Building Green Infrastructures: Assessment of Bioretention Practices Initiatives in Vancouver

LWS 548 Major Project

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

In recent decades, the continued growth of urban development and climate change have led to multiple issues that affect the sustainability of urban drainage systems. The increase in impervious surface areas and extreme rainfall events in urban areas have altered watershed hydrology and groundwater hydrologic. Typical impacts include higher peak flows and runoff volumes, shorter lag times, and reduced infiltration and baseflow. Urban runoff also increases pollutants and nutrients, thereby degrading water bodies downstream in urban creeks. One of the most commonly used practices to mitigate these impacts is bioretention. Bioretention can capture and treat rainwater to return rainfall to a natural pathway and provide aesthetic and ecological values to treat rainfall as a resource.

Despite its widespread use globally, research on bioretention systems remains active, particularly in the areas of its design and performance. This paper reviews a recent study focusing on bioretention, including the development and design application of bioretention systems, the performance of bioswales and rain gardens in hydrologic impact and water quality.

This paper focuses on the analysis of bioretention practices implementation in the City of Vancouver and uses Portland and Seattle as successful examples. In the City of Vancouver, there are a few comprehensive policies and strategies related to G.I. implementations, but with less public support and people's awareness. Both Portland and Seattle are at mature G.I. implementation stages that have also met similar challenges and have overcome them with strategic solutions, such as public engagement and providing Incentives and Rebates. Therefore, the City of Vancouver should learn from these two thriving cities.

INTRODUCTION

In recent decades, urban development has dramatically increased with a projected continuation known as densification (U.S. Environmental Protection Agency, 2021). This increasing urbanization and population growth cause a massive conversion in land use and impact the environment and ecosystems (Wang, Zhou, Pickett, Yu, & Li, 2019). With all pavements and commercial constructions in urban areas, there is an increasing percentage of impervious pavements on the land surfaces, reducing natural riparian vegetations, stream cover, soil loss, and increasing wastewater runoff from industrial and human uses (U.S. Environmental Protection Agency, 2021). Meanwhile, urbanization also accelerated global warming by creating heat islands, which contribute to drier summertime (U.S. Environmental Protection Agency, 2021). All of these alterations finally result in the alteration of natural hydrological processes. The increasing amount of rainwater cannot penetrate the ground, increasing the frequency of urban runoff and stormwater flooding and put pressure on the sewer piping systems (U.S. Environmental Protection Agency, 2021).

With increased rainwater management awareness, different countries have applied different but similar approaches to address stormwater retention and rainwater quality and quantity problems (Jegatheesan et al., 2019). The more recent ones are the water-sensitive urban design (WSUD) in Australia, the "Sponge City" programme in China, the sustainable urban drainage systems (SuDS) in the U.K and the low impact development (LID) in the USA (Jegatheesan et al., 2019). These approaches are referred to green infrastructure (G.I.) (Jegatheesan et al., 2019).

The US EPA has defined green infrastructure (G.I.) as "A cost-effective, resilient approach to managing wet weather impacts that provide many community benefits." (U.S. Environmental Protection Agency, 2020). G.I. is an approach to rainwater management to mimic, protect, and retain the natural water cycle at its source with engineered and ecological practices to bring environmental, social, and economic benefits (Table 2) (City of Vancouver, 2019). It refers to the natural plants, soils, and bioengineered structures (Table 1) to capture and filter rainwater before sending them back to waterways and atmosphere and provide various ecosystem services to enhance the ecosystem and benefit both people and wildlife (Metro of Vancouver, 2015). The significant types of G.I. are bioretention practices (bioswales and rain gardens), rainwater tree trench (RTTs), resilient roofs (green, blue, blue-green, and white roofs), permeable pavement, large scale practices (parks, greenways, and plazas), non-potable water systems, subsurface infiltration practices, and absorbent landscapes.

Table 1. G.I. Typologies. (City of Vancouver, n.d.)

Types of G.I.	Uses	Typical applications
Bioretention practices	- Infiltrate and filter rainwater	- Bioswales. - Raingardens. - Bioretention planters.
Rainwater tree trench (RTTs)	- Multifunctional G.I. - Collect the runoff from impervious areas and support for street trees.	- Structural soil. - Soil cells.
Resilient roofs	- Manage rainwater and support plant growth - Reduce sewer overflow volume	- Green roofs: planting vegetation and soil to absorb rainwater - Blue roofs: temporarily store rainwater before releasing it into the sewer system - Blue-green roofs: blue roof with plants - White roofs: include all above in groups
Permeable pavement	- Provide hard usable surface - Allow rainwater to soak into the underlying reservoir base and the ground - Filter rainwater with different layers	- Pedestrian walkways - Bike lanes - Parking lots - Plazas
Large scale practices	- Engineered wetlands - Floodable spaces - Stream daylighting	- Parks - Greenways - Plazas
Non-potable water systems	- Collect, store, treat and supply non-potable water in buildings and facilities.	- Multi-residential buildings - Single-family house - Civic buildings - Public and personal buildings
Subsurface infiltration practices	- Collect and convey rainwater to store and infiltrate them.	- Infiltration trenches, dry wells, soak ways, chambers, arches, modular systems

Absorbent landscapes	- Absorb and retain a more considerable amount of rainwater.	- Residential front yard - City boulevard - Parks

Table 2. Benefits of G.I. (Ahern, 2007)

