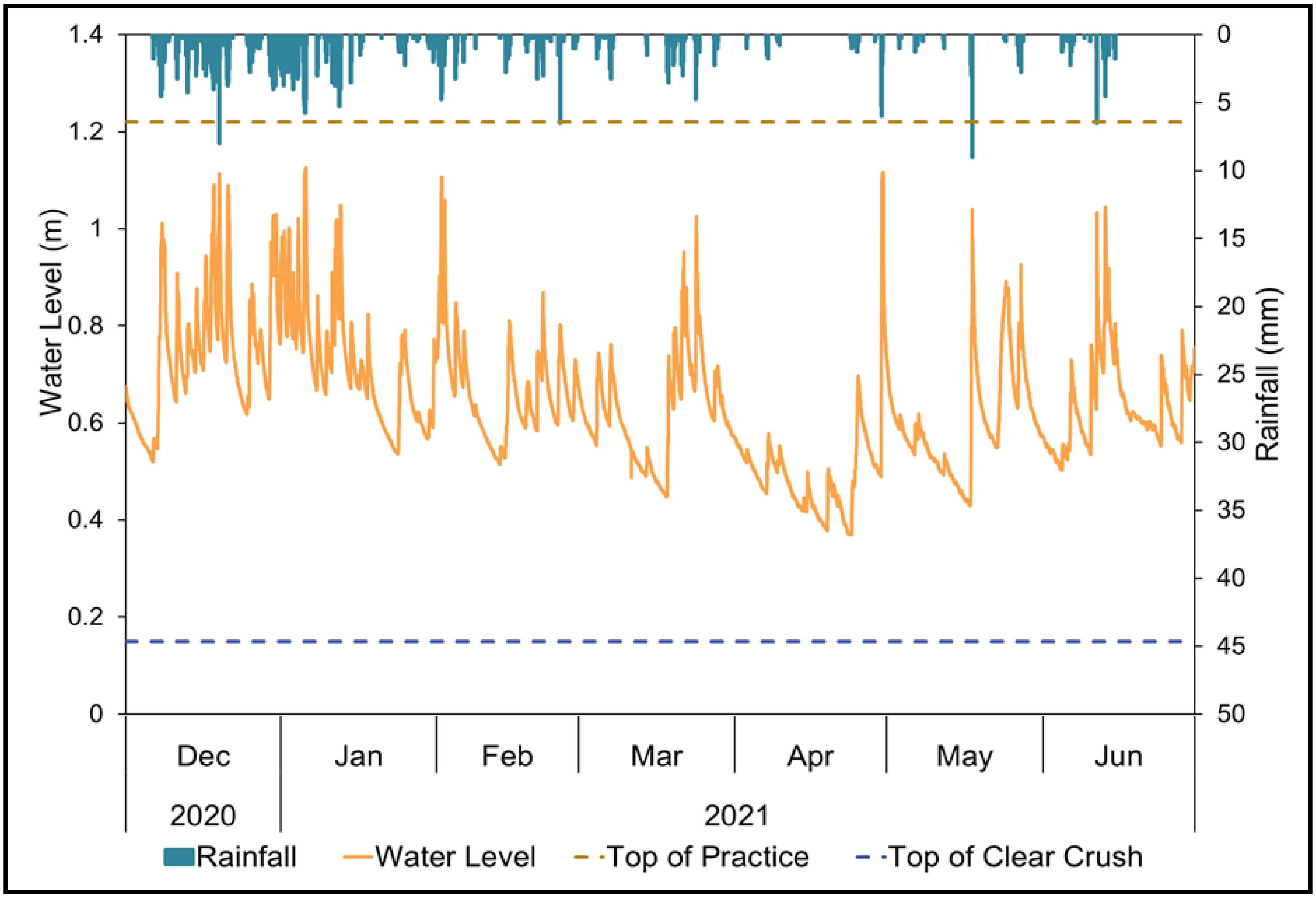


Figure 12 Quebec & 2nd North hourly average rainfall and water level response

The North well displays high drawdown durations and overall infiltration rates that are under-performing compared to the design infiltration rate. During the 2020-2021 monitoring season, 67 events produced a water level change. The drawdown duration, drawdown rates and comparison between design infiltration rate are shown in Table 5.

Table 5 Quebec & 2nd 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	56	9	2	67
Storm Duration (h)	11.9	23.1	37.2	14.2
Antecedent Dry Period (h)	45.3	14.5	25.5	40.5
Well Flood Duration (h)	34.7	38.8	70.6	36.3
Drawdown Duration (h)	27.3	26.0	37.5	27.4
Drawdown Rate (mm/h)	7	16	10	8
Design Infiltration Rate (mm/hr)	10			
% change	-30%	60%	0%	-20%

3.3.2 Middle

Similar to the North well, the middle RTT monitoring well contained standing water at all times over the course of the 2020-2021 monitoring period. The level of standing water in the well is less than the north well and a water level response was seen at with every rainfall event. An entire wet season has not been recorded at this location. Water levels changes for the 2020-2021 monitoring period are shown in Figure 13.

