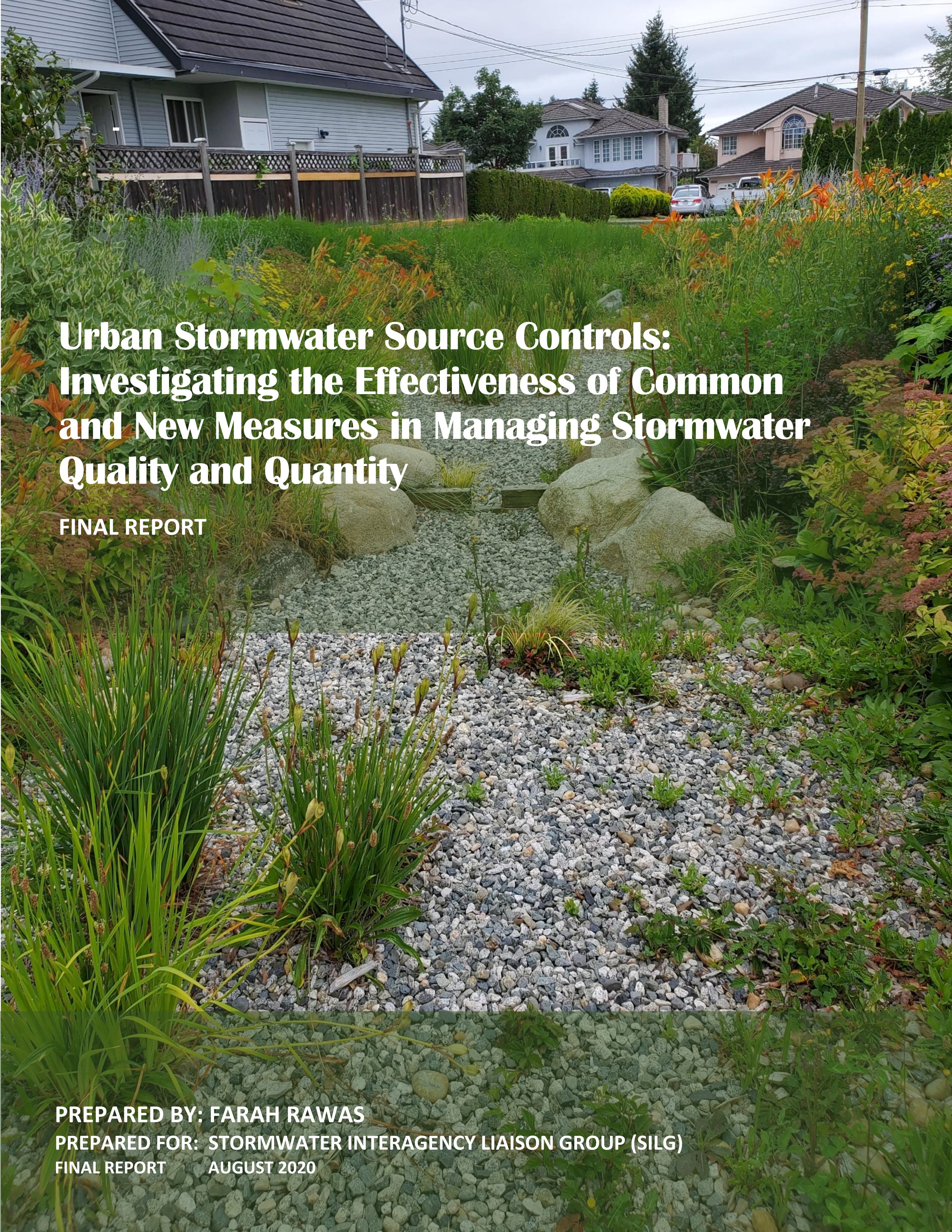

Urban Stormwater Source Controls: Investigating the Effectiveness of Common and New Measures in Managing Stormwater Quality and Quantity

FINAL REPORT

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DISCLAIMER

This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organisations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of Metro Vancouver staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of Carrie Hightower, Robb Lukes, SILG, or the University of British Columbia.

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1. Executive Summary

In 2010, the Integrated Liquid Waste and Resource Management Plan (ILWRMP) stated that stormwater should be managed at its source to protect the environment. Source control measures, such as bioswales, rain gardens, green roofs, and tree trenches, have become more common in Metro Vancouver in the past decade. Cities around the world too are building distributed networks of green stormwater infrastructure systems to capture stormwater before it enters storm and combined sewer.

The literature and practice around green infrastructure (GI) and source control (SC) measures are continuously evolving. The transfer of knowledge through clear and standardized guidelines helps municipalities around the world design, manage and maintain source controls effectively. The Stormwater Source Control Design Guidelines (SSCDG), published in 2012, serves as a guiding document for developers and municipalities around Metro Vancouver in the source control design process.

This project reviews the information gaps and new research and guidance on the six source control measures in the existing SSCDG and sheds the light on emerging source controls. Information from this project, collected both through literature reviews and site visits, will lay the foundation for updating the SSCDG which will be undertaken by the Stormwater Interagency Liaison Group (SILG) in 2020.

The Literature

Recent publications reveal that effective implementation of such measures is not limited to appropriate design and sizing, but also is contingent on the proper installation, maintenance, and operations. Emerging source control approaches augment, rather than replace, existing SC and green and gray infrastructure. Challenges to implementing and maintain SC infrastructure did exist; however, with the growth of experience, resources, and long-term monitoring studies for several SC types, these challenges are circumvented.

Local Visits

During the span of this project, 24 local establishments were visited, and eight professionals from four municipalities were interviewed. The site visits uncovered a lot of local lessons learned around the implementation of source control practices, such as leveraging existing municipal resources and collaborating with community groups to ensure the proper maintenance of this infrastructure. Combining the literature and the field observations, the following recommendations were made:

Maintenance and Operations

- Expand the SSCDGs to include a section on Maintenance and Operations for SCs, preferably in a separate volume. This would help separate the information into "Design" and "Maintenance and Operations".
- Include detailed maintenance protocols for each type, with emphasis on establishment maintenance, to be accounted for at the design phase. This will help give the developers a head start on knowing what needs to be done to make of their establishment a fully functional source control.
- Update of the list of acceptable vegetation on a regular basis to reflect current regional experience and successful establishments.
- Provide guidelines on retrofitting or basic maintenance for older establishments.

Classification of Practices and Pre-treatment

- Include sections on blue-green roofs, soil cells and stormwater tree trenches, and smart approaches.
- Classify the source controls to ones best for "high density / urban" areas and "low density / suburban", and separate "small scale" and "large scale" practices based on required area.
- Expand the guidelines to include a section on pre-treatment practices for each source control.

Performance Measuring

- Develop guidelines for visual and measurable performance indicators and measures.
- Investigate further and develop reasonable performance guidelines and additional gaps.

Olympic Village urban constructed wetland, Vancouver

2. Introduction

In a natural environment, soil and plants absorb rain. But when urbanization is increased, and impermeable surfaces cover the ground, rainwater washes over these surfaces carrying dirt, oil, and other pollutants to rivers and streams, sometimes also causing erosion and flooding (“City of Portland Stormwater Management Manual” 2016). Given the impact of urban stormwater on both humans and aquatic ecosystems, and the increase of urbanization worldwide, the management of urban drainage is a critically important challenge (Chocat et al., 2001; Fletcher et al., 2013).

Figure 1: Downtown Vancouver, Granville Street looking North

Cities around the world are building distributed networks of green stormwater infrastructure (GI) systems to capture stormwater before it enters storm and combined sewers. In recent years, source control (SC) measures such as green roofs, permeable pavements, rain gardens, and vegetative swales have been globally adopted to manage urban runoff and stormwater, protect water quality, and improve watershed health. In Metro Vancouver, stormwater source controls are one of the building blocks commonly recommended by Integrated Stormwater Management Plans (ISMPs) to manage stormwater to maintain and improve watershed health. The 2010 Integrated Liquid Waste and Resource Management Plan (ILWRMP) states that stormwater should be managed at its source to protect the environment. The ILWRMP also identifies managing stormwater as a municipal responsibility while Metro Vancouver's role is to facilitate research on watershed-based stormwater management approaches.

Effective implementation of such measures is not limited to appropriate design and sizing, but also is contingent on the proper installation, maintenance and operations. The continuous evolvement of this field can be attributed to the gained expertise and knowledge from implementing and managing this infrastructure in cities around the world. The Stormwater Source Control Design Guidelines (SSCDG), published in 2012, serves as a guiding document for developers and municipalities in the source control design process. This project investigates the effectiveness of six source control measures in the existing SSCDG in managing urban stormwater quality and quantity and sheds the light on emerging best practices. This project lays a foundation for updating the Stormwater Source Control Design Guidelines (SSCDG) and puts forward tools and recommendations to the Stormwater Interagency Liaison Group (SILG) moving forward.

Project Objectives

The objectives of this project are:

- Review existing source controls in the Stormwater Source Control Design Guidelines (SSCDG)
- Identify promising emerging source controls, including new technologies, pre-treatments or new applications and strategies to deal with densification
- Conduct interviews with local municipalities and document the lessons learned on installation, implementation, performance, operations and maintenance
- Identify the gaps of knowledge in existing Stormwater Source Control Design Guidelines
- Make recommendations to SILG for updating the SSCDGs

The information gathered will also inform the development of better monitoring techniques and metrics to measure the effectiveness of storm water source control infrastructure.

Project Guidance from SILG

In the May 2020 meeting for the SILG, feedback was collected on certain topics to be addressed in this project. The suggestions included the following:

- Identify promising new source controls for possible inclusion in the revised SSCDG, including new technologies, pre-treatments or new applications and strategies to deal with limited space in dense urban settings and developing town centres
- Assessment of source control facility relative effectiveness for both water quality and quantity
- Developing performance monitoring guideline
- Identify apartment building specific source control guidelines
- Identify deficiencies in the current guideline
- Identify how source controls can achieve the desired water chemical characteristics

Chantrell Detention Pond, Surrey

3. Methodological Approach

The project was composed of two main components: literature review and site visits with interviews. The literature review investigated standard and emerging stormwater source control measures, implemented in Metro Vancouver, Pacific North West, and around the world. The literature review expanded on the information present in the stormwater source controls design guidelines (SSCDG) by exploring lessons learned from the design guidelines and case studies of municipalities and research papers.

Rainwater Management Amenities (RMAs), Green Rainwater Infrastructure (GRI), and Source Controls (SCs) are all terms used within the Metro Vancouver region to describe urban and suburban stormwater management facilities and practices. A clear distinction in terminology is presented in section 4, literature review. In the literature review, standard source control measures were reviewed (absorbent landscapes, rain gardens, bioswales, green roofs, pervious pavement, infiltration trenches), and new technologies were identified. The literature review also covered performance monitoring and measurement, as well as certification programs for green infrastructure practitioners and sites.

Along with the literature review, several sites in Metro Vancouver that are home to old and new source control measures of various types were visited. During the site visits, several source controls facilities were observed, photographed, and municipality staff members and engineers were interviewed. Interview questions were prepared by the author and reviewed by the project mentor ahead of site visits. The interview questions (Appendix A) covered the following topics:

- Facility history
- Design objectives and stormwater benefits sought
- Changes to the facility or area over time
- Facility performance
- Water quantity and quality performance and benefits achieved
- Monitoring of facility
- Facility maintenance

Local Sites Visited

Table 1: Summary of sites visited for this project, by location and facility type

Location	Number of Facilities by Type						
	Rain Garden	Bioswale	Curbside Bulge	Permeable Pavement	Green Roof	Detention Pond	Stormwater Tree Trench
City of Vancouver							
Olympic Village		1		1			2
10 Avenue Bikeway							1
Arbutus Greenway			1				
Richard Street Downtown							
City Hall					1		
City of Surrey							
Sunnyside Heights drainage corridor		2					
Chantrell Detention Pond						1	
Sullivan Heights Parking Lot				1			
100 Ave and 144 St		1					
South Surrey Recreation and Arts Centre	1			1			
City of Delta McLosky - BC Hydro Rain Garden			2				
Various North Delta sites	6						
City of Burnaby							
Metrotown, Beresford Avenue	2		1				
						Total	24

Sunnyside neighborhood bioswale, Surrey

4. Literature Review

Terminology

Stormwater Management:

‘Stormwater management’ is the term traditionally used in North America to refer to managing rainfall runoff using conventional “storm-based” approaches to sizing and designing drainage facilities. Urban design thinking has evolved, however, to address the entire spectrum of rainfall events, not just storms, in ways that reflect more natural water systems (Metro Vancouver, 2012).

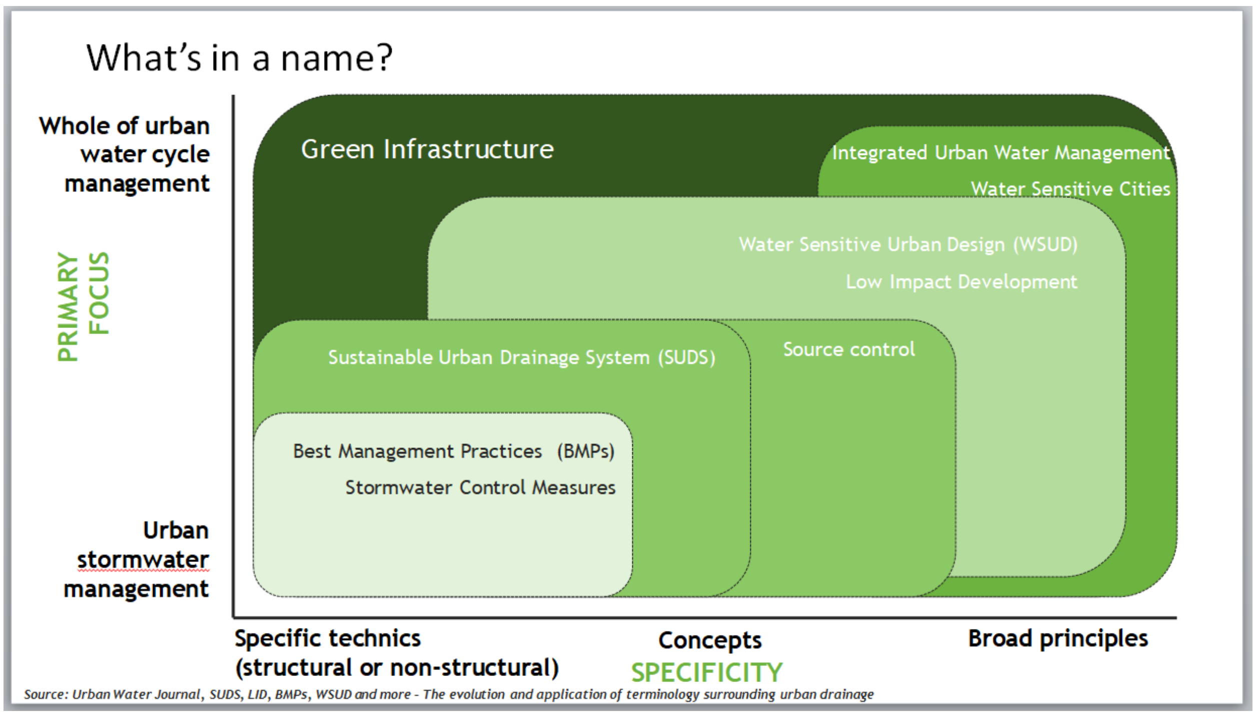


Figure 2: One possible classification of urban drainage terminology, according to their specificity and their primary focus. These classifications may change over time. Urban Water Journal, 2015

Source Control:

The term *Source Control* was initially used to make a distinction between on-site stormwater systems and practices, to be used at the source where runoff is generated, as opposed to larger detention basins that are constructed at the downstream end of a drainage network (Fletcher et al. 2015). Source control as a term was then the focus of the Urban Drainage Design Guidelines published by Ontario and Vancouver in Canada (Metro Vancouver, 2012; Ontario Ministry of Natural Resources, 1987). Throughout this document, the term SCs is used to refer to standard practices that cover topics related to: absorbent landscapes, bioretention, vegetated swales, pervious paving, infiltration trenches, sumps, and drywell, and extensive green roofs.