Environmental Benefits	Social Benefits	Economic Benefits
Improve water quality	Encourage people's outdoor activities	Reduce sewer infrastructure cost
Improve air quality	Enhance people's mental health	Increase property values
Retain and reuse rainwater	Improve people's physical health	Enhance property market
Reduce groundwater runoff	Increase accessibility to nature	Encourage inward investment
Restore aquatic habitats	Reduce crime risk	Improve urban planning market
Promote wildlife biodiversity	The higher hospital recovery rate	Improve tourism
Improve groundwater recharge	Improved productivity at workplaces	Boost local economy
Enhance resilience to climate change		Increase facilities demands
Save energy and resources		Reduce energy cost
Enhance visual amenity		Lower healthcare cost

This paper will only focus on the impacts and initiatives of bioretention practices (bioswales and rain gardens), but all other types of systems also need to be considered if we hope to mitigate the combined impact of climate change and densification, such as constructed wetland, green roofs, rainwater harvesting, soil amendment to increase infiltration, store water, sequester carbon and reduce the need for irrigation, pervious pavements, trees, absorbing surfaces, temporary detention systems etc.

AIM AND OBJECTIVES

One of the most frequently used LID practices is bioretention (bioswales and rain gardens). Although it is used widely, its research is still active, especially its mixed design and treatment (Liu, Sample, Bell, & Guan, 2014). This paper aims to review recent research on bioretention systems, including bioretention system development and performance, including how bioretention can reduce the impact on climate change, reduce the water footprint, and help reduce sewer pressure. A literature review is provided to summarize current bioretention practices, initiatives and policies in Vancouver and the successful examples in Portland and Seattle, including their bioretention practices' program, degree of uptake, challenges and strategies, and the lessons that Vancouver can learn from Portland and Seattle.

The aims objectives are:

- Undertake a general introduction about green infrastructure and its applications.
- Literature reviews with a focus on bioretention practices, the type of programs, uptakes and benefits, and current bioretention practices and initiatives in Vancouver.
- A summary of some successful bioretention practices applications in Portland and Seattle.
- Provide recommendations to enhancing the current bioretention practices initiatives and G.I. in the City of Vancouver.
- Produce a current bioretention practices map of the region of the City of Vancouver.

METHODS

The paper's discussion is based on reviewing the relevant literature about the general benefits and programs of bioretention practices. The analysis summarized available literature data about Portland, Seattle and Vancouver and compared their initiatives. The visualization of current public bioretention assets in Vancouver also showed as a GIS mapping overlay using the data from the City's Open Data Portal.

LITERATURE REVIEW

This section reviews three aspects of bioretention practices: the introduction of bioretention systems and its development, performance, benefits and bioretention practices in the City of Vancouver, and examples of successful bioretention practices in other places, and the comparison among the three cities.

Introduction of Bioretention Systems

Development of Bioretention Systems

Bioretention systems are the at-source structural stormwater best management practices developed in Prince George's County, Maryland, in the early 1990s (Roy-Poirier, Champagne, and Filion 2010). The development and early adoption of bioretention systems were driven by many beneficial characteristics (Roy-Poirier et al., 2010). In the early 1990s, bioretention systems were developed. The benefits are summarized below.

Bioretention systems remove pollutants from water by filtering polluted stormwater through bioactive plants and soil. They play an essential role in the initiatives of low-impact development or water-sensitive urban development because they are smaller in size, aesthetically pleasing, and can achieve sustainable stormwater management goals (Trowsdale & Simcock, 2011). The stormwater management goals include reduction in peak stormwater flows, runoff volumes and stormwater pollution, and the maintenance of groundwater recharge and stream baseflow. The primary benefits are reported as protecting outflow waters from pollution and erosion (Trowsdale & Simcock, 2011).

Design Applications

Bioretention systems are small areas excavated and backfilled with a mixture of highly permeable soil and organic material designed to maximize infiltration and improve growth. The vegetation in bioretention should be tolerant to environmental stresses and include small plants, shrubs and large trees depending on the size of the bioretention area (Roy-Poirier et al., 2010).

There are different design variations of bioretention. Most are designed as bioswales or wetlands implemented on the side of roads, parking lots or other impervious areas. Runoff from impervious surfaces is directed to the bioretention site, where it forms ponds and slowly allows water to infiltrate into the ground. Water flow from heavy rainfall events can bypass the bioretention area and can be conveyed directly to the sewer system. It can also be temporarily detained in ponds and designed storage places. Bioretention systems can also help to reduce pollutant loads to waterways and recharge groundwater through infiltration and evaporation of runoff volumes (TRCA, 2019). Alternative names are commonly used for these types of practices, including rain gardens, bio-pits, dry pits, stormwater planters, and bio-filters (TRCA, 2019).

Even though each bioretention area may have slightly different components, they generally consist of vegetation and filter media covered by an organic mulch top layer. Some applications have gravel drainage systems under the soil. The soil beneath the mulch layer is primarily a combination of sand and a small proportion of silt, clay and organic material that helps improve infiltration rates and filters pollutants from surface runoff. Both plants and mulch in bioretention help improving infiltration and removing contaminants. Native species that can tolerate elevated pollutant levels and fluctuations in soil moisture are commonly planted in the area (TRCA, 2019).

Instead of allowing stormwater to infiltrate into the native soil below, some bioretention systems are designed with an impermeable liner at the bottom of the system. Water flow is transported to the sewer system directly or receiving water body after infiltration through the media. In this type of bioretention system, because of evaporation, peak flows are diminished, and volumes are reduced, but the system does not allow groundwater recharge (TRCA, 2019).

Bioretention Systems Performance

Bioretention systems, in general, can improve site aesthetics, reduce noise, and provide shade and wind cover (Roy-Poirier et al., 2010). Despite all the social benefits that bioretention systems provided, they also play a critical role in stormwater treatment. Extensive studies have been conducted in laboratory and field studies to evaluate the performance of bioretention systems for stormwater flow retention and infiltration and pollutant removal (Roy-Poirier et al., 2010). This section reviews the key findings of these studies.