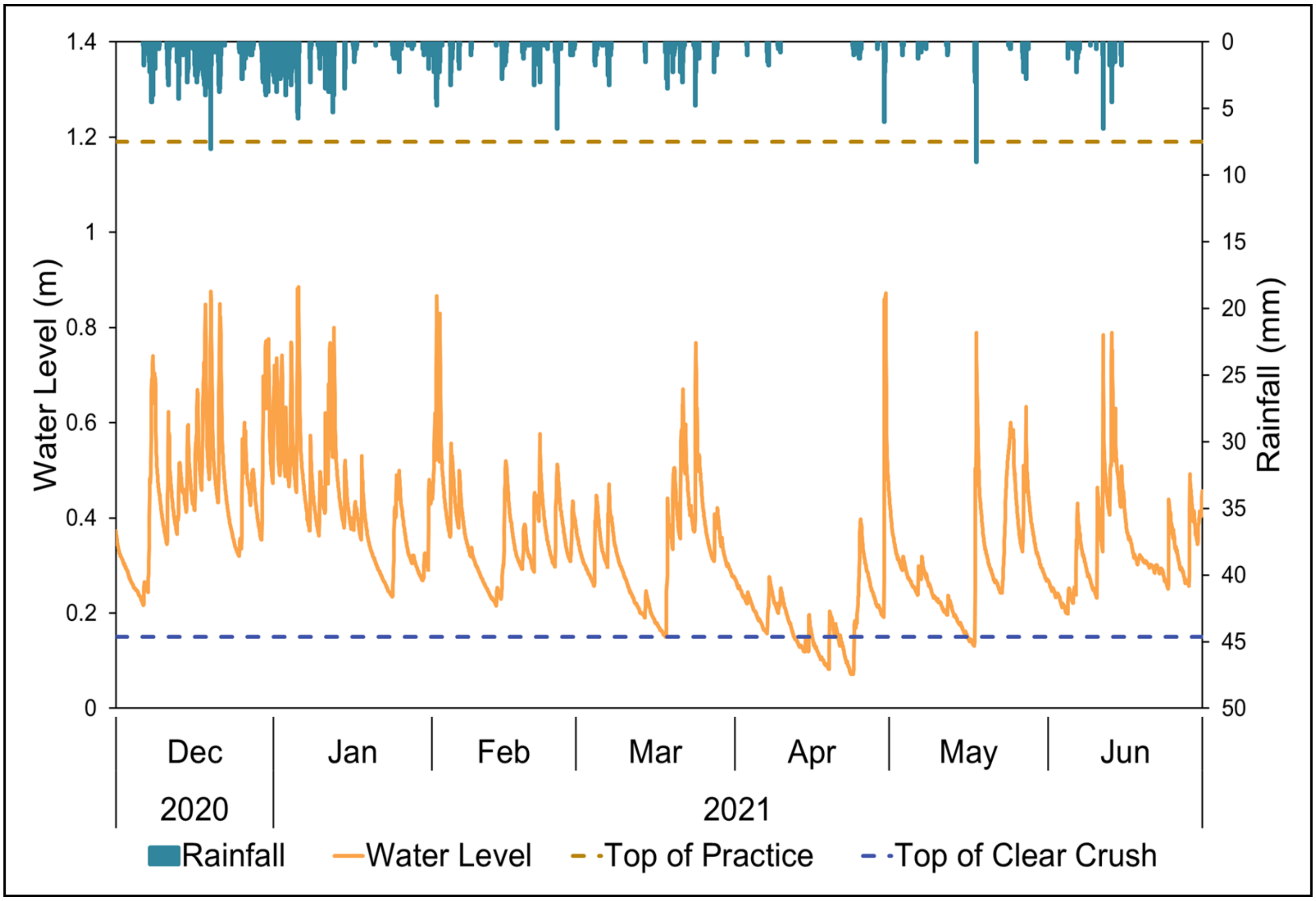


Figure 13 Quebec & 2nd Middle hourly average rainfall and water level response

Over the course of the 2020-2021 monitoring period, 67 rainfall events produced a water level response in the well. The drawdown durations were generally greater than 25 hours and the infiltration rate overall was less than the design infiltration rate. Storm events, drawdown times and comparison to design infiltration rate are shown in Table 6.

Table 6 Quebec & 2nd Middle 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	56	9	2	67
Storm Duration (h)	11.9	23.1	37.2	14.2
Antecedent Dry Period (h)	45.3	14.5	25.5	40.5
Well Flood Duration (h)	36.3	42.3	70.7	38.1
Drawdown Duration (h)	28.5	25.3	43.6	28.5
Drawdown Rate (mm/h)	7	19	11	9
Design Infiltration Rate (mm/h)	10			
% change	-30%	90%	10%	-10%

3.3.3 South

Compared to the North and Middle RTTs, the South RTT monitoring well drained completely and was dry at times over the course of the monitoring period. Several smaller rain events that produced a water level change in the North and Middle well did not produce a response in the South well. An entire wet season has not been recorded at this location. Water levels changes for the 2020-2021 monitoring period are shown in Figure 14.