Green infrastructure

The term green infrastructure (GI) emerged in the USA in the 1990s and is a concept that goes far beyond stormwater (Fletcher et al. 2015). Indeed, GI seems to have origins in both landscape architecture, where it has been promoted as a network of green spaces. GI is defined variously in the US stormwater management literature as “a network of decentralized stormwater management practices, such as green roofs, trees, rain gardens and permeable pavement, that can capture and infiltrate rain where it falls, thus reducing stormwater runoff and improving the health of surrounding waterways” and is now “more often related to environmental or sustainability goals that cities are trying to achieve through a mix of natural approaches” (Foster et al., 2011).

Source Controls

Rain Gardens

Rain gardens are commonly considered as sub-types of bioretention, which capture, filter, and store stormwater. Depending on site conditions, they can be designed to infiltrate or discharge the filtered runoff. Bioretention facilities are engineered vegetated systems with special soils and sometimes internal structures like subdrains. In contrast, rain gardens are simpler and less engineered facilities that are typically used for single family homes and other small lot developments. Rain gardens direct roof and/or paved area runoff to a shallow, vegetated landscape depression amended with compost to allow for onsite infiltration.

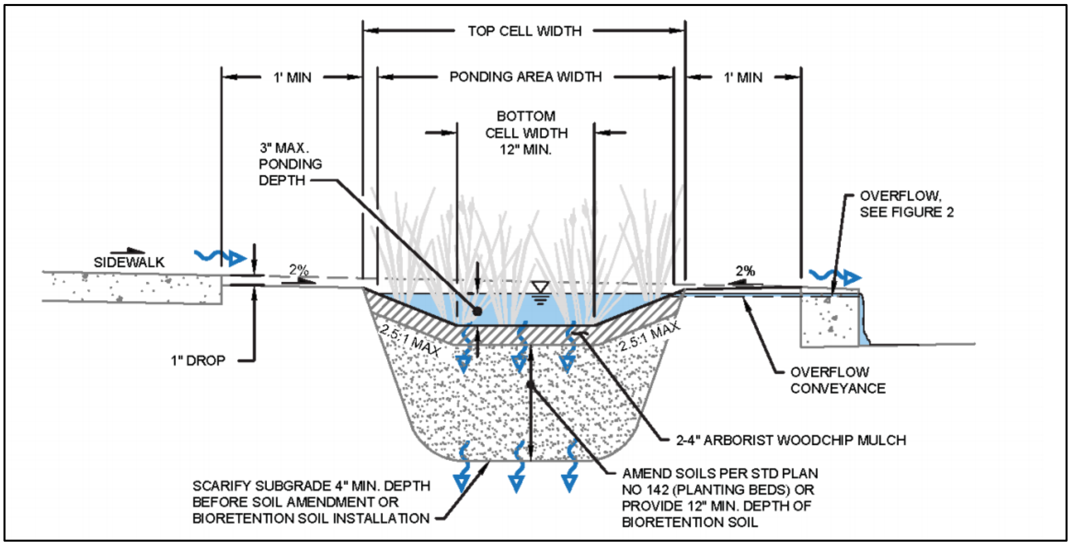


Figure 3: Rain garden section typical details. Source: Seattle Public Utilities Permitting Guidelines, 2016

Design Standards- City of Portland Stormwater Management Manual

Site Suitability: Rain gardens are suitable for sites that have well-draining soils (>2 inches/hour) and have an overall slope of 10 percent or less. According to the City of Portland, new development and redevelopment projects with less than 5,000 square feet of new impervious area are eligible to use this method ("City of Portland Stormwater Management Manual" 2016).

Setbacks: A ten-foot setback from buried oil tanks or retaining walls over 36 inches high is required for safety considerations. It is also recommended to avoid installation over water service lines. The deepest point of a rain garden should be at least 10 feet from all structures. Each downspout or rain drain entering the rain garden must be at least:

• 2 feet from any onsite building foundations without a basement,

• 6 feet from any onsite building foundations with a basement,

• 10 feet from a neighbor's building,

• 5 feet from a property line,

Sizing and grade: The rain garden footprint must be at least 10 percent of the impervious area that drains to each rain garden. The footprint is the area of the rain garden capable of detaining water when full, including facility side slopes. Each rain garden design needs to include an escape route (or overflow) so that stormwater safely drains in periods of heavy rainfall. Escapes routes can simply be low points in the perimeter of the rain garden that allow excess stormwater to safely drain away from building foundations to a driveway, sidewalk, street, or parking lot and without impact to adjacent properties. Escape routes should be planted or rocked to prevent potential erosion issues.

If an escape route is not available given site conditions, a piped overflow is allowed. Overflows need to have an approved disposal location such as a public storm sewer, adjacent creek, or onsite disposal system such as a drywell.

Dimensions and Slopes: The grade of the rain garden must gently slope away from the foundation and neighboring properties. Setback requirements, according to the municipal requirements, must be retained over the entire infiltration area. Rain gardens must not be installed at locations on the site where slope is greater than 10%.

Materials: Water runoff from the roof may be conveyed to the point of discharge in one of the following manners:

• A gutter-grade downspout extension above ground.

• A downspout extension positioned below ground, daylighting into the facility. Where located within the 2-foot or 6-foot setback from building structures, the pipe must be watertight.

Growing Medium: Amend native soils with 3 inches of compost blended into the top 12 inches of native soil.

Vegetation: The entire facility area must be planted with herbaceous plants, or a combination of herbaceous plants and shrubs. The facility area is equivalent to the total area of the rain garden, including bottom and side slopes, as developed in the sizing calculations. Plants should be placed in appropriate zones in the garden based on their characteristics for survival in wet environments. For example, plants near the bottom of the depression need to tolerate wetter feet, and plants closer to the top need less water.

Mulch: Rain gardens may be topped with 2” of compost cover to enhance soil moisture, prevent weeds and control erosion. Bark mulch or equivalent should only be applied above the high-water line.

Maintenance Requirements

These are some of the commonly suggested maintenance requirements for rain gardens specifically, and vegetated bioretention practices similar to rain gardens.

Table 2: Maintenance requirements for rain gardens and bioretention facilities

	Frequency	Activity
Bioretention, Rain Gardens*	Monthly	Remove trash, sediment, and debris that block inlets or outlets or that inhibit plant growth*
	Semi-Annually	Inspect mulching depth*
		Clean curb cuts: Remove accumulation of debris
		Prune trees and shrubs to maintain plant condition and public safety
		Weeding
		Inspect to determine if runoff is infiltrating properly
	Annually	Mulching: replace or add mulch to depth of 2-3 inches
		Maintain access, clear vegetation

		Test pH of soil to maintain at neutral level (range of 6.5-7.5)
		Observe and identify invasive species; map location, species type, and frequency; include photo-documentation
		Cut down perennial plantings*
		Clean-out of the underdrain [1,*]
		Remove invasive species
	As Needed	Erosion gullies observed during growing season should be filled with topsoil until vegetation is established
		Trim vegetation and remove weeds
		Remove woody vegetation within 15 feet of toe embankment or 25 feet from principal spillway or other structural features
		Remove litter and debris
		Remove or replace topsoil and sand/peat layer if infiltration is significantly reduced
		Watering: drip irrigation system maintained, water by hand as needed
		Observe infiltration rates after rain events
		Perform percolation test if rain garden not infiltrating properly*

		Downspout maintenance[2]: clearing it of leaves, making sure it has no cracks or leaks that are impeding water flow*
		Reconstruct or replace when it is no longer functioning

* Rain Garden Only
[1] If Applicable
[2] Particularly for rain gardens in homes

Pre-treatment

Bioretention cells, including rain gardens, require pre-treatment to capture large sediment and debris. Bioretention cells can receive inflow in the form of sheet flow, a surface inlet, or pipe flow. When using a surface inlet, it is recommended to direct the flow to a sediment forebay. Alternatively, piped flow may be introduced to the bioretention system via a perforated distribution pipe (Massachusetts Department of Environmental Protection 2008). Piped flow can also be pre-treated with a chamber that may have screens and hoods that capture floatables, trash, seeds, and sediment. For sheet flow, there are a number or pre-treatment options. These options include:

- A vegetated filter strip, grass channel or water quality swale designed in accordance with the specifications.
- A grass and gravel combination.
- Pea diaphragm combined with a vegetated filter strip specially designed to provide pre-treatment for a bioretention area.

Bioswales

Dry Swales

Properly functioning bioretention practices reduce the quantity of runoff and pollutants being discharged to municipal storm sewers and receiving waters (i.e., rivers, lakes and wetlands) and can help replenish groundwater resources. A variety of terms can be used to describe design variations for the practice of bioretention. A linearly oriented bioretention practice may be referred to as a bioretention swale (i.e., bioswale) or dry swale. Dry swales incorporate a deep fabricated soil bed with a mixture of vegetation and rock into the bottom of the channel. Existing soils are replaced with a sand/soil mix that meets minimum permeability requirements. An underdrain system is also placed under the soil bed. Typically, the underdrain consists of a layer of gravel encasing a perforated pipe. Any stormwater treated by the soil bed that does not infiltrate into the ground flows into the underdrain, which conveys treated stormwater back to the storm drain system.

Enhanced grass swales

Enhanced grass swales are gently sloping vegetated open channels designed to convey and treat stormwater runoff. They can also be referred to as enhanced vegetated swales or enhanced grass swales. Check dams and vegetation in the swale spreads out and slows the flow of water to enhance sedimentation, filtration through the soil and root zones of plants and evaporation back to the atmosphere. Runoff water is delivered to the practice through inlets such as curb-cuts or other concrete structures, sheet flow from paved areas, or pipes connected to other stormwater conveyances (e.g., catch basins, roof downspouts). The planting bed and side slopes are typically covered with a mixture of vegetation, stone, and mulch. They do not feature subdrains like dry swales do. Water not ponded behind check dams, nor absorbed by or evaporated from the filter bed is conveyed to an adjacent drainage system (e.g., municipal storm sewer or other Best Management Practices (BMPs)) at the lowest downstream point by an outlet structure (e.g., ditch inlet catch basin).

Perspectives on Vegetation

The City of Portland stormwater management approach prioritizes vegetation and infiltration to meet stormwater requirements and to maximize environmental, system and urban design benefits. Vegetation and infiltration facilities in the built environment minimize the effects of development on natural resources and the City’s built storm systems and provide numerous environmental benefits. These facility types are more resilient than other, non-vegetated stormwater management methods (e.g., structural detention or manufactured treatment) to changes in hydrology anticipated due to climate change.

Maintenance Requirements

Table 3: Maintenance requirements for enhanced swales

Component	Frequency	Activity
Contributing Drainage Area	Bi-annual	Remove trash, natural debris, clippings and sediment
	Annual	Re-plant or seed bare soil areas
Inlets and Outlets	Bi-annual	Remove trash, natural debris and clippings
	Annual	Remove accumulated sediment Remove woody vegetation at inflow points
Pre-treatment & Flow spreaders	Annual	Remove trash, natural debris, clippings and sediment
	As Needed	Re-grade and re-plant eroded areas when ≥30 cm in length
Perimeter	Annual	Replace dead/diseased plants to maintain a minimum of 80% vegetation cover
	Every 2 years	Add mulch to maintain 5 to 10 cm depth on non-vegetated areas
	As Needed	Re-grade and re-plant eroded areas when ≥30 cm in length
Filter bed	Bi-annual	Remove trash
	Every 5 years	Core aerate
	As Needed	Remove accumulated sediment when ≥ 5 cm depth.

	As Needed	Re-grade and restore cover over any animal burrows, sunken areas when ≥ 10 cm in depth and erosion rills when ≥ 30 cm in length
	As Needed	Add stone cover to maintain 5 to 10 cm depth where specified in the planting plan
Vegetation	Bi-weekly	Watering during first two months after planting
	As Needed	Watering during first two months after planting
	During extreme drought periods[3]	Watering for the remainder of the BMP lifespan
	Monthly	Mow grass to maintain height between 10 to 15 cm.
	Bi-annual	Remove undesirable vegetation (e.g., tree seedlings, invasives/weeds)
	Annual	Replace dead/diseased plants to maintain a minimum of 80% vegetation cover
	Annual	Prune shrubs and trees Cut back spent plants Divide or thin out overcrowded plants

[3] Varied types of vegetation will survive differently through certain amounts of droughts

Pre-treatment and Pollutant Removal through Bioswales

Studies of some of the oldest bioretention facilities in the US show that soil structures and functions developed over time enhance pollutant removal ability. As stormwater runoff flows through bioswales, pollutants are removed through physical, chemical, and biological processes, mostly in the root zone. Above ground plant parts (stems, leaves) slow flow and thereby encourage particulates and their associated pollutants to settle. The pollutants are then incorporated into the soil where they may be immobilized and/or decomposed. Bacteria within healthy soils can help break down carbon-based pollutants like motor oil.

Study data suggest relatively high removal rates for some pollutants (TSS, Nitrogen, some pathogens) , and modest removal capability for phosphorous. Phosphorus removal in bioretention soils increases with the depth of the facility and can be enhanced with soil mixes that have higher clay content or additives like iron. Low pH or oxygen conditions can cause phosphorus to de-sorb however, so the design should allow for dewatering, and pH should be monitored annually if Phosphorus is a concern. Nitrate removal is highly variable. Where it is a concern an elevated under-drain design that creates a fluctuating aerobic/anaerobic zone below the drainpipe can be used to enhance the de-nitrification process.