Hydrologic Impacts

The results of a study over 12 events from the field-scale bioretention facilities have demonstrated that bioretention can effectively reduce the outflow of the rainwater flow volume. There was a significant reduction of about 59% between total outflow volume and the total inflow volume. In addition to the reduction of water runoff, the practical catchment areas of bioretention were also reported. All of the 12 catchments were three times larger than the area used for the LIB, including building roofs and surrounding impervious areas (Trowsdale & Simcock, 2011).

Davis reported similar results from the study of 49 storm events at two field-scale bioretention practices at the University of Maryland, showing bioretention can effectively reduce the impact of development. The study showed that 18% of 49 monitoring events have no detected outflow. Storm events had a smaller inflow (less than 0.5 m3/m2) that was entirely captured by the onsite bioretention cells. The average peak flows observed for the monitored cells were reduced by 49% and 58%, respectively. The times to peak also decreased significantly, with an average factor of 5.8 for one cell and 7.2 for the second cell. Longer peak times allow for better simulation of the pre-development hydrology of the basin (Davis, 2008).

There is also a watershed-level analysis of the performance of 10,000 rain gardens in a metropolitan area in the City of Kansas. This analysis not only explains the role of rain gardens in improving water quality but also shows that rain gardens effectively reduce the total amount of water entering the sewer system and reduce the percentage of runoff (Ma, 2013).

In some cases, the natural and engineered combination will create a better environment and work better than only use natural bioretention systems. For example, in a test area, the tree in the control site was planted in native soil that was found to be compacted and poorly drained. The experimental site placed the tree in a bioswale containing an engineered soil consisting of three-quarters lava rock and one-quarter soil. This greatly increased the porosity and water holding capacity of the site. The engineered soil provided a better environment for tree growth and also served as an ideal medium for the isolation of bacteria from boarding contaminants. The two sites were monitored during 50 separate rainfall events. The bioswales at the experimental site (with engineered soils) reduced parking lot stormwater runoff by 89% compared to the control site (McGarvey, 2014).

Water Quality

In this water quality performance section, bioretention systems will be divided into two main parts, bioswales and rain gardens, based on the different issues and contaminants they deal with.

- **Bioswale**

Bioswales, effectively retain large amounts of runoff and pollutants on-site and consistently reduce the concentration of certain pollutants, such as metals, oil, grease, sediments, nutrients, and other organic contaminants. Overall, bioretention areas play an essential role in reducing runoff volumes and treating the first flush (first 1/2 inch) of stormwater (Ma, 2013).

Nitrogen and Phosphorus Removal

Nutrients, especially nitrogen and phosphorus, are the primary pollutants that concern the protection of aquatic ecosystems. High nutrient loads can lead to eutrophication of receiving waters due to excessive algal blooms and decay that deplete dissolved oxygen in the water (Roy-Poirier et al., 2010). Davis and colleagues conducted bioretention box experiments to study nutrient uptake efficiency. The results showed that the total phosphorus removal rates ranged from 70% to 85% resulting in an average mass removal rate of 82%. Meanwhile, 55-65% of the total Kjeldahl nitrogen (TKN) was removed (Davis, Shokouhian, Sharma, & Minami, 2006).

Oil and Grease Removal

Bioswales are also used as stormwater treatment methods in parking lots and roadways to collect and treat flooding runoff primarily from vehicle emission and tire wear, and oil and grease deposition.

Bioretention columns were tested on 18 soil media of different compositions to determine the best soil for pollutant removal. Based on results, all soil media reported over 96% oil and grease removal. The capacity of oil and grease removal of eight existing bioswales in Maryland was also tested to confirm the previous laboratory results. For all the bioswales, oil and grease removal exceeded 99%, similar to developments in the laboratory study (Roy-Poirier et al., 2010).

One more concern about oil and grease pollution is that they are persistent and can be accumulated within bioretention cells. Thus, the report suggests using a mulch layer in bioretention systems to minimize the accumulation of the hydrocarbons (Roy-Poirier et al., 2010). Removal of oil and grease can also be done in a flow-through separation before the water enters the swale.

Heavy Metal Removal

In Davis's studies, copper, lead and zinc were heavy metal species used to test for metal removal. For all the tested metals, the removal efficiencies were greater than 97%. From the sample testes, the mulch layer took responsibility for the metal retention.

Glass and Bissouma have conducted three months of study that measured the inlet and outlet concentrations of many heavy metals in a parking lot bioretention basin. The results show removal efficiencies of 81% for copper, 66% for cadmium, 79% for zinc, 53% for chromium, 75% for lead, 17% for aluminum, 11% for arsenic, and 53% for iron. It was suggested that because the bioretention system was not well maintained in the field experiment, the removal efficiencies observed were lower than those done in the laboratory.

There is also one concern about the heavy metal removal through bioretention systems because bioretention systems have a limited capability to store the filtered metals. Thus, a large proportion of metal-saturated plant biomass is needed to remove the metals from bioretention systems to avoid the metals accumulated in soil media and plant roots (Roy-Poirier et al., 2010).

TSS Removal

Suspended solids can clog stormwater conveyance systems or damage aquatic environments. (Roy-Poirier et al. 2010).

According to the field study conducted by Sam and Robyn, there were visible changes in TSS concentrations. The sediments discoloured many inflow samples, but outflow samples were clear. The data support the observation that the bioretention system significantly reduced TSS concentrations (median 30 mg/L, maximum 375 mg/L). The maximum concentration measured in the effluent was very high, with an upper quartile concentration at the outlet of only 3.8 mg/L (Trowsdale & Simcock, 2011).