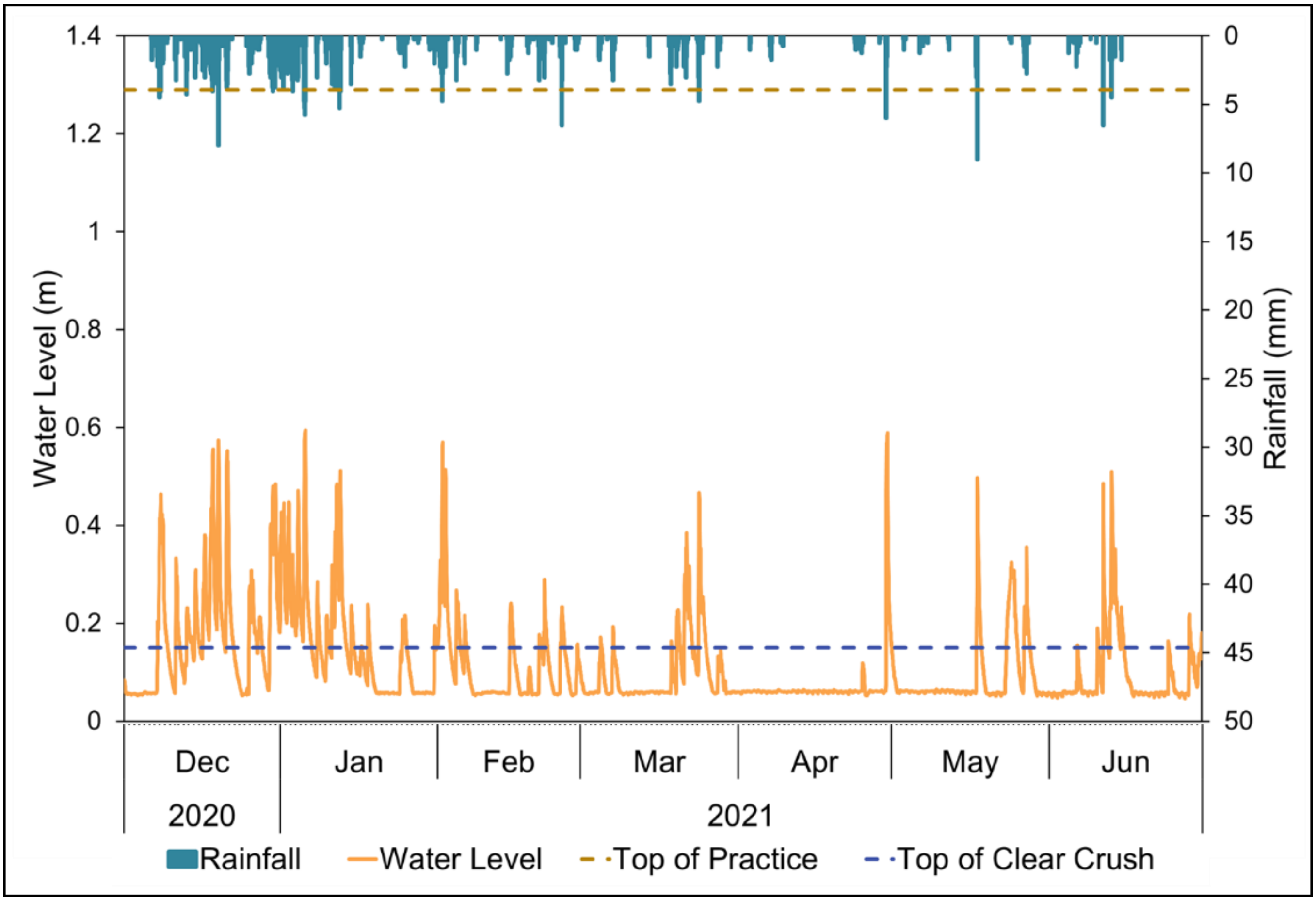


Figure 14 Quebec & 2nd South hourly average rainfall and water level response

Over the course of the monitoring period, 56 events produced a water level change with drawdown durations generally being greater than 20 hours. Overall the drawdown rate is slightly under-performing compared to the design infiltration rate. Storm events, drawdown duration and times and comparison to design infiltration rates are shown in Table 7.

Table 7 Quebec & 2nd 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	46	8	2	56
Storm Duration (h)	13.0	23.0	37.2	15.3
Antecedent Dry Period (h)	32.5	14.9	25.5	29.7
Well Flood Duration (h)	28.8	38.0	68.3	31.5
Drawdown Duration (h)	22.2	23.2	37.6	22.9
Drawdown Rate (mm/h)	8	19	11	10
Design Infiltration Rate (mm/h)		10		
% change	-20%	90%	10%	0%

All three 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, the wells show a water level change when no rainfall event has occurred. During site visits it has been noted that upstream construction is occurring and water from the construction sites has been seen entering the catch basins for this system. This could also explain the introduction of additional sediment that might be clogging the geotextile.

3.3.4 Soil moisture RTT and non-RTT

Comparing the soil moisture in a RTT and a tree trench that did not receive stormwater, the RTT responded rapidly to rainfall events, and overall had higher moisture content in the winter and summer months. A soil moisture sensor is located in the south RTT and provided data on volumetric water content, electrical conductivity and temperature over the 2020-2021 period. A soil sensor was also installed one block north, in a non-GRI tree trench for comparison. The GRI soil sensor was very reactive to rain events, and soil moisture ranged between 25-50%. The GRI RTT had extended periods of near saturation (50% water content) which corresponds with the water level response seen in the monitoring well. The non-GI soil moisture is less reactive in the wet season, remaining at a fairly constant condition of 30%-40%. In the dryer season, the non-GI system quick loses moisture and drops to a level near 10% (Figure 15). The GRI sensor was installed under the bike path and thus has no contact with the elements that may cause moisture loss. The non-GRI soil sensor is fairly shallow (30-cm) and located in the open soil of the tree trench, allowing for a more direct contact with rainfall as it occurs, and more chance of soil evaporation.

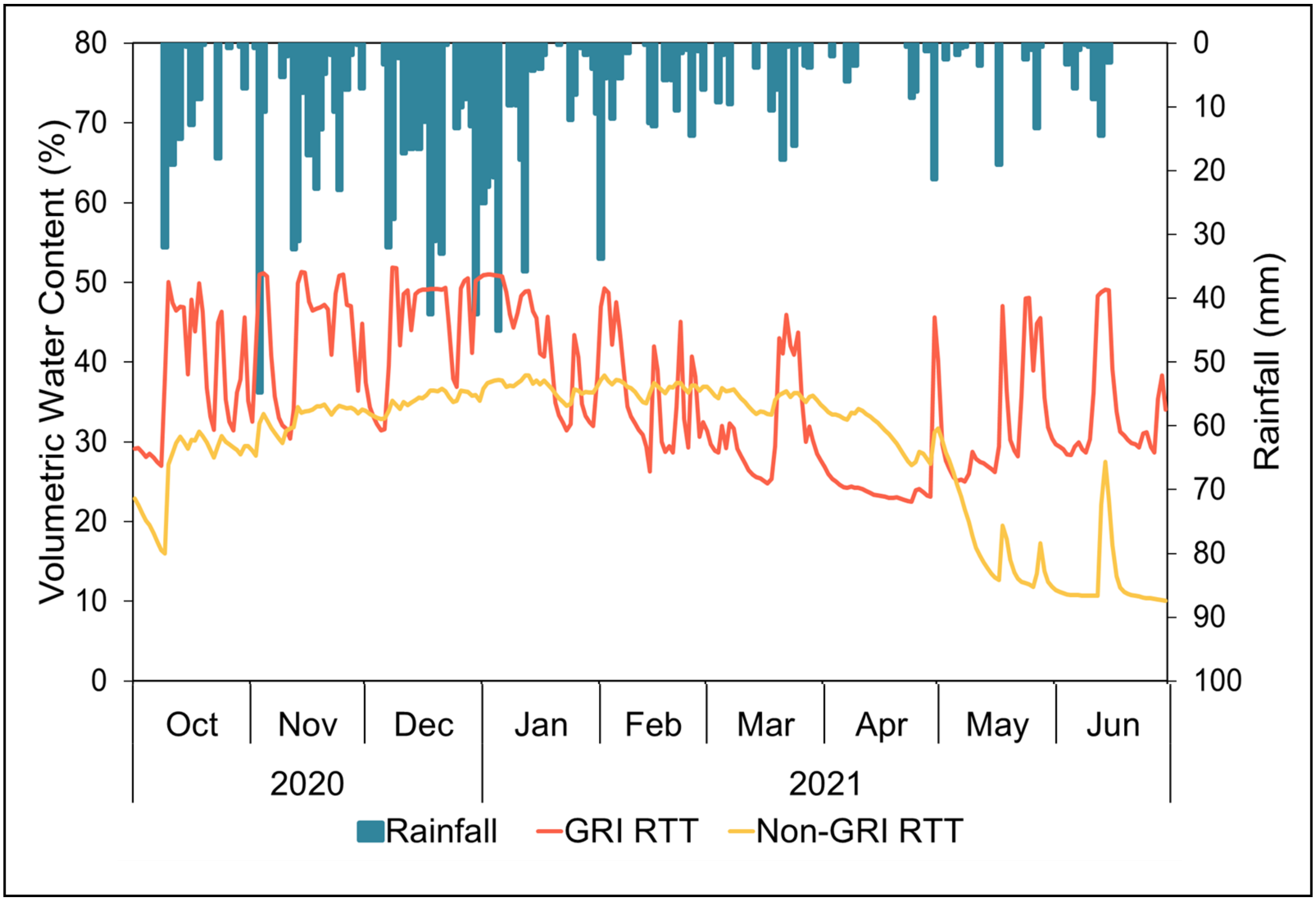


Figure 15 Quebec & 2nd GRI RTT and non-GRI RTT daily average volumetric water content