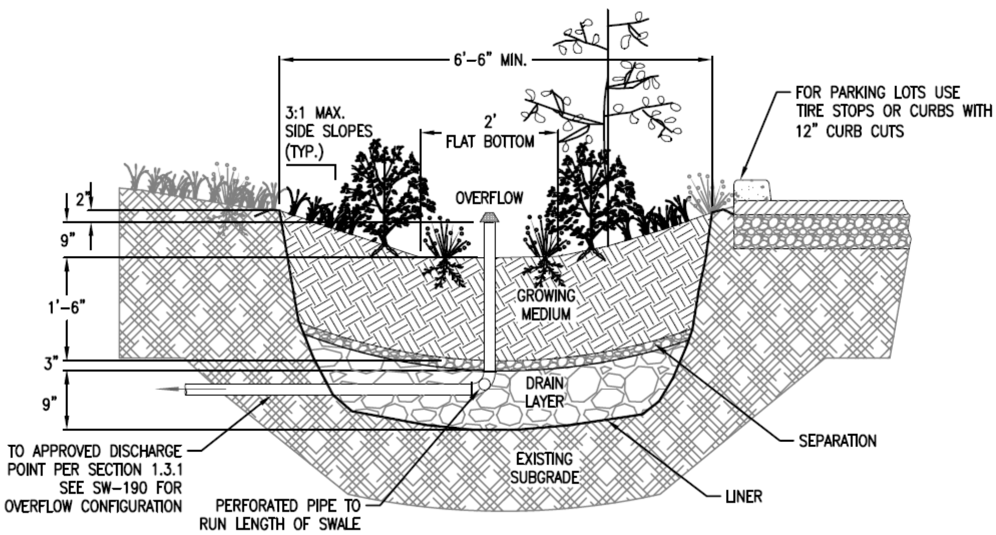


Figure 4: Typical design detail for a lined swale. Source: City of Portland, 2016

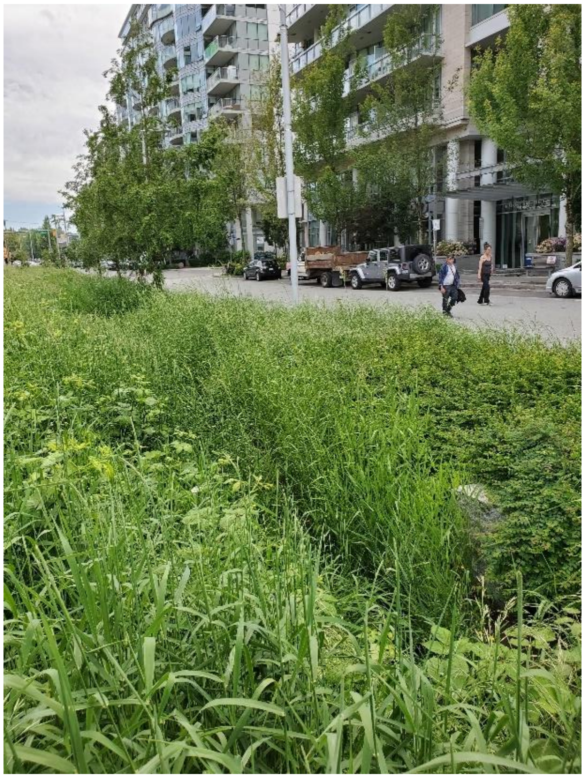


Figure 5: Bioswale with overgrown vegetation, Ontario and 1st St, Vancouver, BA, 2020

Figure 6: Street side separated bioretention bulges with different vegetation cover, Pine St, Vancouver, BC, 2020.

Green and Blue-Green Roofs

Green roofs offer a variety of co-benefits beyond their contributions to stormwater management. In urban centers and in high-rise developments, it is popular to construct green roofs as a roof terrace or amenity space. In this scenario, the proportion of permeable surface area is reduced to provide resident access, and the benefits of direct stormwater capture are restricted to the areas with vegetation planted. Another increasingly popular use for rooftop space is for urban farming. Again, the direct stormwater capture benefit is restricted to the areas with planters. To maximize the utility of a green roof as a source control, coverage with planting should be maximized. In many cases this means only inaccessible roof spaces are used.

The stormwater benefit of all kinds of green roofs is maximized by combining them with rainwater harvesting for subsequent irrigation. Biodiversity opportunities are optimized by planting a variety of species. In the long term, the richness of species can increase owing to 'volunteer species'. The desirability of this diversity varies with the aesthetic concerns of the green roof owner.

Design standards

Green roofs basically consist of a vegetation layer, a substrate layer (where water is retained and in which the vegetation is anchored) and a drainage layer (to evacuate excess water). Based on the depth of the substrate layer two main types of green roof are usually distinguished:

- *Extensive green roofs* with a substrate layer with a maximum depth of about 150 mm. *Sedum* species usually make up the major part of the vegetation. This type may also be installed on sloped surfaces. The slope angle can be as high as 45°.
- *Intensive green roofs* with a substrate layer with a depth of more than 150 mm. Grasses, perennial herbs and shrubs make up the main constituents of the vegetation. Intensive green roofs are typically installed on roofs with a slope of less than 10° and, depending on design and access, they may be used as roof gardens. Intensive green roofs, thanks to the storage capacity of their thick

substrate layer, are more effective in reducing the runoff than extensive green roofs.

Blue-Green Roofs

Green roofs are becoming increasingly important in the challenge of dealing with climate change and urbanisation. One of the challenges for green roof design and construction is the need to trap large volumes of water on roof structures with limited load bearing capacity (Voeten, Werken, and Newman 2016). Blue-green roofs are roofs that combine vegetation and elements of stormwater management in the roof structure, with an extra water storage layer, beyond what is required for the plants to survive (Andenæs et al. 2018). By storing water immediately beneath the green roof substrate and making it available for the plants by capillary action, more water can be stored on the roof without adding more soil or substrate to the system; effectively shifting the weight balance on the roof from 'storing soil', to storing rainwater and effectively retaining water for plant growth rather than discharging it to the sewer.

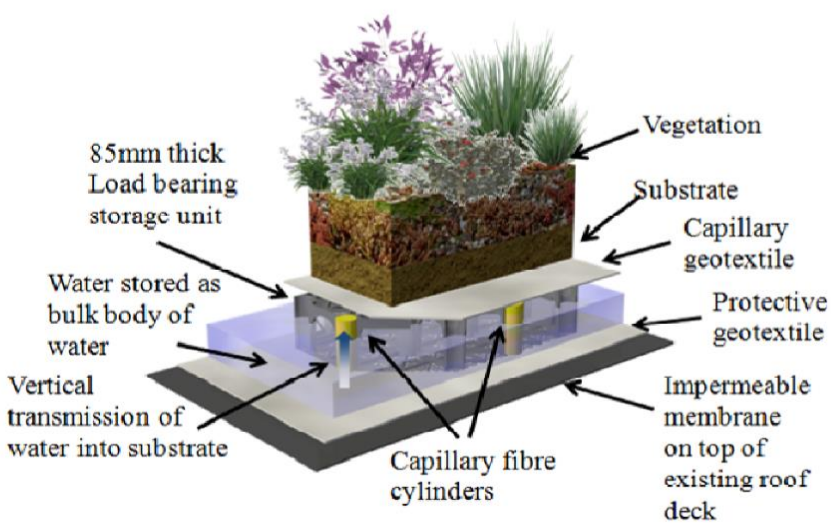


Figure 7: Cross section of green roof using 85 mm void formers as subbase with capillary fibers in vertical cylinders to transport water from the storage layer to the substrate (Voeten et al., 2016).

A study was conducted by (Cirkel et al. 2018) to quantify water availability and water demand for green roofs with and without precipitation storage and the capillary irrigation under Dutch climate, which is a sub-oceanic humid and rainy climate, comparable to that of Metro Vancouver. One year of detailed measurements of actual evaporation showed that storing precipitation water and passive capillary irrigation significantly increases and delays the evaporation reduction. It also decrease of latent heat flux during hot dry periods. Moreover, using capillary irrigation, the start of water shortage was delayed by approximately one month or disappeared. Storing precipitation water and passive capillary irrigation decreases the number of days with high Bowen ratios. The Bowen ratio is used to describe the type of heat transfer for a surface that has moisture. Storage and capillary irrigation thus strongly reduces the sensible heat flux (Cirkel et al. 2018). These findings are consistent with (Voeten, Werken, and Newman 2016), where a roof park experiment was set up to assess the difference in soil moisture content, between traditional drainage layers and a combined water storage/capillary irrigation drainage layer. Very stable soil moisture content in the capillary-fed blue-green roofs during both dry spells and severe rain events illustrated the ability of such system to provide irrigation water throughout the summer months. The consistent soil moisture content enables plants to grow better because water is not a growth-limiting factor.

The key development in the use of these units in green roofs, is the capillary fibre cylinder insertions located in the hollow load bearing columns of the units (example Figure 7). This is because the volume of water that can be stored within the load bearing boxes will always leave an air space between the water body and the overlying substrate. These capillary fibre cylinders allow the passive transmission of water into the substrate. In effect, an equivalent volume of water is being stored within the void space of the box rather than in the interstices of the substrate of a traditional green roof; thus, reducing the load on the roof for the same volume of stored water. In addition, a significantly wider planting choice is possible, without having to increase substrate depth because the plants no longer need to be selected based on drought tolerance (Voeten, Werken, and Newman 2016). This of course assumes that the green roof is designed to provide a continuous supply of supplementary water on the rare occasions when irrigation is required.

Common Issues and limitations

For climates with hot and dry summers plants on rooftops endure harsh conditions regarding temperature and insolation, increasing the need to irrigate. Therefore, many green roof projects must include an irrigation system, increasing the implementation costs, as well as system management costs, namely additional water and energy consumption.

In the past, the primary operational concern for a traditional green roof was the development of leaks. This issue has become rare in modern systems. Green roofs actually protect the roof membrane from UV damage and should increase the lifespan of the roof, protecting the membrane from leaks and often leading to lower lifecycle costs for the roof due to less frequent replacement. Also, many green roofs now come with leak detection systems. However, if a leak is discovered, then a section of green roof would have to be removed for access. Some proprietary systems appear to be easier to remove and replace. This may come at a cost, as the rainwater retention of the system is somewhat reliant on continuous coverage of the green roof surface.

Green Roof Design Techniques to Improve Water Use

Drought Adaptive Native Species

A strategy to cope with water-limited environments might be to find nature-based solutions. One of the solutions often discussed is the use of native plant species, naturally adapted to drought conditions.

Structural Materials with Water Retention Capacity

At the rooftop of a building, plants are exposed to harsh conditions of temperature, radiation, and wind, while thriving in shallow substrates, with limited capacity to hold water. Therefore, in dry hot climates, structural components of the green roof that can help to retain water can play an important role. Commonly, green roof systems include the following layers from top to bottom: vegetation, lightweight substrate, filter, drainage layer, moisture retention layer, and root-resistant waterproofing barrier. Water is mostly retained in the substrate, the drainage layer and the moisture retention layer. Two of the construction elements, the drainage and the water retention layer, can act as interesting reservoirs for water.

Deficit Irrigation vs. Aesthetic Value

In a study in Portugal, two different irrigation levels were studied (60% and 100% of reference evapotranspiration, ET_o) (Paço et al. 2019). Experiments on the *Rosmarinus officinalis* plant species showed that deficit irrigation lower evapotranspiration rates without impacting the aesthetic value of the green roof. This result indicates that it is possible to use those native species under deficit irrigation without losing the expected aesthetic value, which is an interesting plant feature considering that the end-users' preferences more frequently privilege aesthetics, regarding other environmental concerns.

Mixtures of Vascular Plants and Mosses

The high-water retention of mosses can benefit the soil moisture content around the vascular plants, increasing their water use efficiency. The presence of taller vascular plants also provides a shelter for the mosses against solar radiation and wind during summer and helps conserve moisture, as observed by other authors. This mixed composition of species with complementary features constitutes a nature-based solution, replicating what is commonly observed in natural conditions, where biodiversity can act as a driver of ecosystem functioning.

Use of Moss-Dominated Biocrust Roofs

Moss-dominated biological soil crusts (biocrusts) present the ability to lose almost all water from inside the cells and upon rehydration regain normal function and can be grown in two months under controlled climatic conditions. A biocrust roof of this type could be an interesting solution for low-cost green roofs in urban areas with dry and hot summers, since no irrigation is required to prevent plants from dying in dry periods, and they can increase water use efficiency of other vascular plants if irrigation is required.

Maintenance Requirements

Suggest changing this to “Green roofs can be designed to be low maintenance” as some intensive roof designs do require more frequent maintenance to meet aesthetic requirements. Regular inspection is required to see that the drains are free from obstruction, all structural elements are in good repair, and that the vegetation coverage is adequate to prevent wind erosion. During detailed design, all areas adjacent to the green roof itself should be kept free from granular material. Sediment accumulates in gravel edging, which then permits the vegetation to take root and spread.

Rooftop farming is also becoming common. Where large open expanses of roof are being cropped, some Ontario cities have found that measures may be required to reduce erosion of exposed planting medium. Any digging or furrows will reduce the stormwater benefit.

Table 4: Maintenance requirements for green roofs

Approximate Maintenance Frequency	Maintenance Activity
Monthly	Maintain vegetation to 90% plant cover: replace plants as needed
Semi-Annually	Remove trash and debris, weed, prune, replenish bare media, only fertilize if total soluble nitrogen levels fall below 5 ppm
Annually	Replace dead plants
As Needed	Operate and maintain structural components in accordance with manufacturer’s requirements; Clear inlet pipe when clogged and determine condition
	Remove debris and litter to prevent clogging of inlet and interference with plant growth

	Stabilize erosion channels in soil substrate/growth medium with addition plants and soil substrate/growth medium
	Remove invasive or nuisance species
	Manual weeding without herbicides or pesticides
	Irrigation during establishment period (1-3 years) not to exceed ¼ inch of water every 3 days
	Aesthetics maintained, correcting damage and removing vandalism
	Remove standing water manually
	Correct and prevent spills from mechanical systems on roofs
	Irrigation through hand watering or automatic sprinkler

Permeable Pavement

Permeable paving allows stormwater to drain through the surface and into a stone reservoir, where it infiltrates into the underlying native soil or is temporarily detained. Permeable pavers are composed of a layer of concrete or fired clay brick. The pavers are separated by joints filled with no fines crushed aggregate. Permeable pavers are different from porous pavers in that rainwater passes *around* the paver opposed to *through* it.

Another form of permeable pavement are concrete grid pavers. These are generally cellular grid system filled with soil and vegetation or gravel. This system provides grass reinforcement, ground stabilization and gravel retention.

There are also permeable versions of concrete and asphalt, known as porous asphalt and pervious concrete.

Permeable paving is ideal for:

- Sites with limited space for another surface stormwater BMP
- Projects such as low traffic roads, parking lots, driveways, pedestrian plazas and walkways

Figure 8: Sunnyside Drainage Corridor Bioswale and Pervious Pavers combined bioretention practice.