The study of Li and Davis (Li & Davis, 2008) illustrates the concern for removing TSS from bioretention systems. Based on the results of this study, it was concluded that the valuable lifetime of the bioretention filter media is limited by clogging, which is expected to happen before the TSS breakthrough. According to laboratory results, it is recommended to replace the bioretention soil medium every year or every two years, with a 5-20 cm depth, as a potential measure to prevent medium clogging (Li & Davis, 2008).

BOD and Pathogens Removal

Although the number of pathogens in rainwater may be much smaller than that in sanitary wastewater, pathogens in urban runoff are a concern for regulatory agencies because they are harmful to humans and aquatic species. The column test conducted by Rusciano and Obropta in 2007 showed that the bioretention system can reduce significantly pathogens in runoff water. For 13 experiments containing a series of fecal coliforms, the average reduction was 91.6%, and the removal rate ranged from 54.5 to 99.8% (Rusciano and Obropta, 2007).

- **Raingardens**

Rainwater gardens have been recommended as the best management practice for stormwater runoff. However, unlike bioswales, not much onsite performance data on pollutant removal capacity was published. In Haddam, a replica rain garden experiment showed the design is very effective for overall flow retention but has little effect on the concentration of pollutants in the leachate. Rain gardens reduce peak flow rates and increase the lag time of incoming water. The only nutrient retained by the rain gardens was NH3-N. Overall, these rain gardens provided runoff control, but water quality modification was limited. The installation of rain gardens without culverts may not be applicable in all cases (Dietz & Clausen, 2005).

The temperature has also been studied in the rainwater garden system. However, no difference in temperature between the inflow to the rainwater garden and its outflow was found (Ma, 2013).

Summary

The bioswales are the main GI system to deal with both stormwater and pollution reduction that originates from the transportation and traffic system. Rain gardens are a useful GI tool for property owners and they are mainly designed to reduce the amount of stormwater runoff that enters the drainage system. Since property runoff is not very polluted, the pollution reduction function is minimal. All other GI systems that can be done at the property such as rainwater harvesting, green roofs, soils, trees, reduction in impervious driveways should also be considered. Meanwhile, the bio-accumulation and phytoremediation of plants in bioretention is another function to reduce pollutants bot just soils.

Bioretention Practices in Vancouver

Site Background

Vancouver in southwestern Canada, is a growing and expanding city with a rapidly increasing population and has a rising demand for housing. The Metro Vancouver Regional Growth Strategy (2011) anticipates that by 2041, there would be an increase of 150,000 houses and the extra demand for 90,000 jobs in Vancouver. This urbanization puts pressure on housing and employee demands and the need for water resources, sewer systems, and urban drainage ability. (City of Vancouver, 2019) Besides the growing populations, the densification and the increase in climatic variability are the primary reasons for using green infrastructures to cope with large precipitation events in Vancouver (Table 1).

Table 1. Past and Projected Annual Temperature and Precipitation for Metro Vancouver (Metro Vancouver, 2016).

	Past	2050s Change (Projected Average Increases)	2080s Change (Projected average Increase)
Average Annual Daytime High Temperature (Annual)	13 (℃)	2.9 (℃)	4.9 (℃)

Average Annual Nighttime High Temperature (Annual)	4 (°C)	2.9 (°C)	4.8 (°C)
Annual Single Day Maximum Precipitation	69 (mm)	17 (%)	32 (%)
Total Annual Precipitation	1869(mm)	5 (%)	11 (%)

Vancouver's Policies in G.I. Implementation

In 2010, the province adopted an Integrated Liquid Waste and Resource Management Plan (ILWRMP) developed by Metro Vancouver and its member municipalities. Under the ILWRMP, municipalities are required to create an Integrated Stormwater (or Rainwater) Management Plan (ISMP or IRMP) for every watershed catchment within their municipal boundaries to protect the environmental and social health from flooding, municipal pollutant loads and rainfall impacts (City of Vancouver, 2016).

The basic premise of stormwater management plans is that untreated urban runoff is a primary source of pollution and must be managed appropriately. Pollutants contained in rainfall and runoff, including hydrocarbons, heavy metals, sediment, organic matters, and fertilizers can be transported into the surrounding water bodies, such as Burrard Inlet, English Bay, False Creek and the Fraser River. If the stormwater is not treated, these urban pollutants can harm the environment and marine ecosystems (City of Vancouver, 2016).

For over a decade, City staff has supported G.I. implementation in public areas, such as "Country Lanes (2002-2004), the Crown Street Sustainable Streets Project (2006), Creekway Park (2013), and numerous rain gardens and infiltration bumps (2004+)" (City of Vancouver, 2016). A comprehensive community-scale green infrastructure project has been developed for the Olympic Village in the Southeast False Creek neighbourhood (City of Vancouver, 2016). The development of G.I. on private property was stimulated by LEED building requirements and the Sustainable Large Development Policy, which requires stormwater management plans for all development sites over 2 acres (City of Vancouver, 2016).

Following up the ISMP, the government put more attention to G.I. implementations, and Vancouver's government has developed strategies, action plans and policies (Table 2.) to enhance the green rainwater infrastructure planning approach. The most important one that related to the G.I.'s implementation is the *Rain City Strategy*. It is a document that reimagines and transforms how Vancouver manages rainwater to improve water quality, resilience, and livability through creating healthy urban ecosystems.

Table 2. Strategies, Action Plans, and policies.