3.4 Expo Blvd. & Smithe St.

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 showed that the RTT technologies maintained water contents in healthy ranges to support tree health. The volumetric water content in the soil varied between 20% and 60% for the 2020-2021 monitoring period and were always well above wilting point. The sensor at 20-cm depth was very reactive to rain events over the wet season, but smoothed out in the dryer months and remained relatively constant between 20-35%. The water content at 40-cm depth was less responsive to rain events over the wet season and similar to the 20-cm depth, smoothed out over the dry season to remain between 35% and 50%. There is a noticeable dip at the end of June, likely due to and increase in temperature in the area. See Figure 16 for the volumetric water content of the soil profile from 2020-2021 season.

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. Maintenance during the summer months is required to pull the weeds. We suspect due to the location, there is not a lot of foot traffic over the permeable pavement and weeds have the ability to establish themselves.

Photo of permeable pavement at Expo & Smithe, September 2020

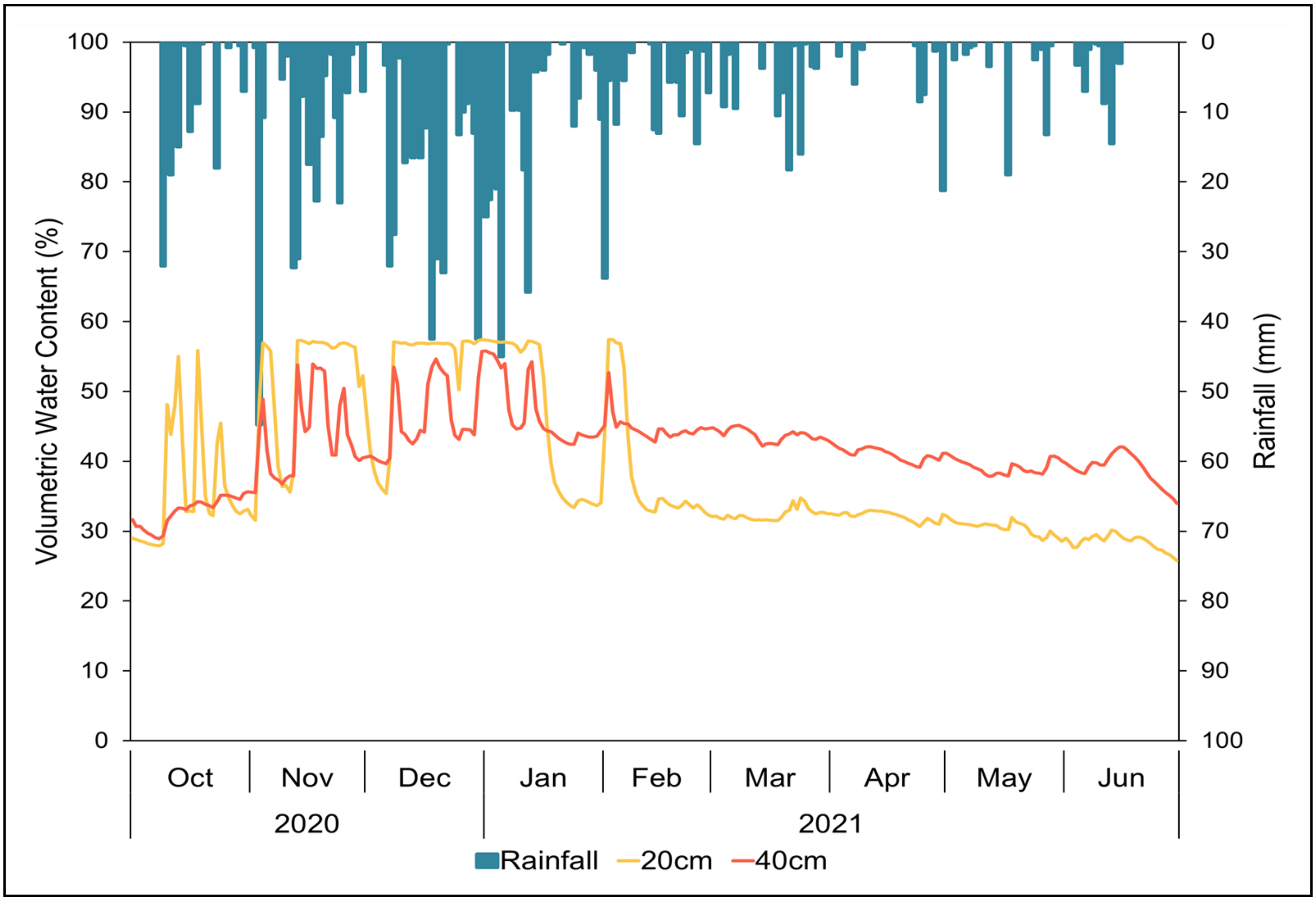


Figure 16 Expo and Smithe daily average volumetric water content and temperature

3.5 Richards St.

The Richards Street project is an 8-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 run-off from the bikeway and roadway. Once complete, this project will feature 100 new trees planted in the median. The project is split in 2 phases; phase 1 consisting of 4 blocks from Dunsmuir St. to Nelson St. and phase 2 the remaining 4 blocks from Nelson St. to Pacific St. Construction of phase 1 began in May 2020 and completed in December 2020, and phase 2 construction began in January 2021 and is on-going.

Soil moisture sensors were installed here to monitor plant health and to ensure moisture levels around hydroelectric lines remain above 10%. Overall, all the blocks are well above the 10% moisture minimum required by BC hydro (Figure 17). All the blocks of Phase 1 at Richards St. with the exception of Block B have intact soil sensors providing data on volumetric water content, electrical conductivity and temperature. The Block B sensor had highly variable readings and it was determined the data was unreliable and as such the data is not shown here. The sensor in Block B is installed directly into structural soil, and we think 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. Block A demonstrates the greatest daily variation of all the blocks, and moisture levels remain between 30-40%. Block C North displays the highest moisture levels of all the blocks with values ranging between 35-42%, while the Block C South displays the lowest levels ranging between 25-35%. Block D moisture levels range between 25-35%.