Design standards

The fundamental components of a permeable paving system are:

- Surface elements:
    - Interlocking pavers with open joints
    - Precast pervious slabs or pavers
    - A cast in place surface without fines, so that the finish is pervious to water

- A bedding course to stabilize the surface
- Underground storage layer of aggregate

The fundamental components of a porous paving system are:

- Pervious surface
    - Asphalt, Concrete, Pavers,
- Storage "bed" storage reservoir
- Geotextile Fabric Line

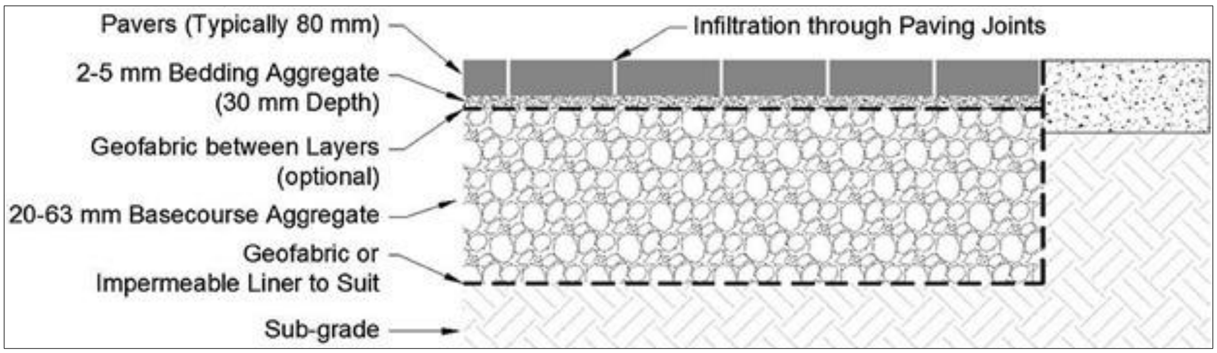


Figure 9: Typical permeable pavement structure (Boogaard, Lucke, and Beecham 2014)

Maintenance Requirements

Table 5: Maintenance Requirements for Permeable Pavement

Component	Frequency	Activity
Contributing Drainage Area	Bi-annual	Remove trash, natural debris, clippings and sediment
	Annual	Re-plant or seed bare soil areas
Overflow outlets	Bi-annual	Remove trash, natural debris and clippings
	Annual	Remove accumulated sediment
Pavement Surface	Bi-annual	Remove trash, natural debris and clippings
	Annual	Remove accumulated sediment (sweep or vacuum)
	Annual	Replace/top up joint or grid fill material (if applicable)

	Annual	Remove undesirable vegetation (e.g., tree seedlings, invasives/weeds)
	As Needed	Plow snow and apply de-icing salt during winter
		Replace damaged or ravelling pavers
	Every 3 years	Re-paint lines/parking space divisions (if applicable)
Vegetation[4]	Bi-weekly	Water during first two months after planting
	As Needed	Waterfor the remainder of the first two (2) growing seasons (i.e., May to September) after planting or until vegetation is established
	During Drought	º Water for the remainder of the BMP lifespan
	Monthly	Mow grass to maintain height between 5 to 10 cm.
	Annual	Remove undesirable vegetation (e.g., tree seedlings, invasives/weeds)
	Annual	Overseed and top dress bare areas with compost to maintain a minimum of 80% grass cover
Sub-drain & Monitoring well	Annual	Flush out accumulated sediment with hose or pressure washer

[4] Applies to grid systems with vegetation only

Pre-treatment

In most designs, the surface acts as pre-treatment to the stone reservoir below. Periodic vacuum sweeping and preventative measures like not storing snow or other materials on the pavement are critical to prevent clogging. Another pre-treatment element is to have a choking layer above the coarse gravel storage reservoir. It should be noted that clogged permeable pavements that have not been regularly swept can typically have high infiltration rates restored through vacuum sweeping.

Common Issues and limitations

Stormwater infiltration practices, like permeable pavements, should not receive runoff from high traffic areas where large amounts of sediment or winter traction sand are applied (e.g., busy highways), nor from pollution hot spots (e.g., source areas where land uses or activities have the potential to generate highly contaminated runoff such as vehicle fuelling, servicing or demolition areas, outdoor storage or handling areas for hazardous materials and some heavy industry sites). To reduce risk of groundwater contamination, infiltration of runoff from source areas that are comparatively less contaminated such as roofs and low traffic areas should be prioritized.

Absorbent Landscapes

Absorbent landscapes are vegetated areas designed to absorb and retain larger amounts of rainfall than conventional compacted landscapes. Tree clusters are another residential landscape alternative. Tree clusters improve water quality, generate organic soils, absorb greenhouse gases, and provide shade for homes. Tree clusters require larger lot sizes, preferably with no overhead wires. They can be planted as standalone features or as part of a larger residential absorbent landscape. Examples include large evergreen trees to intercept rainwater in their branches; plentiful surface vegetation to absorb water, prevent erosion and encourage evapotranspiration; and healthy soil with the right sand and organic matter content, which offers the right balance of permeability and water holding capacity. Absorbent landscapes can improve water quality, reduce runoff and increase biodiversity while creating aesthetic appeal.

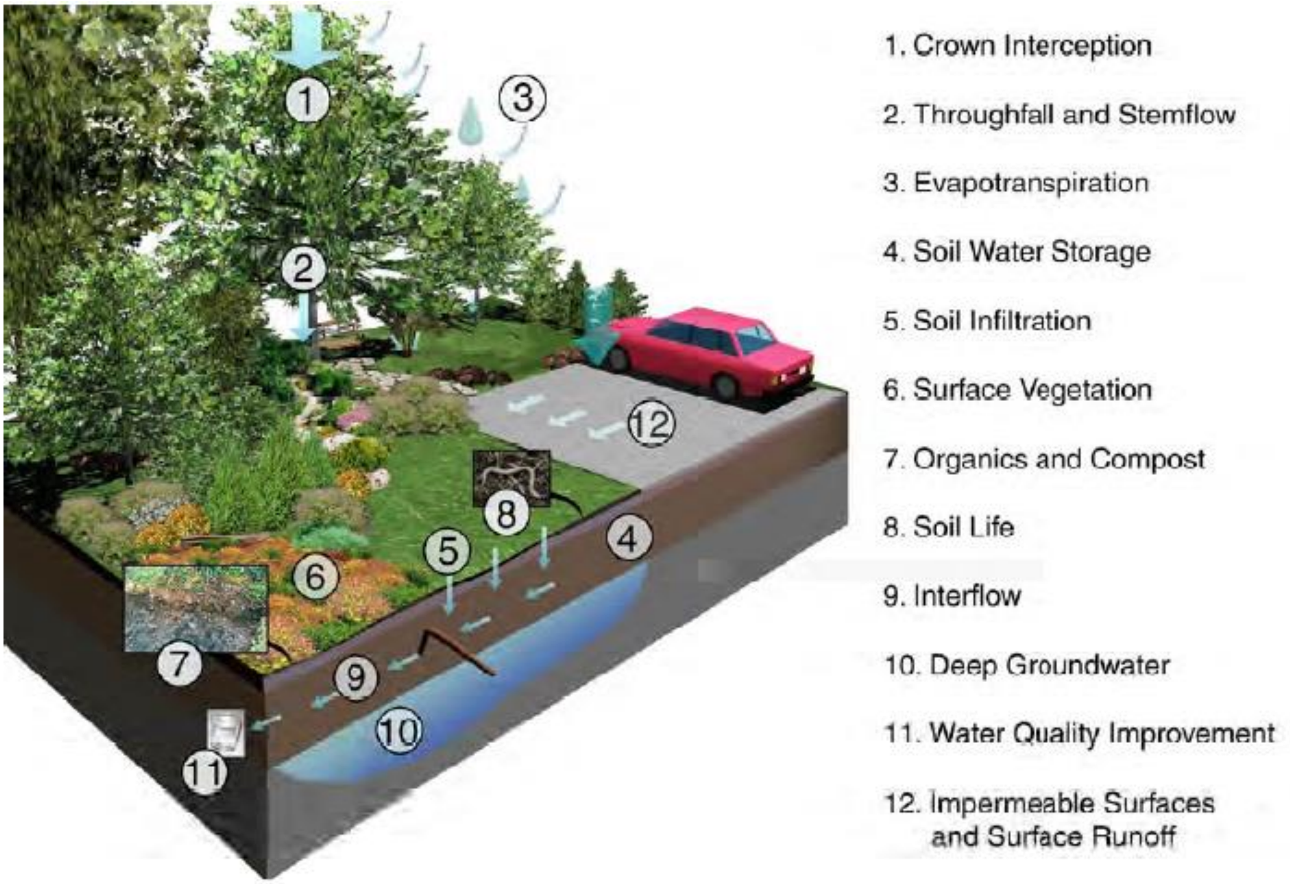


Figure 10: Absorbent landscape stormwater elements, SSCDG 2012

Maintenance requirements for absorbent landscapes

Well-designed landscape alternatives require little maintenance and less irrigation after establishment than turf. Maintenance of absorbent landscapes is largely similar to that needed by any green space, with weeding and replacing dead plants should be at a minimum conducted once in the spring and once in the fall. In addition, the overflow needs to be inspected monthly and maintained as needed to be kept free of debris. Vegetation maintenance is covered in other types of SCs in the previous sections. In addition, for large landscapes, one should also consider the maintenance activities for trees in Table 6.

Table 6: Maintenance requirements for trees

Frequency	Maintenance Activity
Semi-Annually	Inspect tree health
As Needed	Mulching, watering, and protection of young trees during the first three years
	Rake and remove fallen leaves to prevent material from entering storm drains; Remove dead and nuisance vegetation
	Pruning conducted by certified arborist or qualified professional, or homeowner should learn proper methods
	4-6 inches of hardwood mulch should be added around newly planted trees (avoid redwood and cedar mulch)
	Install irrigation system to establish tree
	Minimize use of fertilizers, consider using mulch instead
	Plant evergreen shrubs and ground cover near tree
	Inspect to determine survival rate and replace

Smart Systems

While stormwater systems do change (albeit slowly), their design performance is often regarded as static due to limited ability to adapt to changing climate and land uses once constructed (Kerkez et al. 2016). Rather than replacing entire systems, smart systems technology promises to augment existing green and gray infrastructure. This approach relies heavily on sensor and information technology to make existing stormwater systems more adaptive by embedding them with connectivity and intelligence.

Present uses of sensors range from regulatory compliance to performance studies of individual stormwater facilities (Kerkez et al. 2016). These technological advances have the potential to become highly transformative, by enabling stormwater infrastructure to evolve from static to highly adaptive (Figure 2). By coupling the flow of water with the flow of information, modern stormwater infrastructure will adapt itself in real-time to changing storms and land uses, while simultaneously providing a highly cost-effective solution for cities that are otherwise forced to spend billions on stormwater reconstruction.

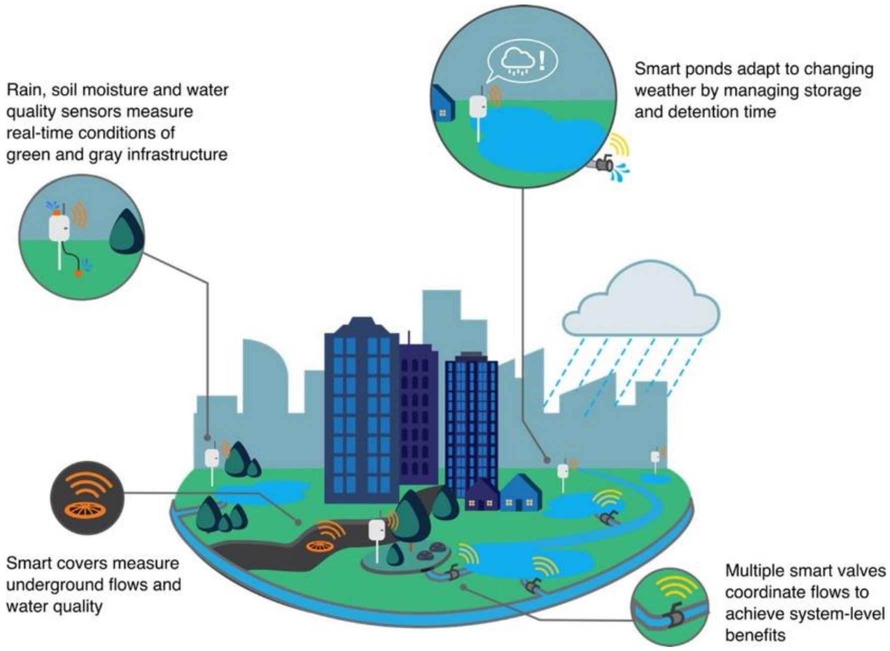


Figure 11: System-level stormwater measurement and control (Kerkez et al. 2016).

Given advances of modern sensors and data acquisition systems, it is now feasible to monitor green and gray infrastructure projects pre- and post-construction to provide in situ performance metrics. Water flow, stage, precipitation and soil-moisture can now be measured seamlessly and continuously. The development of robust and affordable in situ water quality sensors for nutrients, metals or bacteria is still evolving.

Low-cost, reliable and secure actuators (e.g., valves, gates, pumps) can now be attached to existing stormwater systems to control the flow of water in pipes, ponds and green infrastructure. Examples include inflatable pillows that can be used to take advantage of underused inline storage, or smart outlet structures that control water levels in response to real-time data and weather forecasts.

Real-Time Control of Individual Stormwater Facilities

Traditionally, stormwater facilities are designed as compromises between flood control (detention) and water quality control (retention), with limited ability to adapt functionality to individual storm events. Retrofitting an existing site with a real-time control valve permits it to serve both as a detention and retention basin, as well as a spectrum of in-between configurations. It has been shown, for example, that by temporarily converting a detention basin to a retention basin, the removal efficiency of total suspended solids (TSS) increased from 39% to 90% and the removal of ammonia-nitrogen increased from 10% to nearly 90% (Carpenter et al. 2014).

Flow modulation for stream protection was demonstrated at two pilot sites owned by Clean Water Services (CWS) in Washington County, Oregon. In one system (sized to retain 0.2 in. of rainfall), the addition of real-time control to an existing wet pond reduced the volume and duration of channel forming discharges by approximately 25%. In a second facility (a dry detention pond), the use of real-time control was used to minimize release rates in smaller, more frequent storm events while maintaining the ability to match predevelopment peak flows during larger storms. This enhancement was modeled to reduce the volume of erosive flows by nearly 60% and the volume of wet weather discharges by nearly 70% compared to a passive basin. Based on whole lifecycle cost estimates, it was determined that a real-time control retrofit of an existing stormwater detention facility would be approximately three times lower in lifecycle cost than the equivalent passive alternative (Boyle et al. 2016).

Soil Cells and Stormwater Tree Trenches

Stormwater Tree Trenches (STTs) are multifunctional green rainwater infrastructure (GRI) practices that provide both storage for rainwater and support to street trees. This type of GRI practice, typically located in dense urban environments, directs urban rainwater runoff from adjacent impermeable areas such as streets, parking lots, sidewalks, plazas and rooftops into underground trenches for treatment and then infiltration or uptake by street trees.

There are two types of STTs in the City of Vancouver: structural soil and soil cells (Vega 2018). Soil cells consist of plastic or concrete 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 12: Built in 2014, this stormwater planter on Central Parkway in Mississauga uses supported soil cells and is functioning well.