Documents	Goals	Targets
Rain City Strategy	1. Treat Vancouver's abundant rainwater as a resource. (City of Vancouver, 2019) 2. Reduce the demand for potable water by encouraging beneficial reuse. (City of Vancouver, 2019) 3. Restore the role of urban watersheds to support urban and natural ecosystems and provide clean water. (City of Vancouver, 2019)	Capture and treat 90% of average annual rainfall in Vancouver by using GRI. (City of Vancouver, 2019) "Manage urban rainwater runoff from 40% of impervious areas in the city by 2050." (City of Vancouver, 2019)
Rainwater Management Bulletin	"Provides further direction for rain city strategy in that it establishes the site-specific requirements developers must meet in submitting rainwater management plans, including guidelines for volume reduction, release rate and water quality." (City of Vancouver, 2018)	
Sustainable Large Development Bulletin	"Provide principles of sustainable site design in land development and management practices." (City of Vancouver, 2018)	

Green Buildings policy for rezoning	"Provide two pathways to compliance for green building rezoning: Near-Zero Emissions Buildings, and Low Emissions Green Buildings." (City of Vancouver, 2010)	
City of Vancouver Biodiversity Strategy	"Increase the amount and ecological quality of Vancouver's natural areas to support biodiversity and enhance nature access." (Vancouver Board of Parks and Recreation, 2016)	"Restore or enhance 25 ha of natural areas by 2020." (Vancouver Board of Parks and Recreation, 2016)
Urban Forest Strategy	Protect, plant, and manage trees to create a diverse, resilient, and beautiful urban forest on public and private lands across the City. (City of Vancouver and Vancouver Park Board, 2018)	Plant 150,000 trees by 2020. (City of Vancouver and Vancouver Park Board, 2018)

Current Bioretention Practices in Vancouver

Currently, there are several successful bioretention projects in the City of Vancouver, including 63rd Avenue and Yukon Street boulevard improvements, Burrard and Cornwall, Olympic Village and Hinge Park, and St George Rainway (City of Vancouver, n.d.). These projects provide comprehensive G.I. implications, including bioretention practices initiatives and educational materials for people to learn from.

Below is a map of Vancouver's bioretention distribution in the public realm (Figure 1.). In the map, the yellow polygons represent the locations of current bioretention assets in the city; the blue polygons with dashed boundaries represent the watershed catchment areas in the region of the City of Vancouver. There is a total of 151 bioretention practices in the city. According to the visualization, in general, bioretention is distributed evenly throughout the city. There are some aggregates of them in the Balaclava and Champlain watersheds.

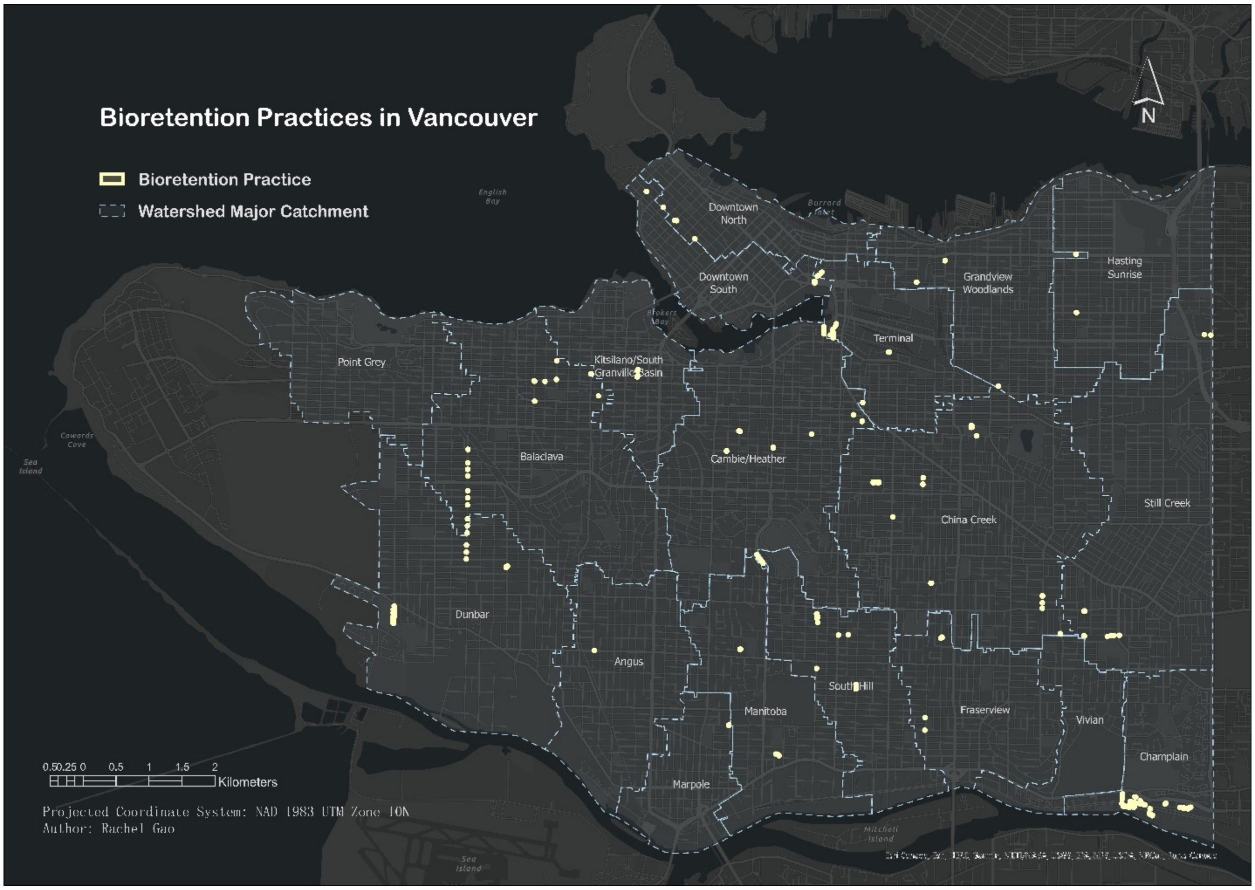

Figure 1. The distribution of bioretention practices in the public realm in the City of Vancouver.