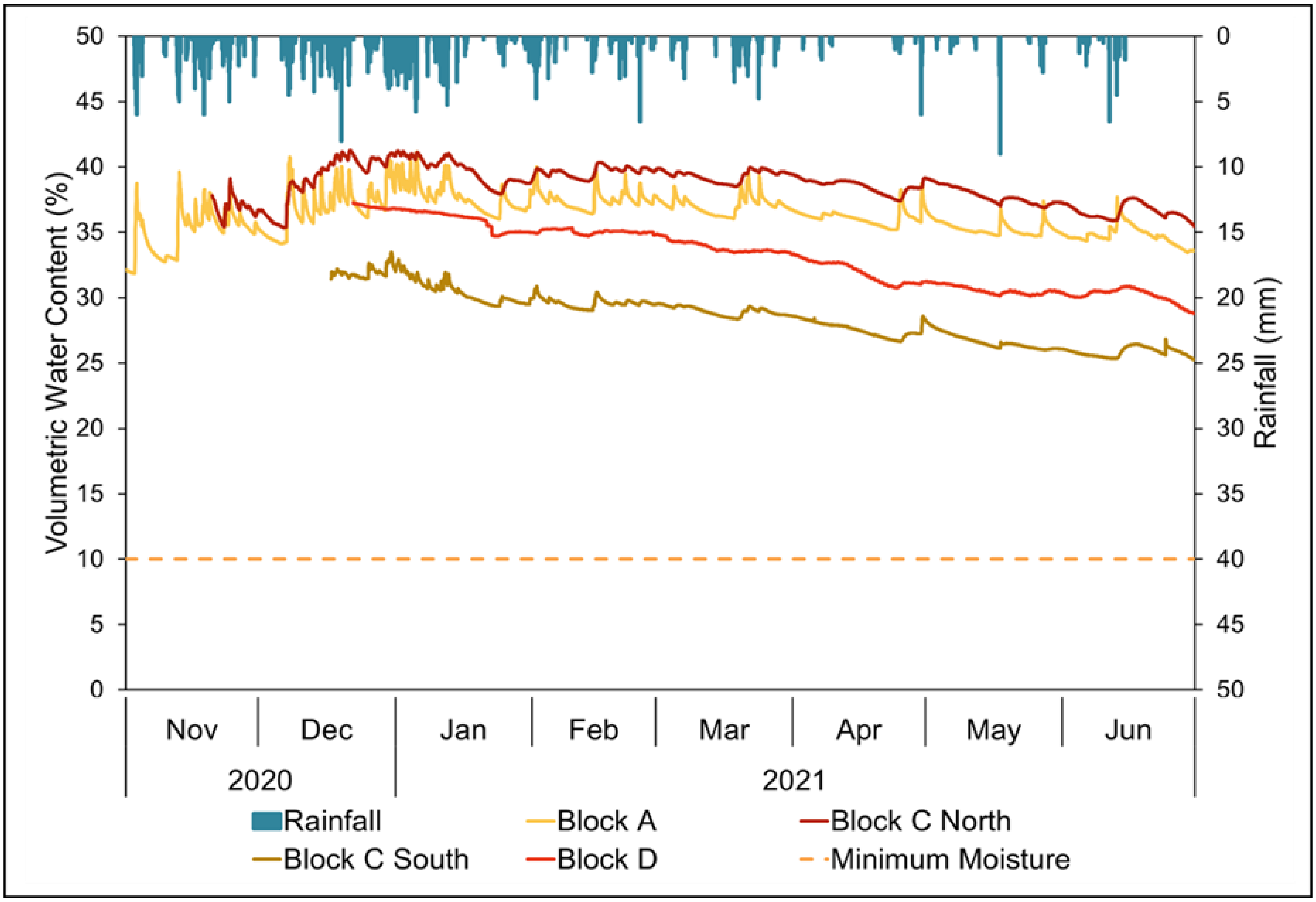


Figure 17 Richards St daily average volumetric water content for Block A, Block C and Block D

Two species of trees were planted in phase 1: Brandon Elms (Block A) and American Hornbeams (Block B, Block C, Block D) in February 2021. The trees were watered twice over the 2020-2021 period, on May 5, 2021 and June 21, 2021. Deep injection probes that added water directly into the soil and rootball were used to maximize water retention. A moisture level change was not recorded at any block during these watering periods, though perhaps this was because the soil moisture sensor is not located within the root bulb.

3.6 Burrard St. & Cornwall Ave.

Two infiltration trenches were built under the existing grass boulevards at the intersection of Burrard Street and Cornwall Avenue in 2017. The North trench manages a drainage area of 663 m^2 and the South trench manages a drainage area of 396 m^2. A monitoring well with a water level logger was installed in each infiltration trench to track water level changes during storm events and the infiltration performance of the practice over time. A falling head infiltration test was performed prior to construction and as a result both trenches were designed for a 5 mm/h infiltration rate. Monitoring occurred from February 2018 to May 2019. The loggers were removed from practices due to safety concerns accessing the wells in the high-traffic area.

The monitoring wells in both the North infiltration trench and South infiltration trench were functional and provided data on drawdown rate over the course of the monitoring period. The two infiltration trenches showed rapid responses to rainfall events, and rapid drawdown times as well.

3.6.1 North

The North infiltration trench drawdown durations were less than 12 hours and had drawdown rates above 30 mm/h. This trench was only monitored for one season, with intermittent data gaps, as shown in Figure 18. Between the monitoring period of March 2018 and May 2019, 34 events produced a water level change and the well flood duration, drawdown time and drawdown rate were calculated and compared to the design infiltration rate, as shown in Table 8.