According to a literature review conducted by a previous sustainability scholar, STTs have been used in the Lower Mainland of B.C., across North America, and Europe (Vega 2018). However, only a few systems, which were in other climate regions, have been monitored for performance. Those studies found in some cases up to 98% rainwater volume reduction to the stormwater system and delay in peak flows. As for water quality, they perform similar to bioretention systems. Soil cell STT were found to be effective in removing heavy metals such as copper, aluminum, zinc and iron, and can reduce total suspended solids and phosphorus with at least 70% efficiency (Page, Winston, and Hunt III 2015).

Figure 13: Soil cell installation on Central Parkway in Mississauga

Function and Components

When dealing with green infrastructure such as STT, it is important to understand the limitations of the design in order to not overdesign. (Tu et al. 2020) investigated the hydrological of an overengineered tree trench system to identify factors contributing to, compounding, and mitigating the risk of plant stress. Overdesign can have negative implications for plant water availability in systems, causing the GRI to function as grey infrastructure. This was demonstrated by the study in systems where soil pits are embedded in infiltration beds, overdesign can raise the storm size required for water to reach the soil media, reducing plant water availability between storms, and ultimately inducing physiological stress (Tu et al. 2020).

With appropriately designed inlets, street tree stormwater control measures have significant potential to retain runoff; however, low inlet capacities due to blockage by sediment and debris can cause poor retention (Szota et al. 2019), which could further limit water availability in trenches and soil pits, limiting STTs potential to reduce tree drought stress and increase growth (Caplan et al. 2019). For example, a study by (Szota et al. 2019) quantified both the runoff retention performance of infiltration trenches retrofitted alongside established street trees and observed no clear reduction in tree drought stress or increase in tree growth.

Innovative design can be used to maximize runoff capture efficiency under typical sediment and debris loads (Szota et al. 2019) in the evolving practice of passive irrigation of street trees with stormwater. (Caplan et al. 2019) suggests the following modifications of aspects of typical trench designs:

- increasing infiltration into soil pits from above by replacing the overlying concrete sidewalks with permeable pavement or short-stature vegetation (e.g., grasses), or by directing stormwater from impermeable surfaces surrounding soil pits towards exposed soil surfaces
- increasing the water holding capacity of the soil mix (e.g., by increasing the clay fraction) to prolong the period that water is readily available
- increasing the frequency that soil pits come in contact with stormwater from below, i.e., reducing the water depths required for stormwater to reach soil pits, this could be accomplished by making trenches shallower or by making soil pits deeper, though providing soil-filled channels through the gravel bed may also be feasible in some cases.

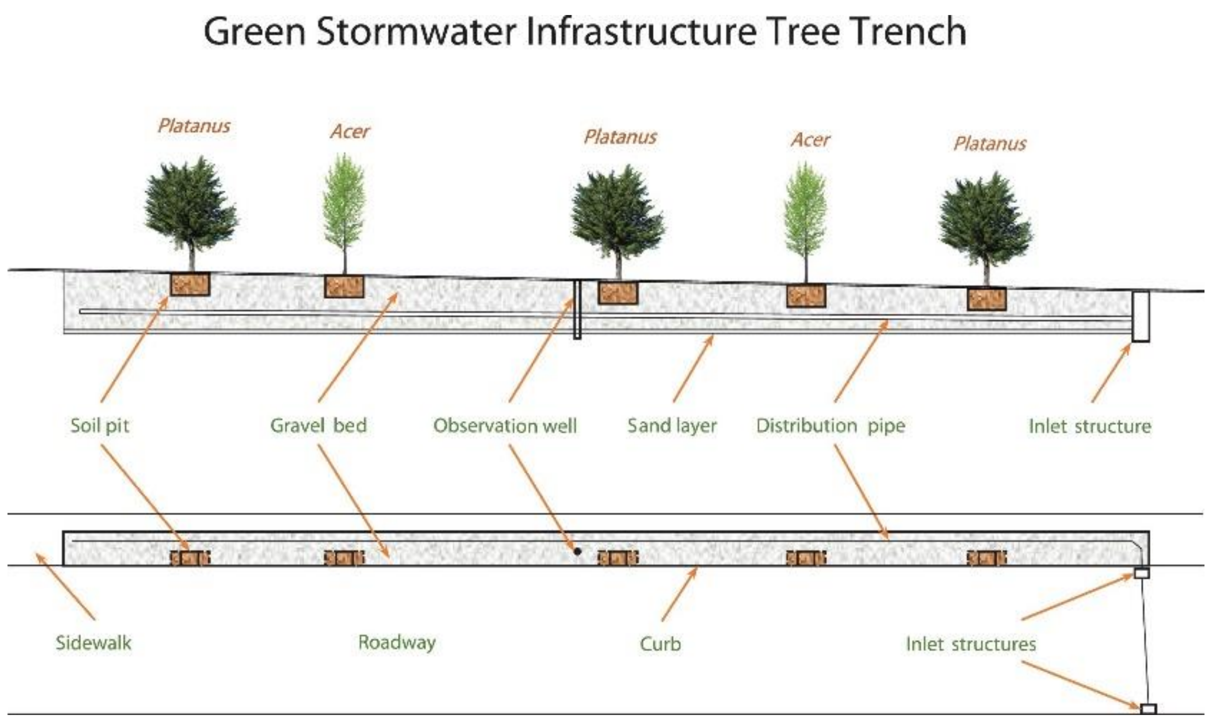


Figure 14: Elements of a green stormwater infrastructure tree trench from (Caplan et al. 2019). The trench is shown in section view (top) and plan view (bottom). Dashed lines depict the extent of soil pits below the sidewalk.

Maintenance of Stormwater Tree Trenches

While STT may have less maintenance than a bioswale or bioretention rain garden, they still require regular maintenance (Table 2). The frequency of vacuum truck cleanouts of pre-treatment catch basins will depend on the street's uses, traffic volumes, and leaf drop. At a minimum, catch basin sumps should be vacuumed at least once a year, and access for inspections and maintenance must be provided (Vega, 2018).

Additional Pre-treatment Components for Source Controls

Pre-treatment is needed to remove debris, dust, leaves, and other debris that accumulates on inlets and prevents clogging within the rainwater management system. Different levels of pre-treatment should be provided, depending on the target water quality and whether the water will be harvested and used. Pre-treatment devices should be easily accessible for inspection and maintenance.

Filter Strips

Filter strips are gently sloped, vegetated areas designed to manage sheet flow from adjacent impervious surfaces such as walkways. The vegetation slows and filters the runoff, allowing some or all of it to soak into the ground. Filter strips should be integrated into the overall site design and can be used to help fulfill a site's landscaping area requirement.

Buffer Strips

Buffer strips are natural areas between development and receiving waters. They are intended to protect the stream and valley corridor system, and to preserve vegetated riparian areas within the valley system to minimize the impact of development on the stream itself (i.e., filter pollutants, provide shade, and bank stability, etc.). Although buffer strips may only provide limited benefits in terms of stormwater management, they are an integral part of the overall environmental management. The protection of stream and valley corridors provides significant benefits to wildlife, aquatic and terrestrial habitats, and linkages between natural areas.

Oil/grit Separators

Oil/grit separators are a variation of the traditional settling tank designed to capture sediments and trap hydrocarbons (oils) in stormwater run-off. An oil/grit separator is an underground retention structure that takes the place of a conventional manhole in the storm sewer system. There are essentially two design types of oil/grit separators available: three-chamber and bypass. Three-chamber separators operate most effectively when constructed off-line; only low flows should be directed to the separator.

Maintenance

Regular maintenance is critical for filter strips to be effective and to ensure that flow does not short-circuit the system. Conduct semi-annual inspections during the first year (and annually thereafter). Inspect the level spreader for sediment buildup and the vegetation for signs of erosion, bare spots, and overall health. Regular, frequent mowing of the grass is required. Remove sediment from the toe of slope or level spreader and reseed bare spots as necessary. Periodically, remove sediment that accumulates near the top of the strip to maintain the appropriate slope and prevent formation of a "berm" that could impede the distribution of runoff as sheet flow.

Table 7: Maintenance Requirements for Vegetated Filter Strips

Component	Frequency	Activity
Contributing Drainage Area	Bi-annual	Remove trash, natural debris, clippings and sediment
	Annual	Re-plant or seed bare soil areas
Inlets and Outlets	Bi-annual	Remove trash, natural debris and clippings
	Bi-annual	Reconfigure splash block if displaced
	Annual	Remove accumulated sediment
Filter bed	As Needed	Remove accumulated sediment when ≥ 5 cm depth Re-grade and restore cover over any animal burrows, sunken areas when ≥ 10 cm in depth and erosion rills when ≥ 30 cm in length
	As Needed	Add stone cover to maintain 5 to 10 cm depth where specified in the planting plan
	Bi-annual	Core aerate
	Every five years	Remove Trash
Vegetation	Bi-weekly	Watering during first two months after planting
	As Needed	Watering for the remainder of the first two (2) growing seasons (i.e., May to September) after planting or until vegetation is established
		Watering for the remainder of the BMP lifespan
		Mow grass to maintain height between 5 to 10 cm
		Remove undesirable vegetation (e.g., tree seedlings, invasive/weeds)
		Replace dead/diseased plants to maintain a minimum of 80% vegetation cover

		Prune shrubs and trees
		Cut back spent plants
		Divide or thin out overcrowded plants

Sullivan Heights Park, Surrey

5. Local Site Visits and Interview Findings

Twenty-four local establishments were visited, and eight professionals from four municipalities were interviewed. This section highlights the various experiences of Metro Vancouver municipalities (Burnaby, Delta, Surrey, and Vancouver) with the design, construction, and maintenance of different source control projects. While some of the presented projects are examples of outstanding SCs implementation, others can highlight important lessons learnt about the pivotal role of proper design and maintenance plan. The information below is synthesized from the interviews which were guided by the questions in the Appendix.

Bioswales

In Vancouver, 60% of the GI practices and a big asset class are bioretention practices such as bioretention bulges. These practices are multifunctional and provide several co-benefits in addition to stormwater management, such as:

- Calming traffic and minimizing crossing distance and making streets safer,
- Cost effectiveness
- Being easy to maintain, like any vegetated landscapes without stormwater features
- No-regret design, providing ecosystem function even if not maintained properly

Figure 15: 100 Ave, Surrey, roadside bioswale

Sunnyside Neighborhood Concept Plan

On the other hand, in Surrey, the Sunnyside neighborhood concept plan, drainage corridors were used in lieu of traditional community detention ponds. These drainage corridors are open channel bioswales to provide volume reduction, peak attenuation, and water quality treatment to minor storm runoffs. The width of the corridor ranges from 5, 10, to 20 m, sized to manage small rain events (30 mm in 24 hours).

Figure 16: Sunnyside Drainage Corridor Bioswale

100 Ave and 144 St (100 Ave roadside bioswales)

The City took the opportunity to incorporate green stormwater measures with the widening of 100 Avenue to provide water quality treatment and infiltration. Road runoff collected and discharged in vegetated bioswale, and overflows into storm sewer during major storms.

Road Runoff Capture

Curbside Bulges

Curbside bulges are installed along 2-4 lane roads. The performance target for the City of Burnaby's RMAs is to drain 90% of the 6 months 24 hours rainfall in 1 day. Table 1 shows the ratio of maximum impervious drainage area to the RMA surface area for different roadway and land use classifications.

Table 8: Maximum Ratio of Impervious Drainage Area to RMA Surface Area

Roadway/Land Use Classification	Maximum Ratio of Impervious Drainage Area to RMA Surface Area
Major/Minor Roadways and Sidewalks	15:1
Residential/ Collector Roadways and Sidewalks	30:1
Sidewalk and Boulevard Areas, No Roadway	50:1

Figure 17: Pine Street and 8th Ave Bioretention Bulge

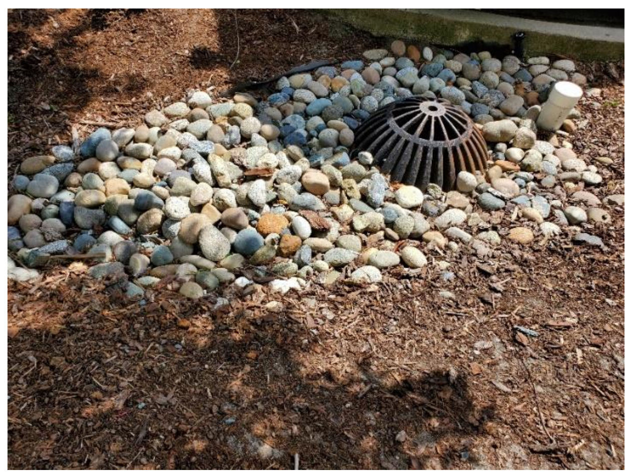


Figure 18: Curbside bulge overflow

Rain Gardens

Surrey Recreation Centre Demonstration Rain Gardens

In 2009, the South Surrey Recreation Centre, located at 14601 20 Ave, identified a drainage problem in their parking lot. Roof water from the centre was ponding in the parking lot due to poor drainage. The site provided an excellent opportunity to showcase the benefits of incorporating absorbent landscaping and rain gardens, by its public exposure and by the buy in from the Recreation Centre administration to develop an educational and awareness plan around the facility for community and youth groups. The rain garden is approximately 150m^2 and was completed at the end of 2011.

Figure 19: South Surrey Recreation and Arts Center Rain Garden during a rain event.

In both Delta and Burnaby, rain gardens have been installed with the intention of being accessible public spaces. In the City of Burnaby, rain management amenities (RMA) are implemented in the cities four town centers to infiltrate runoff from wide sidewalks, reduce urban heat island, and increase tree canopy. In Metrotown, RMAs are installed alongside Beresford Street as part of an architectural statement "Mayor's Avenue Walk". These RMAs are top loaded with runoff from the sidewalk and are not connected to the street runoff. Developers have experimented with several vegetation combinations and have included exotic plants such as Palm trees for aesthetic reasons. It was found; however, that certain exotic drought tolerant plants do not survive the winter climate in British Columbia. This has led the City of Burnaby to reduce the list of approved vegetation for these amenities. The City of Burnaby currently does not have specific performance monitoring programs in place for these RMA, but have so far seen no rainwater-related issues with this infrastructure (ponding, etc..) between 2012 and 2020, and are assumed to be performing as needed (Wong 2020).

Linear Design/Surface Infiltration Examples

Figure 20: Willington Ave Rain Management Amenity

Figure 21: Beresford St near Willington Avenue

In North Delta, 26 rain gardens have been installed between the years 2009 and 2017 (figure 3). Some of which are built to infiltrate site and roof runoff and parking lots, such as the McCloskey-BC Hydro rain garden and the North Delta Recreation Center, or alongside streets and avenues. The Cougar Creek Streamkeepers is a community organization that coordinates, promotes, and helps maintain rain gardens in North Delta.