(All GIS data is provided by the Green Infrastructure Implementation Department of the City of Vancouver.)

Bioretention practices in Seattle and Portland

Seattle and Portland, two of the most successful cities to adopt G.I. They have a comprehensive strategy to minimize CSO, stormwater runoff pollution, and flooding (McGarvey, 2014). Both cities have their own G.I. implementation methods and related successful projects and outstanding achievements on stormwater management (Table 3). Meanwhile, there are also challenges and barriers when implementing G.I. as a new infrastructure in urban planning. Portland and Seattle have both come up with effective strategies to overcome those barriers. Their challenges and strategies are also Vancouver and other cities' lessons (Table 4).

Table 3. G.I. implementations and achievements in Portland and Seattle (McGarvey, 2014).

City	GI Implementations	Achievements
Portland	Use of green roofs (called eco-roofs by the Portland Bureau of Environmental Services), "green streets with bioswales, bioretention areas (also called rain gardens), flow-through bioretention planters, downspout disconnections, street sumps and sedimentation manholes, targeted sewer separations and detention tunnels" (McGarvey, 2014).	Portland has reduced CSO discharges to the Columbia Slough and Columbia River by 99% and 94%, respectively (McGarvey, 2014). More than 35% of the City's stormwater runoff in combined sewer/stormwater basins is managed by G.I., and the number is expected to rise to 43% by 2040. This extensive G.I. network has also eliminated a significant amount of nonpoint source pollution from stormwater runoff (McGarvey, 2014).
	There was a project underway in Portland, Tabor to the River, which encompasses the entire urban watershed (about 6 square kilometres), including 500 green street improvements, 100 small G.I. installations on private sites, 5,300 new trees, 24,690 meters of combined replacement sewer/stormwater pipe and underground overflow storage facilities as a long-term comprehensive solution to the area's localized flooding and CSO problems (McGarvey, 2014).	The project, Tabor to the River, demonstrates the cost savings potential of integrated community-wide G.I. implementation (McGarvey, 2014). The City of Portland projected $63 million in savings from this project's strategy than using only traditional infrastructure and storage tunnels (McGarvey, 2014).
Seattle	In the early to mid-2000s, Seattle Public Utilities (SPU) implemented a series of successful G.I. Street improvements. In 2010, this approach was widely used throughout the community (McGarvey, 2014).	Initial surveys of the six communities targeted by the program estimated that G.I. could reduce 80% of the stormwater entering the combined sewer/stormwater systems (McGarvey, 2014). To date, G.I. has been strategically installed in specific neighbourhoods that drain into natural creek basins, with a significant reduction in peak stormwater runoff flows and nonpoint source pollution (McGarvey, 2014).

	In 1998, the new Mayor, Pail Schell, initiated the Urban Creeks Legacy Program to protect marine habitats, dedicating $15 million to restore four major urban watersheds; Piper’s Creek, Thornton Creek, Longfellow Creek and Taylor Creek. After recognizing the importance of reducing the polluted stormwater runoff entering the creeks, SPU Natural Drainage Systems (NDS) initiative was created to coordinate and carry out this task (McGarvey, 2014). In 2001, a street retrofit pilot project, SEA (Street Edge Alternatives) Street, was completed. “This project implemented 201m right-of-way (ROW) features a full-length bioswale on both sides, one sidewalk instead of two, and a decreased road width of 4.3m from 7.6m. To increase the installation’s absorptive and pollutant filtering capacities as well as the aesthetic quality of the bioswales, 1,100 shrubs/grasses and 100 evergreen trees were planted” (McGarvey, 2014).	The project was a huge success, far exceeding the original stormwater runoff retention goal of 19 mm per rainfall event (McGarvey, 2014). Environmental Engineering the bioswales retained an incredible 99% of stormwater runoff from the ROW and properties to the east of the street (total 2.3 acres). In 2003, the SEA Street project gained regional and national recognition as “an innovative approach to sustainable urban stormwater management.” (McGarvey, 2014). During the monitoring period, the bioswale retained half of the region's annual rainfall, with any rainfall event of 25mm or less is fully retained. Of the 235 measured storm events, only 49 caused an overflow in Piper Creek, and most of these had a significant reduction in peak flows (McGarvey, 2014).  Figure 2. Before and After aerial photos of SEA Street in Seattle (Lee, 2007).

Table 4. Challenges and Strategies to the Implementation of G.I. in Portland and Seattle (McGarvey, 2014).