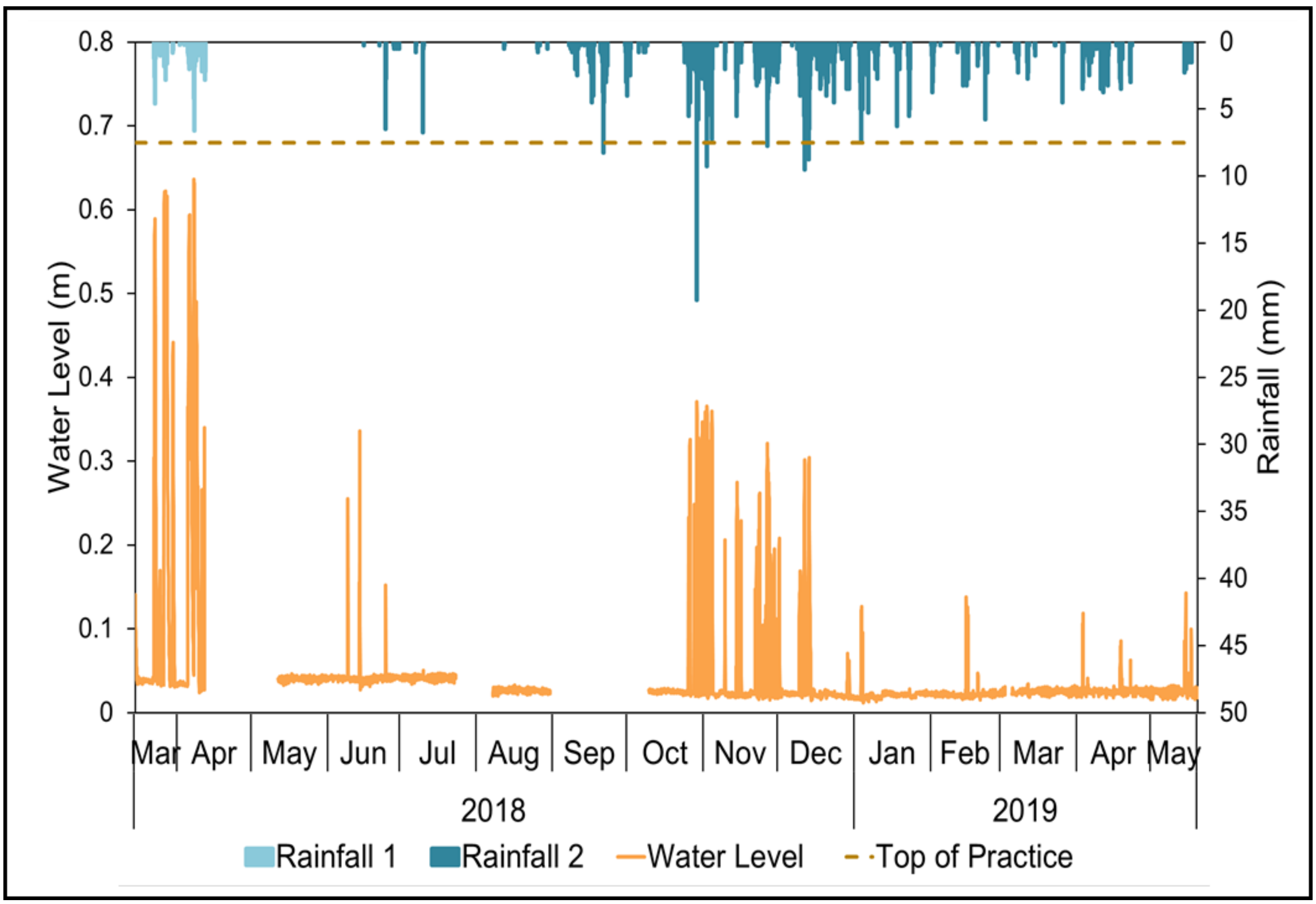


Figure 18 Burrard and Cornwall North hourly average rainfall and water level response

Table 8 Burrard and Cornwall North 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	18	8	8	34
Storm Duration (h)	8.8	21.7	33.8	17.7
Antecedent Dry Period (h)	29.5	58.7	37.7	38.3
Well Flood Duration (h)	7.2	19.0	19.7	12.9
Drawdown Duration (h)	4.7	11.6	9.1	7.4
Drawdown Rate (mm/h)	83	31	42	61
Design Infiltration Rate (mm/h)	5			
% change	1560%	520%	740%	1120%

3.6.2 South

The South infiltration trench drawdown durations were higher than at the North trench, but were generally under 24 hours. Similar to the North well, the monitoring period only included one wet season before it was terminated. The entire monitoring period, including periods of data gaps, are shown in Figure 19. Between the monitoring period of February 2018 to May 2019, 57 rainfall events produced a water level change. The well flood duration, drawdown times and drawdown rates and comparisons to design infiltration rate are shown in Table 9.