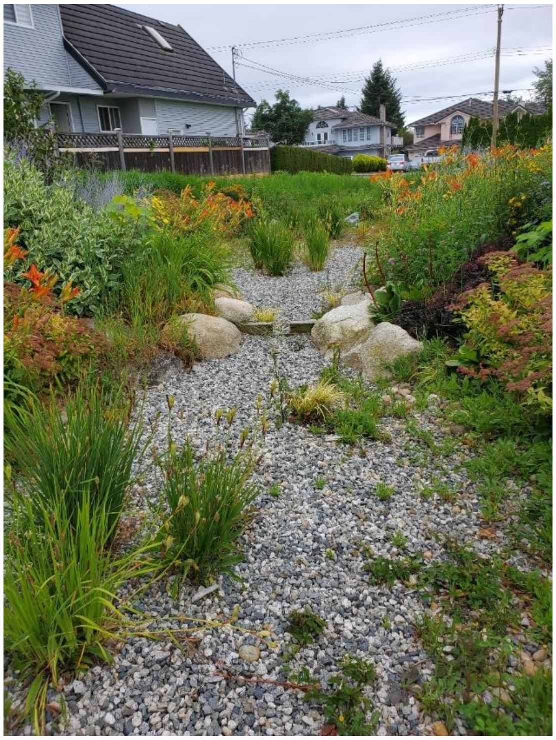


Figure 22: McCloskey – BC Hydro Rain Garden in North Delta

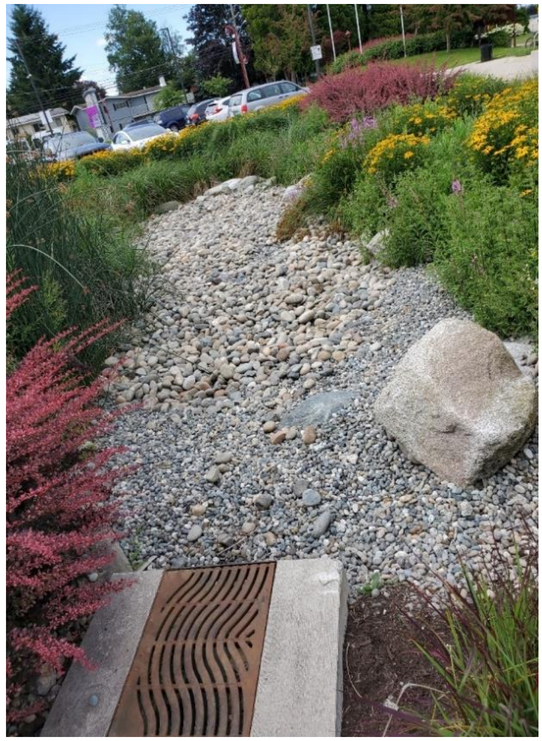


Figure 23: North Delta Recreation Center Rain Garden

There are no performance measures for water quality and quantity put in place, however, the engagement of the community through the Streamkeepers program helps keep an eye on the gardens and note the common issues. The common issues with the maintenance and installation of these gardens inform future designs. Some of the common issues related to design include:

- **Overuse of rock**: rocks can make it more difficult to extract weeds, especially the case with river rock. It is now recommended to maximize the "soil-sponge" for water absorption and then add rock for aesthetics and erosion protection where water flows. A 5-cm layer of ¾" crush mixed with torpedo gravel (50-50) is said to provide stability and ability to weed.
- **Geotextile Material**: geotextile is found to interfere with the opening of new pores in the soil by roots and soil organisms.

- **Confusing rain garden depth with garden capacity**: A densely planted shallow garden is found to manage water better than a deep one that is close to the water table.
- **Insufficient water intake drop-off**: It is important to provide a leeway for sediments to build up at the intake, without blocking water flow entirely until next maintenance.
- **Failure to maximize infiltration space**: Many gardens are designed so that water makes a beeline from intake to emergency overflow drain. Instead, water should be guided to meander or pool throughout as much area as possible.

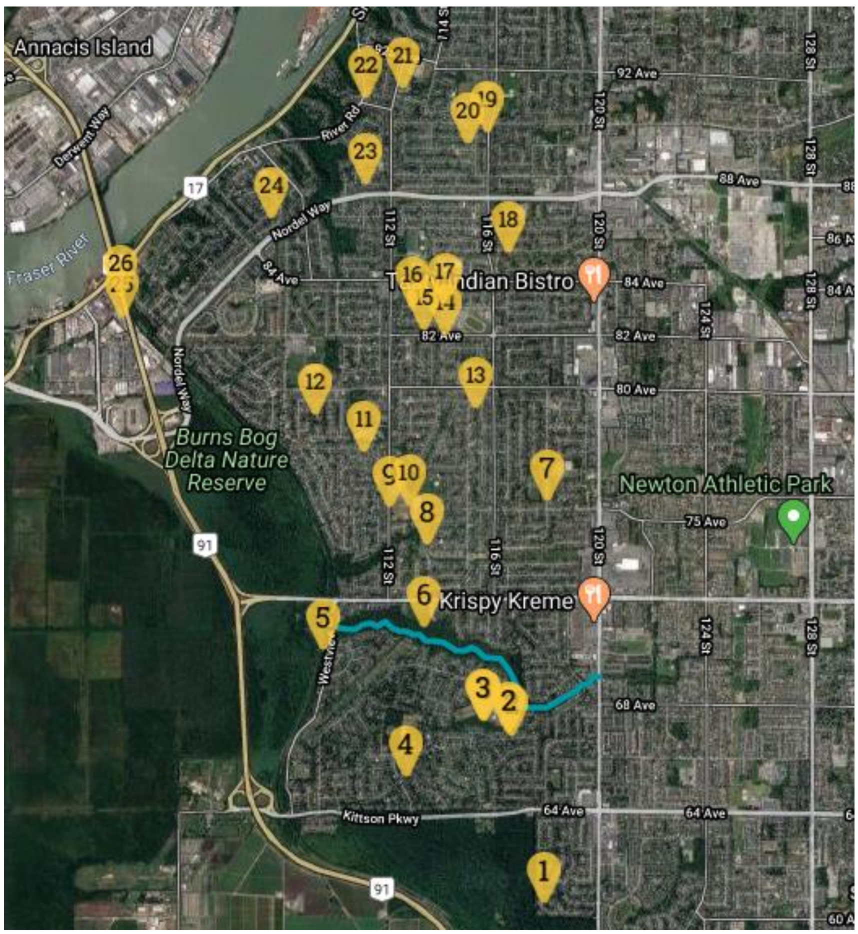


Figure 24: North Delta Rain Gardens Map

Soil Cells

Stormwater tree trenches, such as the ones implemented on the 10th avenue Bikeway, were sought by the City of Vancouver to maximize the use of the right of way by adding a functional stormwater management component. Also multifunctional in nature, stormwater tree trenches have proven to be ideal for constrained areas where large swales don’t fit, while meeting the city requirement for mminimum soil volume for street trees.

Subsurface infiltration facilities are also widely spread in the city to provide pretreatment for road runoff before entering the sewer system.

Figure 25: Quebec Street and 1st Avenue Bioretention Planters

Figure 26: The construction of subsurface infiltration component underneath a bike path in Downtown Vancouver, Richards and Dunsmuir.

Figure 27: Permeable Pavers in Athletes Way at Columbia - Olympic Village

Detention Ponds

Cantrell Detention Pond located at 2860 140 St

In January 2003, Ocean Park developments applied for the subdivision of lot 2866 – 140 Street. As part of their requirements for subdivision they were required to provide interim detention on each of 5 new lots being created. Due to the proximity of the proposed 28 and 140 Street detention site It was noted that the Lot 4 could be a viable alternative for an open detention area that would provide significant costs savings. A comparison between the detention system in the road allowance and on lot 4 - 2866 – 140 St. determined that the cost savings are in the order of $440,000. The City purchased the lot for $232,000 in 2003. The pond is currently well-maintained by the community.

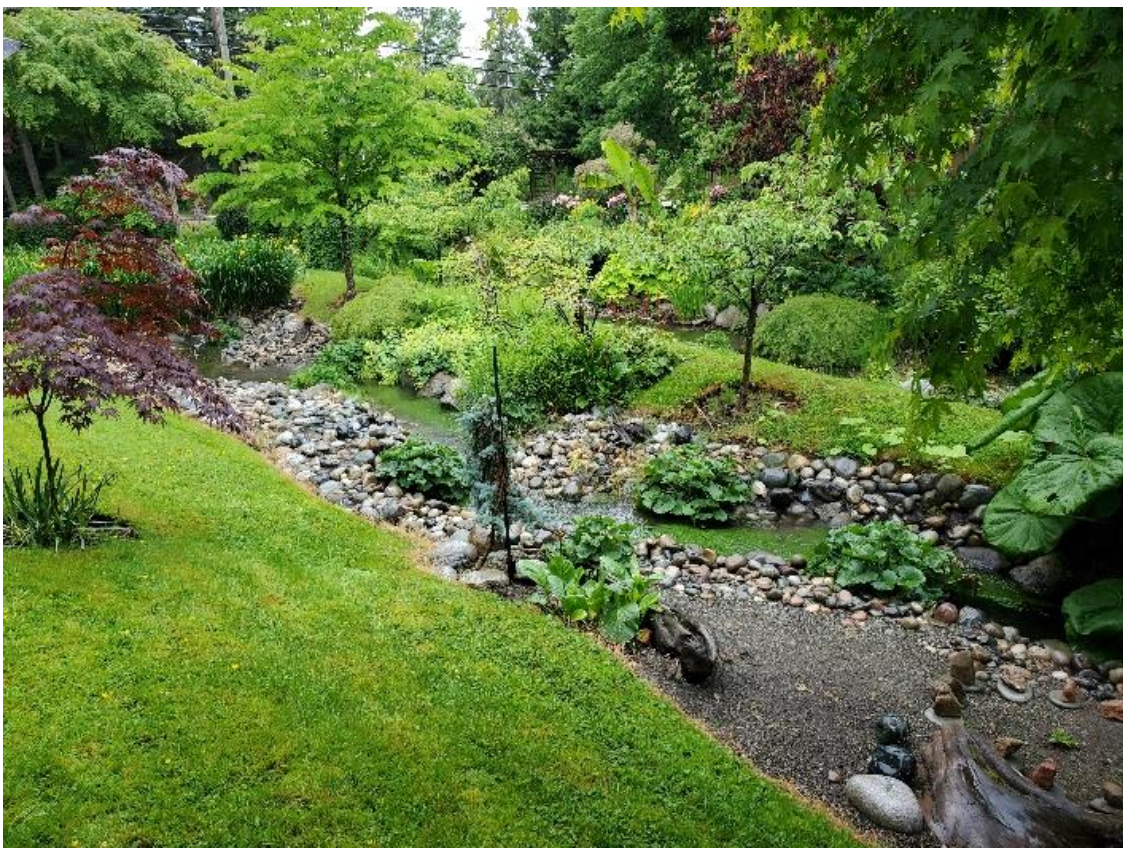


Figure 28: Cantrell Detention Pond

Permeable Pavement

Olympic Village was designed with innovative rainwater management tools such as green roofs, permeable pavement and swales, and energy efficiency systems such as heat recovery from sewage. One of these tools is the permeable paving stones used in parking spots along Athletes Way, which allows rainwater runoff to pass through tiny gaps in the surface and soak into the soil below. As a mitigation to the frequent maintenance requirement for roadway permeable pavers to prevent clogging, these pavers are used on sidewalks and not roadways in Olympic Village. However, it was further demonstrated through the experience of the City of Vancouver staff that permeable pavement on truck accessible areas (roadways rather than sidewalks) are easier to maintain, due to the need for access of vacuum truck.

Sullivan Park Parking Lot Porous Pavement

The porous pavement project was completed in conjunction with the Sullivan Park detention pond in 2007. The porous pavement project was constructed as a demonstration project for the long-term performance of porous asphalt under traffic.

Figure 29: Sullivan Park Parking Lot Porous Pavement

Abandoned bird nest found in a Rain Garden in Delta during tour.

6. Maintenance and Operation

Understanding Conventional Concerns About Source Controls

When SCs were newly introduced to municipalities, operating and maintaining them so that they continue to function properly was considered a challenging task. That was the case 10 and 15 years ago. However, with the growth of resources and collection of information from the field, these challenges can be circumvented. Below are highlights of typical concerns that are cited (Detwiler 2019; Meng Ting et al. 2017).

Uncertainty Regarding the long-term effectiveness

Several cities stated that incorporating GI aligns with their long-term goals, but to have a measurable impact, their plan requires a broad and continuous effort on an incremental basis. Several long-term monitoring studies have been completed that demonstrate the long-term effectiveness of GI, further monitoring guidelines are discussed in this section.

Lack of Awareness or Poor Public Perception of Green Infrastructure

Some municipalities have struggled with a poor public perception or lack of awareness about green infrastructure practices which can create a barrier to effective maintenance and their overall success. Voluntary homeowner incentive programs (EPA 2009) offer an opportunity to engage residents and educate them about maintenance responsibilities. Workshops, tours, and other events offer opportunities to educate the general public about green infrastructure practices. Volunteer programs can also create opportunities for collaboration with community groups to engage residents to take a proactive role in maintenance of green infrastructure practices.

Operation and Maintenance Burden

In some research studies, interviewees cited the heavy maintenance burden of GI as a major challenge, especially when the required maintenance is manpower driven. Many green infrastructures, especially those that include vegetation, require regular maintenance to ensure such green tools are functioning properly. Maintenance tasks include on-site inspection, trash collection, weeding, and irrigation, which can be labor-intensive.

Also, what should be recognized is the multi-functional nature of GI. Often, vegetated GI is taking a space that would have been landscaped anyway, such as a median, a boulevard, a bump-out, or planter. Now the landscaped space is providing a stormwater function but with only a minor increase in maintenance tasks. Similarly, removal of sediment from GI is reducing maintenance from siltation and wear that may happen on downstream infrastructure like pipes and outfalls.

It is important to recognize that while green infrastructure may require more maintenance resources than gray infrastructure it also provides many watershed protecting services that gray infrastructure cannot. Gray infrastructure fails to meet the water balance and water quality objectives necessary to meet the goals set out in the Integrated Watershed/Stormwater/Rainwater Management Plans. Green infrastructure are the only tools to achieve those goals, but they can also provide many other ancillary benefits (urban heat island reduction, climate change resiliency, biodiversity support, public health, etc.) that gray infrastructure does not.

Designing for maintenance can also vastly reduce maintenance costs. Pre-treatment is often overlooked but can simplify maintenance and protect and extend the life of the green infrastructure asset. For example, Figure 30 compares two inlets, one that frequently clogs as it has no pre-treatment and another that has an easily cleaned sediment pad and a drop behind the inlet that allows space for debris and sediment to collect without blocking the flow through the inlet (Lukes, interview 2020).