Challenges	**Portland**	**Seattle**

Social	- Public concerns about public safety about bioretention and bioswales areas because of the possibilities of the increase of the conflicts between pedestrian and vehicle. - Public concerns about reducing public areas for parking and fire access increase the conflict with their agricultural spaces. - Language barriers cause some residents do not understand the function of G.I.	- Public concerns about changing the uses of public spaces within streets.
Institutional	- Some other city departments did not think G.I. is a natural form of infrastructure. - Conflicting with internal priorities: G.I. implementation took the funding and internal culture priorities from the ones that should be focused on the sewer and treatment plans. - The increase of maintenance requirements of G.I. caused resistance from the Operations and Maintenance department.	- The increase of maintenance requirements of G.I. caused resistance from the Operations and Maintenance department. - Resistance from the Engineering department because they thought G.I. is a second-class method to manage stormwater.
Economic	- Developers said that the combination of G.I. and conventional infrastructure cost more than just implementing the traditional infrastructure in the earlier years. - It was challenging to compete with other more familiar infrastructures or urgent problems for funding, especially when municipal budgets are tight. - It is difficult to find funding for long-term maintenance. - Lack of public education on the overall economic trade-offs between G.I. and traditional infrastructure.	- The recession in the U.S. has led to tighter budgets, which has increased opposition to G.I. implementation.
Technical	- Because Portland's communities have different soil profiles and infiltration rates, G.I. installations need to be designed to adapt to site conditions. - It was challenging to find space on the ground in the CBD for G.I. to go for full coverage. - G.I. facility would encounter erosion problems where the slope is steep.	

<table>
<tr><th>Strategies</th><th>Portland</th><th>Seattle</th></tr>
<tr><td>ROWs and Pilot Projects</td><td colspan="2">To overcome the resistance of implementation G.I. in ROWs, Seattle and Portland both start this process with small but visible pilot projects that could show the benefits of G.I. and its ability in stormwater management. For example, Seattle’s first pilot project, SEA Street, was a success.</td></tr>
<tr><td>Public Engagement</td><td colspan="2">Public engagement plays an essential role in the success of G.I. implementation in Portland and Seattle, including actively informing the public about the significant benefits of these approaches and providing outreach and education in their various initiatives—in Seattle, holding conferences and forums, meeting with advocacy groups such as Sustainable Seattle to build engagement capacity, publishing articles in local magazines and running social media campaigns. In Portland, the Bureau of Environmental Services (BES) also provided free educational programs to schools to teach people knowledge about stormwater management, CSOs, and G.I.’s benefits. Meanwhile, both cities tried to understand what the residents want from the new G.I. and let them be involved in the conceptual design process.</td></tr>
<tr><td>Provide Incentives and Rebates</td><td colspan="2">Incentives and rebate programs educate residents about G.I.’s impact on the aquatic environment and provide them with tangible reasons to take action. For example, in Portland's successful downspout disconnection initiative, the house owners could have 35% off their stormwater utility fees to manage their roof runoff.</td></tr>
<tr><td>Change the Internal Culture</td><td colspan="2">According to the government in Portland and Seattle, the biggest challenge in the implementation of G.I. was the lack of credibility with existing municipal departments such as transportation, operations and maintenance, sewer and engineering. This is mainly because of the questions about the effectiveness of G.I. To overcome this challenge, in the past 10-15 years, Portland and Seattle have fully monitored all types of their G.I. installations and got very positive results. Portland’s BES also put their monitoring data online to be transparent with their results and gave their G.I. implementation reports every two years. It was also necessary to have a core group of staff to work on G.I. implementation and through their professional and passionate communication with other departments to improve the internal culture surrounding G.I.</td></tr>
</table>

Comparison of initiatives in Portland, Seattle and Vancouver

Seattle implemented its CSO Reduction Plan from 2010 to 2015. It targeted 11 areas of Seattle that remain vulnerable to CSOs in the combined sewer/stormwater system. Following that, from 2016 to 2025, the city also worked on a long-term water quality plan, "Plan to Protect Seattle's

Waterways". This plan identifies areas in Seattle that need CSO reduction projects, evaluates CSO reduction solutions in the affected areas, selects a preferred alternative for each affected area, and recommends a schedule for design and construction projects. Both programs follow a core strategy that prioritizes source reduction of stormwater, maintenance and rehabilitation of existing systems, and the storage of overflows in underground storage facilities.

One of the earliest CSO reduction projects initiated was in Ballard, an older neighbourhood in northwest Seattle. Because the CSO mix was found to contain an average of 90 percent stormwater, an active program was developed to retrofit 20 neighbourhoods in Ballard with GI, including street retrofits that were similar to SEA Street and the Broadview and Pinehurst Green Grids, as well as an "incentivized downspout disconnection called 'RainWise' program" (McGarvey, 2014). Under this initiative, homeowners in the areas are strategic to CSO reduction. They could install rain barrels and/or bioretention areas to receive precipitation from roofs and other impervious surfaces. Then, they can apply for rebates from the city (McGarvey, 2014).

To further reduce the amount of stormwater entering the combined sewer/stormwater system, Ballard's CSO mitigation project also retrofits the driveways with permeable materials. The final goal is to use GI to reduce 95 percent amount of stormwater runoff entering their combined sewer/stormwater system. A large underground storage reservoir was also constructed near the CSO outfall to handle overflow volumes. Seattle's CSO Reduction Plan constitutes an integrated solution that combines GI and traditional sewer/stormwater infrastructure to minimize CSO while increasing resilience to localized flooding without creating residual problems with pollution. It is a promising alternative to Vancouver's sewer separation program (McGarvey, 2014).

Unlike Seattle's Ballard neighbourhood CSO Reduction Plan, Portland's "Tabor to the River" project is a comprehensive and integrated stormwater management retrofit for an entire urban watershed of 6 square kilometres (2.3 square miles). The area is served by a century-old combined sewer/stormwater system that is susceptible to flooding during heavy rains. However, because it contributes to CSOs and causes frequent basement backups and localized street flooding, rather than separating the combined sewer/stormwater infrastructure, the city developed a plan that included: rehabilitation and replacement of 24,689 meters of combined sewer/stormwater pipe, adding 500 new green street facilities, planting 5,300 trees, installing 100 stormwater GI projects on private property, and removal of invasive plant species for the area's parks. This project would save the City of Portland a reported $63 million comparing to conventional infrastructures supported by storage tunnels. In 2011, a set of combined sewer/stormwater overflow tunnels, called “Big Pipe”, was completed. Since then, there were only 6 CSOs have been recorded, which was tremendously better than 50 CSOs in 2002. The city planning to increase the city’s stormwater runoff in combined sewer/stormwater drainage basins that managed with GI from currently 35% to 43% by 2040 (McGarvey, 2014).