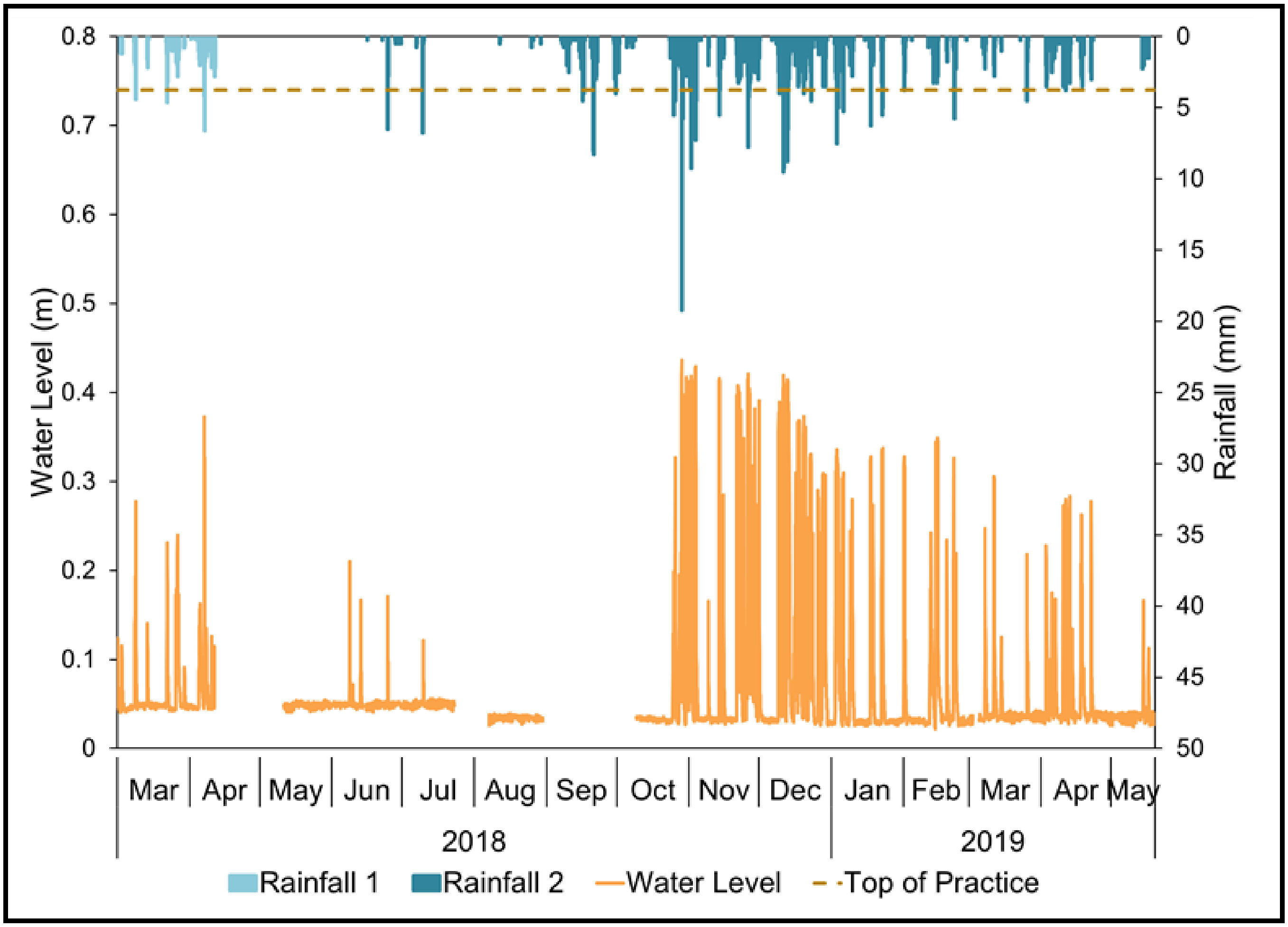


Figure 19 Burrard and Cornwall South hourly average rainfall and water level response

Table 9 Burrard and Cornwall South 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	36	15	6	57
Storm Duration (h)	11.3	22.7	37.7	17.1
Antecedent Dry Period (h)	30.2	58.8	43.7	39.1
Well Flood Duration (h)	18.8	33.0	47.5	25.6
Drawdown Duration (h)	13.3	21.9	22.2	16.5
Drawdown Rate (mm/h)	30	17	18	25
Design Infiltration Rate (mm/h)		5		
% change	500%	240%	260%	400%

The North and South infiltration trenches were one of the first practices to be monitored by the GI branch. At this time, there was no visual inspection component to the monitoring program. As such, visual observations and photos are not available for these sites.

4 Performance Objectives

This section summarizes the performance monitoring results presented in Section 3 relative to the objectives for GRI specific to the City of Vancouver. The six objectives addressed during the 2018-2021 monitoring period are a subset of the full monitoring objectives presented in Appendix A.

4.1 Compliance 1 (C1): Evaluate surface ponding: should not be ponded for longer than 24 hours.

This objective applies to the practices with surface ponding only, which include Yukon St. & 63rd Ave., and Quebec St. & 1st Ave. Through visual observations 24 hours following extreme rain events (> 48 mm), there was no surface ponding lasting at these sites. During visuals observations during and immediately following rain events, ponding at the surface only occurred during the most intense period of a rainfall event, but did not stay ponded once the rain intensity lessened or stopped.

4.2 Compliance 2 (C2): Evaluate subsurface storage: storage should empty in no more than 72 hours.

As can be seen in the water level response figures presented in Section 3, drawdown times are very short. Drawdown durations ranged from 0.4 to 28.5 hours, and the average drawdown time was 14.5 hrs, across all sites monitored. Therefore the 72 hour drawdown objective is being surpassed, and there is likely capacity for more subsurface storage. The bioswale average drawdown time were less than 2 hours, whereas the non-vegetated infiltration trenches had longer drawdown time. RTTs had significantly longer drawdown times, which may be due to clogged media or underlying geotextile layer due to the upstream construction in this catchment area. Though the RTTs drain more slowly than the other practices, the subsurface storage empties in less than 72 hours, thus meeting this objective.

4.3 Compliance 3 (C3): Determine if retention/filtration target is being met

This objective was only able to be evaluated at one RTT located at Quebec & 1st – Location C which was designed to retain a design retention value of 27 mm. The weighted average retention value was 18 mm. The large and extreme events are more than meeting this objective, with retention values of 31 mm and 71 mm respectively. Additional flow monitoring is required to determine if the retention is changing over time. As inflow is modelled, it assumes that all rainfall is entering the system and no bypass is occurring. One possible issue is that inflow volumes may be larger than what is actually occurring in the systems. This can lead to higher estimated retention values for large and extreme storms when we would expect bypass to occur.

4.4 Performance 1 (P1): Evaluate whether design infiltration rates are matching drawdown rates.

Average drawdown rates and design infiltration rates are summarized in Table 10 below. The bioswales and infiltration trenches had drawdown rates in excess of the design infiltration rate by a considerable difference, with measured drawdown rates 4-23 times higher than design infiltration rate. As noted above, a longer drawdown period was observed at RTT. This may be due to media or geotextile layer clogging, though we cannot be certain of the cause. Regardless, the drawdown rates in RTT are very close to the design infiltration rate.

The purpose of this objective 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. The safety factors applied to the design infiltration rate ensure very conservative designs are implemented, meaning that these systems lose water much more quickly than anticipated. We recommend reducing the safety factor to between 1 and 2 (decreasing the measured infiltration rate by a factor of 1-2), instead of higher safety factors of 2 to 9. We will continue monitoring at select locations over time to determine if the drawdown rate changes over time, but currently the time period of monitoring is too limited.

Table 10 Summary water level analysis for 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 & 63rd					
North	Bioswale	1.6	367	39	841
Quebec & 1st					
Location D	Bioswale	0.4	237	10	2270
Quebec & 2nd					
North Well	Soil Cell RTT	27.4	8	10	-20
Middle Well	Soil Cell RTT	28.5	9	10	-10
South Well	Soil Cell RTT	22.9	10	10	0
Burrard & Cornwall					
North Well	Infiltration Trench	7.4	61	5	1120
South Well	Infiltration Trench	13.3	25	5	400
Average		14.5	102		

4.5 Performance 2 (P2): Monitor soil moisture for plant health

The effect of soil moisture on plant health is not easily discerned from the data presented at the bioswales and RTTs monitored during the monitoring period. During the dry summer periods, we saw a decrease in soil moisture at all monitored sites, though the volumetric water content was not below 5% at any sites. We did not see die-off associated with extended summer dry periods, however this is not a reliable evaluation metric as all sites are newly constructed and under an establishment period, and therefore supplemental watering was 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, but we do plan to continue monitoring the volumetric water content, and will add monitoring the growth of the trees to this study.