Figure 30: Street side bioretention inlet clogged without pretreatment and an inlet with sediment pad and drop behind the inlet that reduces potential for clogging and eases maintenance

Financing Operations and Maintenance

One of the primary challenges for effective operations and maintenance of green infrastructure practices is identifying appropriate funding mechanisms. In many communities, stormwater programs are financed through general funds which compete with schools and other priorities. Communities are now using a variety of funding mechanisms from charging new development for maintenance over the lifecycle, funding through water and sewer usage rates, or applying a stormwater utility fee by impervious area as the Victoria Capital Region has done (Victoria Stormwater Utility, 2016). It is also important to differentiate establishment maintenance which is 2-3 years from long term maintenance. Establishment maintenance, which is for establishing young plants and is a different care regime than long term maintenance, should be funded out of capital budget as a vegetated green infrastructure practice is not fully functional until the plants are established (refer to section 6). After establishment, a lower effort maintenance regime can be applied. A frequent mistake is overlooking the initial establishment effort which can lead to more long-term maintenance problems and cost.

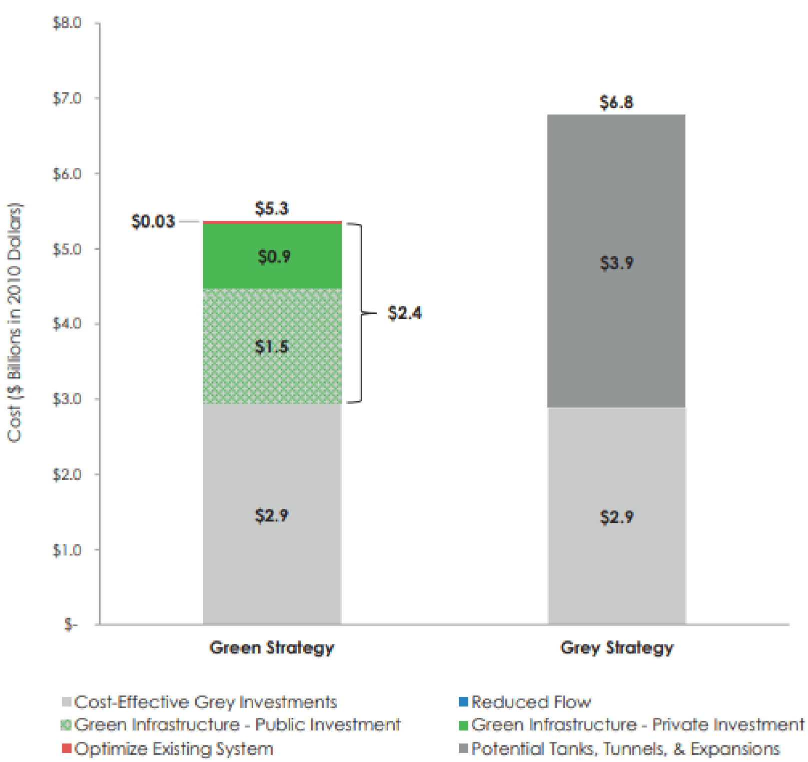


Figure 31: City of New York costs of Combined Sewer Overflow Scenarios after 20 years. Source: City of New York

Limited Training and Certification in Green Infrastructure Operations and Maintenance Available

Limited opportunities exist for practitioners such as landscape contractors, engineers, or landscape architects to become certified or receive training in operating and maintaining green infrastructure practices, though such programs are beginning to be more commonly offered. Developing maintenance standards for green infrastructure will create a baseline from which to create tailored trainings and certifications following existing models such as the North Carolina State University's Best Management Practice Inspection and Maintenance Certification, the Chesapeake Bay Landscape Professional (CBLP) certification program, or training programs held by local governments. Leveraging existing municipal resources and collaborating with community groups can expand training and certification programs that can ultimately lead to employment and business opportunities for people with applicable skills to maintain green infrastructure.

Local Solutions

One of the most frequently mentioned issues in maintenance is invasive species overtaking the intended vegetation. This problem is heightened when the planting was too sparse in the rain garden to begin with. The goal should be that when the green infrastructure feature is mature, it should have no bare soil. Regular mulching reduces the need to weed, conserves moisture in the ground during dry periods, and improves water absorption by reducing water compaction. Wherever there is bare soil, a good maintenance practice is to increase regular mulching and/or supplement plantings.

High maintenance costs for pruning is also attributed to the selection of plants which their mature height will interfere with sightlines. Tall and short plans (eg limbed-up trees paired with dwarf shrubs, ferns, groundcover) are now known to make for cheaper, easier maintenance. Each City has dealt with maintenance costs through its own capacity.

Figure 32: Bioswale near Ontario At and 1st Ave, Vancouver, BC, June2020

The City of Burnaby hires contractors to perform the maintenance on each RMA. The cost of this maintenance is paid for by the developers in the beginning of each project containing an RMA. Since 2015, the city collects 20 years upfront of maintenance dollars from developers to maintain site RMAs such as the side-walk rain gardens. The City is also in the process of standardizing the design specifications and requirements for RMAs as well as routine inspection, irrigation, and maintenance to be used as guidance for the contractors.

The City of Delta rain gardens heavily rely on community members for regular maintenance. Several rain gardens are built on school premises and are integrated to the curriculum of specific classes. It requires a lot of effort to pass these curriculums from one teacher to the other and recruit new teachers every year to sustain this program. When this occurs, it often leads to the lack of proper maintenance for these rain gardens. To mitigate this, Cougar Creek Streamkeepers also host multiple work parties a year in order to weed and replant the gardens where needed.

The City of Surrey faces challenges over who is responsible to maintain the residential drainage corridors. The City intends to maintain wider corridors and have the homeowners maintain the 5 m corridors; however, there is no program being implemented. A similar resident-lead program to the Chantrell Detention Pond could possibly be implemented to successfully maintain the bioswales.

For roadside bioswales, the maintenance is less challenging. Typically Engineering maintains grass in road right of ways and Parks maintains the planted areas like medians and frontage roads. For the rain garden in Surrey Recreation and Arts Centre, maintenance is provided by Parks as this asset is higher on the priority list for being on the premises of a civic center.

During my interview with Mr. Robb Lukes about the specific maintenance challenges or burdens associated with GI, he mentioned that all landscapes, even ones without stormwater management components will also require similar maintenance efforts. For bioswales, special requirements like inlet cleaning from sediment take place. Even if these landscapes do not receive the optimal maintenance or get taken over by weeds or invasive species, they will still in most cases serve their stormwater treatment purpose. Traffic management and truck accessibility must also be considered in the siting and designing of GI, as traffic management can be expensive and some maintenance is done more easily with trucks.

Maintenance and operation also teach designers many lessons for future designs. For example, creeping of turf grass into herbaceous bulges taught designers to put a concrete barrier around vegetation. Another example is pedestrian interactions and safety with GI features, which have taught designers to consider slope steepness and fencing as part of bioswale design.

At the City of Vancouver, O&M for GI are divided into two categories: establishment maintenance and long-term O&M.

Establishment Maintenance

Like other vegetated practices, an establishment/warranty period follows the installation of most GI practices. The establishment period is typically a contractually obligated period where the contractor responsible for installation is also responsible for maintenance of the GI, for a predetermined length of time. The vegetated system is not fully functional until the establishment period is complete; therefore, this period is part of the construction/ installation process and is paid for through capital funding in the City of Vancouver. They also include 3 years of establishment in the capital cost for bioretention and bioswale assets and ensure that additional care required during establishment is conducted by a qualified contractor.

Figure 33: Bird Nest in North Delta Rain Garden

Long-term maintenance

Following the establishment period, a long-term O&M program is required to ensure the city's assets are protected against risks of failure. At the City of Vancouver, on-going maintenance for vegetated GI comes from general funds. With the formation of the GI branch, oversight and management of the City's GI program now lies within the branch, however maintenance activities remain distributed across various departments, including Street Activities, the Park Board, Streets and Sewers. The City has considered specialized training programs such as The National Green Infrastructure Certification Program (NGICP) that provides the base-level skill set needed for entry-level workers to properly construct, inspect and maintain green stormwater infrastructure (GI).

Performance Measures and Monitoring

Performance targets provide the foundation for implementing common sense solutions that eliminate the source of stormwater related problems. Performance indicators are measured metrics that inform practitioners on the effectiveness of stormwater facilities relative to the targets.

Chapter 6 in the *"British Columbia's Stormwater Planning, A Guidebook for British Columbia"* offers a framework to develop performance targets to managing the complete spectrum of rainfall events from rainfall capture (infiltration best management practices) for small storms, runoff controls for large storms (storage) and flood risk management for the extreme storms (ensure that the drainage system can safely convey extreme storms to the receiving water course). The BC Stormwater Planning guidebooks calls for performance target that are quantifiable and have a feedback loop so that adjustments and course corrections can be made over time.

New source controls are built to fulfill certain runoff volume and rate criteria, based on a presumptive performance of each practice type. Continuous monitoring help determine the relative effectiveness of green infrastructure and

Performance targets and design criteria provide a basis for:

- integrating appropriate stormwater management policies with land use and community planning
- selecting appropriate site design practices to reduce runoff and improve water quality at the source.

In Metro Vancouver, monitoring the effectiveness of stormwater measures usually occurs at the watershed scale by measuring water quality, flow and Benthic Invertebrate Index at key creek and river sites. Performance measures for Green Infrastructure vary by municipality and are not consistently adopted.

Figure 34: Barrier used to separating bioretention vegetation from grassed boulevard helps to prevent vegetation creep from one area to the other, Pine St, Vancouver, BC, June 2020.

Performance Indicators

There are many scientifically proven indicators for the performance and sustainability of green infrastructure. Widely used criteria to compare the effectiveness of green infrastructure are: runoff volume, peak flow, total suspended solids, and total nitrogen.

Innovations in green infrastructure design should be monitored for effectiveness. Monitoring to address specific questions, like performance of older facilities or the effectiveness of certain maintenance.

Flow monitoring:

Flow monitoring aims to measure the volume reduction and peak flow reduction that is achieved by water being retained in the source control practice as well as the lag time for the run-off to reach the stormwater sewer.

Total Nitrogen:

Total nitrogen measurements for runoff consist primarily of soluble forms of nitrogen. This is particularly important to monitor because excess nitrogen causes eutrophication and algal blooms, leading to reductions in dissolved oxygen and degradation of aquatic communities.

Total Suspended Solids:

Total suspended solids (TSS), the amount of particulate matter suspended in water, is both easy to monitor and an important component of water quality. Suspended solids in stormwater can cause sedimentation in rivers and streams and aid in the transport of heavy metals and phosphorous. Measuring TSS is an inexpensive way to assess the quality of water discharged for pathogens, metals, and other nutrients.

Turbidity is especially easy to measure, but it is important to note that turbidity's relationship to TSS varies widely from location to location. Turbidity should not be used in place of TSS unless a local relationship has been established and sensing equipment has been properly calibrated.

Inspection and monitoring have been built into most of the reviewed cities' guidelines for rainwater management. Monitoring by observation is one of the most widely used methods

Below is the City of Burnaby's guideline on inspection for Rainwater Management Amenities:

> *Inspections of newly constructed RMAs should be conducted every 1-2 months and following storm events larger than a 6-month, 24-hour storm event (≥47mm rainfall in a single event). After observing and recording first year's performance and maintenance needs, a customized inspection schedule can be created with a minimum inspection frequency occurring twice per year.*

Other Performance Indicators

Indicator-based frameworks for assessing the sustainability performance of GI projects strive to understand the environmental performance of GI as well as the social and economic benefits (Pakzad, Osmond, and Corkery 2017). These indicators include:

1. Climate change adaptation and mitigation;

2. Human health and well-being;

3. Healthy ecosystem;

4. Biodiversity;

5. Economic benefits;

6. Alignment with political issues and city strategies;

7. An active travel network;

9. Food production.

Performance Targets and Monitoring of the City of Vancouver GI

There are two performance targets set by the City of Vancouver for green infrastructure: water quality and quantity.

- Water quantity target is defined with 48 mm volume retention of 90% of average annual rainfall, to the maximum practical extent possible.
- Water quality performance target is defined as 80% removal of Total Suspended Solids (TSS) from 90% of average annual rainfall. There are no performance targets for water nutrient, metal, and pathogens removal; these areas of concerns are often addressed by achieving the 80% TSS removal.

The City currently has monitoring wells, among other monitoring infrastructure, in place for tracking performance of green infrastructure. According to the City of Vancouver Senior Engineer in Green Infrastructure Implementation, Mr. Robb Lukes, performance monitoring has benefits in four main areas:

1. Demonstrating regulatory compliance,
2. improving designs,
3. optimizing maintenance and operations, and
4. comparing the performance and effectiveness to literature values

Monitoring Wells

Monitoring wells with HOBO water level loggers are installed in certain locations (including West 63rd Avenue and Yukon Street and Quebec Street and 1st Avenue) to track water level changes during storm events and the infiltration performance of the practice over time.

The monitoring data to date has found that the implemented green infrastructure at the mentioned sites have exceeded the presumed performance. Post-construction infiltration rates are often far higher than the conservative rates determined during the geotechnical investigation.

Certification Programs

One of the previously cited concern about implementing effective source control measures in the limited certification and training available. This section presents existing certification programs focused on stormwater management for both practitioners and sites. These programs provide gold standards and targets for the performance of stormwater management infrastructure within developments seeking the citification. In addition, developing maintenance standards for green infrastructure will create a baseline from which each municipality can create tailored trainings and certifications for staff.

NGICP

The National Green Infrastructure Certification Program (NGICP), based in the United States, provides the base-level skill set needed for entry-level workers to properly construct, inspect and maintain green stormwater infrastructure (GI). Designed to meet international best practice standards, NGICP is a tool that can be used to meet a wide range of needs, including professional development for existing GI professionals and as part of a larger workforce development to provide candidates with the technical skills necessary to enter the green workforce and earn a livable wage.

The implementation of the NGICP is governed by Bylaws and a Policy and Procedures Manual. NGICP is a new program that is growing and constantly evolving, therefore suggestions regarding how program implementation can be improved are always welcome.

The certification process consists of the two steps:

1. Applicants for the NGICP certification exam are required to complete a NGICP exam training course provided by an approved trainer and have a high school diploma or equivalent.
2. To maintain GI certification, all certified individuals are required to recertify every two (2) years, at which time a certified worker must document participation in a minimum of 14 contact hours of continuing education training in topics directly related to constructing, inspecting or maintaining green infrastructure during each two-year certification cycle.

The certification application fee is 200 USD and does not include the cost of the exam training course, which varies by location Since the NGICP is a US program, Canadian participants would normally have to travel to the US to obtain the certification. However, in December 2019, the Toronto and Region Conservation Authority (TRCA) hosted the NCICP training and certification program, for the first time in Canada, at a fee of 380 CAD. This was a pilot for the International Green Infrastructure Certification Program (IGCP) with more training planned in 2020.

Salmon-Safe Certification

Salmon-Safe certification is available to BC municipalities and regional districts, developers and other landowners in both the private and public sector. The certification can apply to such places as parks and natural areas, college or university campuses, business sites and residential developments in urban, suburban and rural settings. Land can be certified even if it has no watercourses on it. This recognizes that commercial, industrial and residential activities, even those not immediately adjacent to streams and rivers, have long-term cumulative impacts on fish and other aquatic species.