Vancouver is at a critical crossroads in its stormwater management strategy. Vancouver started its Citywide Integrated Rainwater Management Plan (IRMP) in 2016, April. The IRMP provides a long-term GI strategy to protect the water bodies surrounding Vancouver. With the 90% of rainwater capture target, Vancouver has started many GI initiatives in both public and private sites (City of Vancouver, n.d.). Currently, from available data, there are 151 bioretention assets in the public realm. However, in terms of CSOs, the city has chosen to completely separate its remaining combined sewer/stormwater system by 2050, representing approximately half of its service area. This constitutes a considerable economic commitment to traditional infrastructure, costing $35 million per year and expected to cost $1 billion to complete. Therefore, Vancouver should consider what has been done in Portland and Seattle, which was to modify the sewer separation program so that can coordinate with traditional infrastructures upgrades and with the integrated GI network (McGarvey, 2014).

CONCLUSIONS

Bioretention is a promising technology that relies on ecological interactions in natural systems to capture and naturally treat stormwater and remove urban pollutants. Bioretention also allows stormwater to infiltrate into the ground to restore groundwater aquifers and reduce the peak flows through sewer systems and urban creeks. Because bioretention plants are highly tolerant to various hydrologic conditions, the system can be used in a variety of environments. Bioretention systems also can significantly reduce the amount of stormwater through infiltration and evaporation.

Therefore, this system can be used in urban areas to offset the increase in stormwater volume associated with urban development (Roy-Poirier et al., 2010).

Bioretention in Vancouver has been wildly implemented with 151 current public practices throughout the city. However, from the current situation, to meet the City's target to constitute about 10% of the extreme events' annual rainfall by G.I. implementation will be impractical. Therefore, the city should combine G.I. with a network of stormwater pipeline systems to provide a better level of service across the range of rainfall to mitigate climate change (City of Vancouver, 2016). It is also necessary to use all of the types of GI and combine natural and engineered systems to approach the goal.

Meanwhile, because of people's perception of water as an abundant resource in Vancouver, the green infrastructure implementation has been set back for at least a decade (Sobchak, 2018). The public's low awareness of the stormwater flooding and climate change issues and little education and policies about G.I. also lead to low voluntary projects, especially at property scale and slow progress. Therefore, the need to scale up the initiatives and raise the public's awareness is necessary (Sobchak, 2018). Therefore, the City of Vancouver should look closely at Portland and Seattle's examples and consider the strategies for those two cities. For instance, public engagement and free education programs at schools provide incentives and rebates to residences to encourage G.I. implementation at private properties.

RECOMMENDATIONS

- Green infrastructures, especially bioretention systems, play a critical role in rainwater management in urban areas.
- The main challenges of the GI implications in Vancouver are not technical problems but how to buy in to initiate GI. Thus, the City of Vancouver should enhance the public involvement and Government Department Collaboration to buy in and promote GI that learnt from Portland and Seattle (McGarvey, 2014):
    - Successful approaches for public engagement in GI (McGarvey, 2014):
      - Demonstration projects to show successful initiatives and prove the value of the property when bioswales were introduced. These projects could reduce insurance costs due to the

reduction of risks of unusual events, and provide nicer roads, vegetation and neighbourhood.

- Achieving GI through financial incentives for homeowners and other existing property owners, which are valuable in their potential to educate and build "goodwill" with utility ratepayers, and get everyone to be involved in addressing stormwater issues. For example, subsidized trees, eco-roof incentives, reduce utility rates or taxes based on the number of impervious covers people remove from their property or managing roof runoff on their properties.

- Incentives for developers have also proven to be an effective financial incentive, such as density bonuses, tax abatement, floor area ratio bonuses, eco-roof incentives, etc.

- Public workshops, presentations, education programs, stakeholder meetings and 1:1 conversation between canvasser and homeowners to have the public involved in monitoring and maintaining some of these systems.

- Successful Approaches to get Government Department to collaborate in GI projects (McGarvey, 2014):

  - Prove to different departments that it was less expensive to build GI than traditional engineering, and show that it was easier to build using a combination of natural and engineered combinations.

  - Have a core group of staff to work on G.I. implementation and through their professional and passionate communication with other departments to improve the internal culture surrounding G.I.

  - By taking staff to visit GI initiatives in other places that were deployed several years ago, they were able to overcome concerns about long-term management and replacement issues by showing them that the systems would work and require less maintenance than expected. It was a learning experience, and by getting feedback from the engineers, modifications were made to the early-built systems to improve performance.

  - Successful pilot projects, monitoring data, technical manuals and GI training programs for staff have greatly assisted to legitimize GI with many people from other departments.

- The City of Vancouver should also pay more attention to transforming conventional stormwater management techniques to an integrated system that requires a high degree of G.I.

- This paper does not take financial factors into account, so there might be a different idea when considering the budget problem. Still, the broad conclusions will be the same because the implementation of G.I. will eventually save the cost of sewer maintenance.
- Further research should focus on the relationship between G.I. implementation and sewer systems and how bioretention systems can cooperate with separate sewer systems to improve rainwater management better and minimize CSOs.

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