4.6 Performance 3 (P3): Assess peak flow attention.

Though this objective was only evaluated at one site – Location C RTT at Quebec & 1st the results from the RTT flow monitoring showed very high peak flow reductions. The average peak flow reduction was 75%, which was higher for normal events (79%), and lower for extreme events (61%). As green infrastructure is designed for water balance management and performs best under routine conditions, the decreased peak flow reduction with higher rainfall events is expected. Further flow monitoring should be conducted to determine if other GRI assets perform similarly.

5 Conclusion and Recommendations

The current monitoring suggest that the GRI assets monitored have been effective and are performing well within the Vancouver climate. The GRI assets covered in this report are helping to inform six of our priority objectives:

Compliance 1 (C1): Evaluate surface ponding: should not be ponded for longer than 24 hours. No sites monitored displayed any ponding lasting longer than 24hours meeting the CoV infiltration standard as well as not allowing potential mosquito habitat to form.

Compliance 2 (C2): Evaluate subsurface storage: storage should empty in no more than 72 hours. All monitored wells had short drawdown times, with an average of 14.5hrs. We can conclude there is capacity for more subsurface storage.

Compliance 3 (C3): Determine if retention/filtration target is being met. The average retention for the monitored RTT's was 18mm, compared to the 27mm retention design target. However, we only have data from one RTT so we cannot make assumptions of the retention performance across different GRI typologies.

Performance 1 (P1): Evaluate whether design infiltration rates are matching drawdown rates. Five of the seven monitoring wells displayed drawdown times equal to or greater than the design infiltration rate. In over half the cases, the monitored drawdown rate was 400% greater than the design infiltration rate. This would indicate that re-evaluating how factors of safety are applied is necessary. We recommend using a safety factor of between 1 and 2, instead of safety factors between 2 and 9.

Performance 2 (P2): Monitor soil moisture for plant health. Soil moisture was variable throughout the monitoring period at different GRI typologies. Overall, the moisture range was amenable to the health of the vegetation. More complete visual condition assessments of plants will allow a greater correlation to soil moisture and plant health in the future.

Performance 3 (P3): Assess peak flow attention. Peak flow reduction was assessed at one rainwater tree trench, and we saw an average peak flow reduction of 75% across 125 events. The peak flow reduction was highest for normal events (<24 mm) and lowest for extreme events (>48 mm), which is expected for green infrastructure which is designed to retain low-intensity, routine events. Further flow monitoring is required at other GRI typologies to determine if they perform similarly.

The City of Vancouver will continue to monitor activities at existing and newly built assets to help inform our objectives. Moving forward, we are looking at piloting new technologies and partnerships that can help us move the monitoring program forward and address more of the priority objectives. Further details of the future of the GRI monitoring program are available in the Green Infrastructure Monitoring Strategy, September 2021, which can be made available upon request.

6 References

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Appendix A: All Monitoring Program Objectives, Objective Categories, and Data Collection Methods

		Monitoring Objective Category			Potential Methods to Address Objective				
#	**Objective**	**Compliance**	**Performance**	**Optimization**	**Field Monitoring**	**Desktop/ Modeling**	**Literature Review**	**Lessons Learned**	**Student Research Project**
P1	Evaluate whether predesign infiltration rates are matching real world infiltration rates		x	x	x				
P4	Determine infiltration capacity of permeable pavement and track whether that is changing over time.	x	x		x				
C1	Evaluate surface ponding – no more than 24hr	x	x	x	x			x	
C2	Evaluate subsurface ponding – no more than 72hr	x	x	x	x				
	Determine the life cycle costs of GRI practices including tracking maintenance activities and costs			x			x	x	
P2	Monitor soil moisture in bioswales for plant health and seasonal variations.		x	x	x				
C3	Determine if retention and/or filtration target for particular GRI asset is being met	x	x		x				
C4	Evaluate load reduction and effluent concentration of GRI for target pollutants: solids, nutrients, metals				x				
	Evaluate nutrient and pollutant loading impacts on plant health		x				x		x

		Monitoring Objective Category			Potential Methods to Address Objective				
#	**Objective**	**Compliance**	**Performance**	**Optimization**	**Field Monitoring**	**Desktop/ Modeling**	**Literature Review**	**Lessons Learned**	**Student Research Project**
P3	Assess the peak flow attenuation for design events		x		x	x			
	Determine assumption protocols for GI assets			x				x	
O3	Optimize pre-treatment methods for bioretention			x				x	
O1	Optimize plant species selection in GI assets			x			x	x	x
	Evaluate catch-basin enhancements			x			x	x	x
	Identify an appropriate methodology for testing permeable pavement performance						x		x
	Calibrating SWMM models for GI assets with monitoring data		x	x		x			
	Identify construction monitoring requirements							x	
P5	Determine infiltration capacity of bioretention media; assess whether it is changing over time.		x		x				
	Meet accessibility standards	x					x		x
	Evaluate proprietary treatment devices and their effectiveness for pollutant removal and maintenance requirements	x	x		x		x		

		Monitoring Objective Category			Potential Methods to Address Objective				
#	Objective	Compliance	Performance	Optimization	Field Monitoring	Desktop/ Modeling	Literature Review	Lessons Learned	Student Research Project
	Evaluate the performance of GRI assets in peat soils. What is the infiltration potential of peat soils and how is moisture maintained in peat soils?		x				x		x
	Evaluate the movement of infiltrated storm water towards utilities or building foundation	x	x		x		x		
	Evaluate the performance of GRI assets in till soils. Does water move down into the till or is it flowing laterally?		x		x	x	x		x
	Assess the winter maintenance impacts on GI. How does street salt and traction sand impact GI?		x		x		x		
O2	Identify the best mulch specifications to use in soil mixes			x			x		x
	Demonstrate the ancillary benefits of GI such as biodiversity, heat island effect reduction, health benefits		x	x			x	x	x
	Ensure the implementation of GI assets and their co-benefits are distributed in an equitable manner and address the needs of all peoples	x		x		x			x
	Evaluate social benefits of GRI assets. How often are people visiting? How many people are educated and understand its function.			x			x	x	x

		Monitoring Objective Category			Potential Methods to Address Objective				
#	Objective	Compliance	Performance	Optimization	Field Monitoring	Desktop/ Modeling	Literature Review	Lessons Learned	Student Research Project
	Evaluate compost amendments as a nutrient loading possibility (phosphorus, salts and hydrocarbons via biochar)		x	x			x		x
	Establish methods/recommendations for ameliorating clogged soils			x			x		x
	Monitor settlement that may occur in structural soils under curbs or bike lanes		x					x	x
	Assess the potential for long term soil contamination at GRI sites	x	x		x				x
	Evaluate phytoremediation abilities of plants			x			x		x