Figure 35: Salmon Safe Logo

Stormwater management is one of the core urban standards for the certification, along side water use management, and erosion prevention and sediment control, chemical and pesticide reduction and water quality protection, and enhancement of urban ecological function.

Salmon-Safe development should go beyond minimum regulatory requirements and use creative and thoughtful approaches to benefit urban ecology and salmon habitat through stormwater management practices. The stormwater standards are:

Standard U.1.1: Existing site improvements related to stormwater management have been inventoried.

Standard U.1.2: An offsite drainage analysis has been conducted.

Standard U.1.3: Site layout responds to site conditions in a way that conserves contiguous existing vegetation, minimizes impervious or semi-pervious areas, eliminates effective (or connected) impervious area and minimizes stormwater runoff.

Standard U.1.4: Stormwater management planning results in clear benefits to water quality and flow control. Stormwater management planning generally follows a hierarchy that prioritizes total onsite treatment and infiltration.

Standard U.1.5: Parking and roadway design deliberately minimizes the footprint of impervious area and associated stormwater runoff.

Standard U.1.6: Building design deliberately minimizes the footprint of impervious area and associated stormwater runoff.

Standard U.1.7: Stormwater facility design results in water quality and flow control benefits that meet predevelopment hydrology planning goals established in U.1.4.

Standard U.1.8: Stormwater facilities and infiltration features are fully integrated with habitat-based site features

Standard U.1.9: Construction practices avoid or reduce short- and long-term negative stormwater impacts resulting from construction.

Standard U.1.10: The appropriate managing authority within the development has adopted a long-term stormwater management plan as a concise written document to formalize the existing low impact development practices.

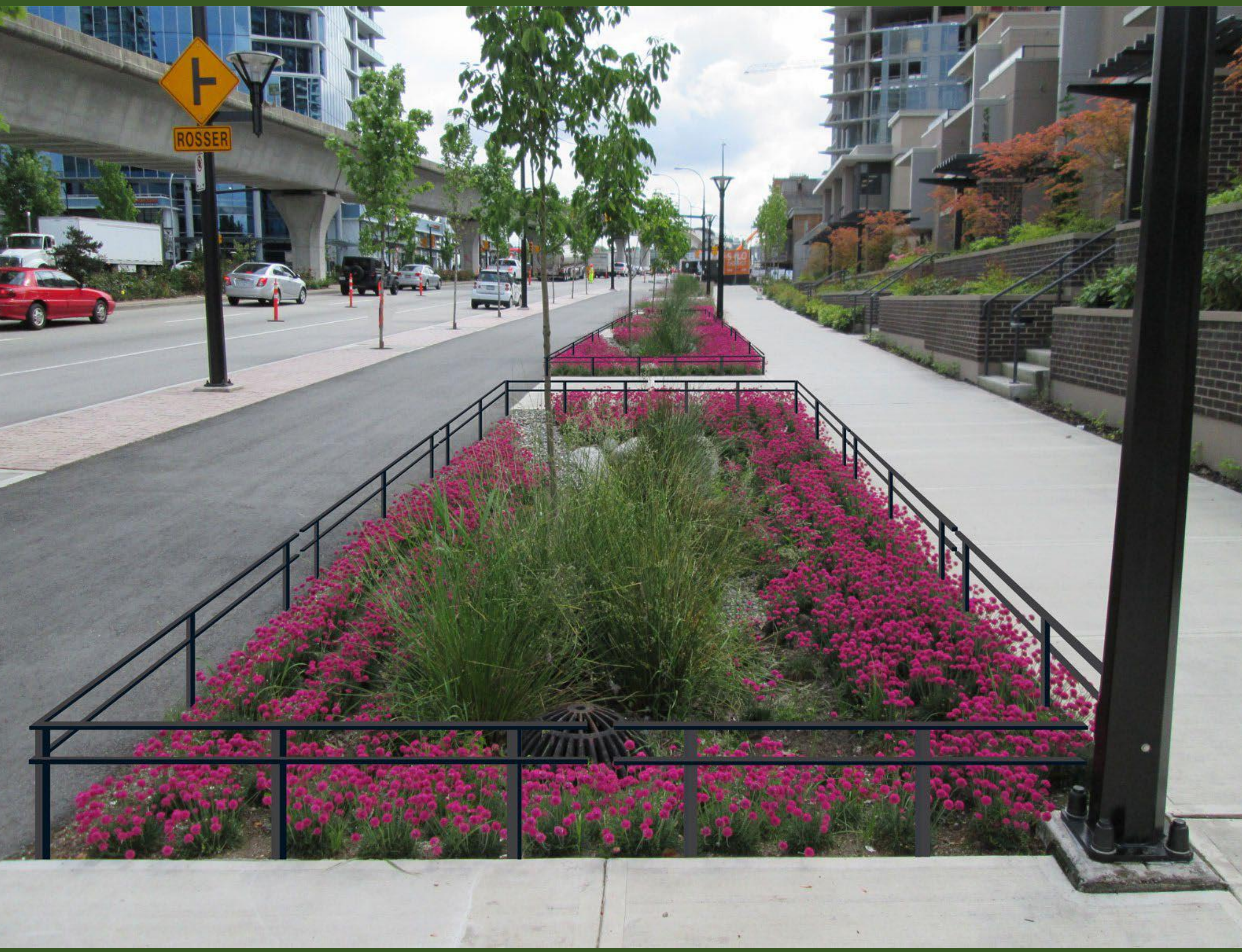
Salmon-Safe Communities for BC is managed by Fraser Basin Council. In 2015, the MEC Head Office was the first urban site in BC to be certified as Salmon-Safe due to progressive water management practices. The second site in 2016 was the Vancouver International Airport. The MEC Vancouver flagship store in Olympic Village is the third Salmon-Safe urban site in BC (2019), with several more sites seeking certification in various stages of development.

Salmon-Safe Urban Development Certification is valid for five years, subject to annual verification of satisfactory progress in meeting any conditions to the certification. After the five years are up, developments may be recertified through a recertification process composed of a project site audit and assessment.

LEED Rainwater Management Credit

LEED Sustainable Sites (SS) credits 6.1 (Stormwater Management, Rate and Quantity) and SSc6.2 (Stormwater Management, Quality) are intended to reward projects for design and construction strategies which achieve significant environmental benefit that exceeds standard practice. Applicants can gain credit through several rainwater management aspects, such as:

- Reducing the use of water by harvesting rainwater (25% to 50% reduction)
- Using low-impact development (LID) and green infrastructure to manage onsite runoff from the 95th percentile rainfall events.
- Reducing stormwater runoff and non-point source pollution
- LEED v4 and LEED v4.1 Building Design and Construction (BD+C) and Operations and Management (O+M) Rainwater Management credit allows projects to gain rainwater retention points through the purchase of off-site rainwater retention credits through a local Stormwater Retention Credit (SRC) market.



Rainwater Management Amenity at Lougheed Highway, Brentwood Town Centre, Source: City of Burnaby Town Center Standards

7. Recommendations

The literature and practice around green infrastructure and source control measures are continuously evolving. The transfer of knowledge through clear and standardized guidelines will help municipalities overcome the barriers associated with certifying, managing, and maintaining source controls around Metro Vancouver. The timely updating of the Stormwater Source Controls Design Guidelines will serve to catch the stakeholders up with the rapidly growing literature and key lessons from implemented SCs.

The recommendations presented here are based on the experiences gained within Metro Vancouver and from practices in cities with similar climates.

Recommendations Specific to the SSCDG:

Maintenance and Operations

The 2012 volume of the SSCDGs offers limited information on the operations and maintenance needs of the listed source controls. The addition of comprehensive operations and maintenance protocols would offer a valuable addition to the guide which could happen through the following:

- Expand the SSCDGs to include a section on Maintenance and Operations for SCs, preferably in a separate volume. This would help separate the information into “Design” and “Maintenance and Operations”.
- Include detailed maintenance protocols for each type, with emphasis on establishment maintenance, to be accounted for at the design phase. This will help give the developers a head start on knowing what needs to be done to make of their establishment a fully functional source control.
- Update of the list of acceptable vegetation on a regular basis to reflect current regional experience and successful establishments.
- Provide guidelines on retrofitting or basic maintenance for older establishments

Classification of Practices and Pre-treatment

The 2012 SSCDGs includes six main source control topics: absorbent landscapes, bioretention facilities, vegetated swales, pervious paving, infiltration trenches, sumps, and drywells, and extensive green roofs. Modern practices include modified and new designs that should be added and classified by development type:

- Add sections on blue-green roofs, soil cells and stormwater tree trenches, and smart approaches.
- Classify the source controls to ones best for “high density / urban” areas and “low density / suburban”, and separate “small scale” and “large scale” practices based on required area.
- Expand the guidelines to include a section on pre-treatment practices for each source control

Performance Measuring

In addition to regular operations and management, setting guidelines for visual and measurable performance indicators and measures is needed, such as: visual indicators of plant and soil health, scheduled inspection for different storm sizes, and a reference of long-term monitoring programs.

Recommendations for Additional Considerations to be Investigated:

Due to the limitation of time, certain topics related to source controls were noted down as important to be further investigated:

- Guidelines for growing healthy street trees and trees in rain gardens
- Provide guidance on source control modifications or enhancements to address particular pollutants of concern in a receiving water, such as bioretention soil mix designs that capture nutrients.
- The digitization of the SSCDG and the development of a tool that municipal staff can use to discuss source control options with developers, such as the use of Wiki formats to facilitate the process of updating information

8. Conclusion

In 2010, the Integrated Liquid Waste and Resource Management Plan (ILWRMP) stated that stormwater should be managed at its source to protect the environment. Source control measures, such as bioswales, rain gardens, green roofs, and tree trenches, have become more common in Metro Vancouver in the past decade. Cities around the world too are building distributed networks of green stormwater infrastructure systems to capture stormwater before it enters sewers.

The literature and practice around green infrastructure and source control measures are continuously evolving. The transfer of knowledge through clear and standardized guidelines helps municipalities around the world design, manage and maintain source controls effectively. The Stormwater Source Control Design Guidelines (SSCDG), published in 2012, serves as a guiding document for developers and municipalities in the source control design process.

This project investigates the effectiveness of six source control measures in the existing SSCDG in managing urban stormwater quality and quantity and sheds the light on emerging best practices. Information from this project will lay the foundation for updating the SSCDG which may be undertaken by the Stormwater Interagency Liaison Group (SILG) in 2021.

The literature reveals that effective implementation of such measures is not limited to appropriate design and sizing, but also is contingent on the proper installation, maintenance, and operations. Emerging source control approaches augment, rather than replace, existing green and gray infrastructure. For example, blue-green roof capillary irrigation systems that increase rainwater retention while reducing irrigation demand. Smart sensor systems and real-time control allow us to adapt the functionality of the infrastructure systems to individual storm events. Finally, collocating street trees and engineered stormwater catchments in ‘tree trenches’ offers a space-efficient strategy for providing ecosystem services and managing stormwater simultaneously.

Challenges to implementing and maintain SCs do exist and have been documented and cited in the urban sustainability literature, such as issues related to maintenance and funding. However, with the growth of resources and long-term monitoring studies for this infrastructure types, these challenges can be circumvented. There are existing certification programs focused on stormwater management for both practitioners and sites. These programs provide gold standards and targets for the performance of stormwater management infrastructure within developments seeking densification.

During the span of this project, 24 local establishments were visited, and eight professionals from four municipalities were interviewed. The site visits uncovered a lot of local lessons learned around the implementation of source control practices, such as leveraging existing municipal resources and collaborating with community groups to ensure the proper maintenance of this infrastructure. Also, the establishment maintenance period, which is a contractual obligation for the contractor responsible for installation, ensure the appropriate maintenance for a predetermined length of time. Following the establishment period, a long-term operations, inspection, and maintenance program is required to ensure the city's assets are protected against risks of failure.

The recommendations presented in this report are based on the experiences gained from practices in world-class cities with similar climates to Metro Vancouver, combined with the knowledge gaps and needs identified within the Metro Vancouver region. The recommendations for the SSCGs are divided into three topics: Maintenance and Operations, Classification of Practices and Pre-treatment, and Performance Measuring. The 2012 volume of the SSCDGs offers little information on the operations and maintenance needs of the listed source controls. The addition of operations and maintenance protocols will offer a valuable addition to the guide. Also, modern practices like blue-green roofs and soil cells include modified and new designs that could benefit urban high-density areas.

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10. Appendix

Interview Questions

1- Questions about the site or facility:
   a. What year was this facility installed and the year of any major change or upgrade happened?
   b. What are the main stormwater features of this site?
      i. Example: type of infiltration (partial, full), type of storage, other (per type)
   c. What was the motivation and rationale for picking this type of green infrastructure?
   d. What was the design goal (WQ, Volume, Peak Flow)?
   e. Were there any lessons learned from design and construction?

2- Changes to the facility over time:
   a. Were there any alterations that prevented this site from functioning properly?
   b. How have the following things changed about this facility since installation?
      i. The overall ecosystem health of the facility
      ii. The frequency of maintenance (dredging, weeding, etc…)
      iii. The individuals/entities responsible for operation and maintenance
      iv. The priority of taking care of this asset as opposed to other city assets
      v. The cost of operating and maintaining this asset
      vi. The density of building/development in the area surrounding and the volume of traffic

3- Questions about facility performance:
   a. Was there a specific certification that the city/municipality/owner sought or looked at?
   b. What is your opinion as a (manager, engineer, gardener) on the performance of this facility?
   c. What co-benefits has this asset provided? (saved space, provided habitat, supported urban tree canopy, increased public safety, added an aesthetic amenity, reduced urban heat island)
   d. Would you implement this practice again? What would you do differently?
   e. *Sub-surface infiltration specific (infiltration trenches, dry wells,..)* – How is the runoff pre-treated before it is infiltrated?
   f. What methods are available to monitor the following:
      i. Water quantity: volume reduction, peak flow reduction
      ii. Water quality: pollutant removal, other
      iii. Soil characteristics: soil moisture and salt migration
   g. How often does the monitoring happen and when did it start?
   h. Is the overflow being inspected monthly?

i. What are the performance measures put in place and what are the units of measure?
j. What technologies are used or required in measuring performance/ or maintenance?
k. Is there data on the runoff quantity before and after the installation?
    i. If no, has there been any noticeable change in small storm induced floods?
    ii. What have been the most significant benefits of this facility for storm water?

4- Questions on facility maintenance:
    a. Is this in your asset management work, how do you schedule and prioritize the work?
    b. Are their pieces of information or resources that are missing from the guidelines?
    c. What are the key maintenance practices done on this site?
    d. How often are each of these maintenance practices done or need to be done?
    e. What training has been done or resource is available for the staff members responsible to look after the facility, if needed?
    f. What maintenance difficulties or issues are associated with this facility?
    g. Which entity is responsible for operation and maintenance of this facility?