Researching City-scale Water Resource Improvement through Rainwater: Green Roof in Private Realm

by

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Abstract

Rainwater management has been challenging for many jurisdictions, including the City of Vancouver, as population growth and climate change strain the drainage and sewer systems leading to implications for water safety. Urban rainwater runoff discharges directly to the sewer and drainage system and contributes to pollutants that are toxic to fish and other aquatic species. The green roof, a well-established green rainwater infrastructure, is an innovative approach to enhancing rainwater management and making the urban landscape more sustainable, environmental, and livable using vegetation.

From the literature review, a green roof ensures the quality and quantity of collected rainwater, improves building energy efficiency, absorb air pollutants, reduce urban heat island effect and gas house emission, bring aesthetic benefits, and preserve habitat for displaced creatures. The ongoing green roof performance has restrictions on many factors: substrate layer depth, temperature, moisture condition, weather events intensity and period, and proper operation and maintenance. Overall, green roof retains precipitation effectively even aged, with a higher percentage in a moderate climate.

Portland and Toronto prioritized on-site infiltration by green rainwater infrastructure in their rainwater management strategies and policies, although their approaches and requirements may differ. Portland and Toronto both have an independent green roof standard in addition to their rainwater management strategy. Portland focuses on a post-occupancy inspection program to monitor the green roof's ongoing performance, while Toronto established a Green Roof Bylaw to encourage the implementation of green roofs. Both cities have advanced strategies which could provide a valuable example with lessons learned from other jurisdictions, including City of Vancouver. This research aims to analyze the available green roof monitoring program in different cities with their establishing process and provide suggestions to jurisdictions for developing comprehensive monitoring programs in the private realm to ensure the implementation and performance of green roofs and other green rainwater infrastructures.

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Chapter 1: Introduction

In 2019, the City of Vancouver developed the Rain City Strategy (RCS) as a part of the green rainwater infrastructure (GRI) planning process to implement sustainable rainwater management across the city. With the vision of embracing rainwater as a valued resource for local communities and natural ecosystems, RCS aims to remove pollutants from water and air, increase managed impermeable area, reduce the volume of rainwater entering the pipe system, improve water using efficiency, mitigate urban heat island effect, and increase total green area. Over the coming three decades, RCS will be the guideline for Vancouver's transfer to a water-sensitive city against urgent water challenges by improving and protecting water quality, increasing water resilience, and enhancing livability in both public and private properties. As a comprehensive green rainwater infrastructure, green roofs are expected to be an important part of Vancouver's strategy as the city grows and density increases in the decades to come.

RCS currently has the design standard "capture and clean rainwater from a minimum of 48 mm per day" for public properties and 24 mm for private properties. Public properties are streets, public spaces, civic facilities, and parks managed and monitored by the city. Property owners mainly manage private properties, and there are certain barriers for the city to monitor the rainwater collecting performance, including cost, labour intensity, typologies, enforcement, etc. The appropriate approach to managing and monitoring private properties' rainwater management targets is a foreseeing task. Although the standards have been set, a comprehensive monitoring program is essential in private realms to manage and ensure the ongoing performance of onsite green rainwater infrastructure. Research on specific infrastructures' rainwater collection performance and board city monitoring programs is necessary to manage GRI tools in city-scale private properties fully. The green roof contains a complete infiltration system and has great sustainable benefits for rainwater collection. It is an ideal GRI tool for conducting rainwater collecting performance research. The research outcomes on a green roof can reflect on all kinds of GRI tools containing a complete infiltration system.

Monitoring and managing green roofs on private properties involve a number of perspectives that include technical performance, equity, enforcement, legal implications, and finance. The technical design is only one step to ensuring green roof rainwater collecting performance. Post-constructed inspection, maintenance, and responsibilities are also in consideration. After researching and discussing with the City of Vancouver staff, I proposed that an advanced quality assurance and quality control (QV/QC) program for private property green roof management should require standards on the following topics:

Natural Performance: What are the major natural factors that affect green roof rainwater collecting performance? For example, how will rainfall volume, temperature, snow condition, and green roof age affect green roof performance qualitatively or quantitatively? What's the potential influence on inspection or maintenance?

Development Considerations: How is the program established? What is the scale of monitoring infrastructures? How is liability minimized? What methods are used to ensure the management program? What are the threshold and penalties? How is the program funded?

Supporting Legal Agreements and Tools: What are the legal agreements, bylaws, or other tools to ensure monitoring in all development phases? The legal agreements and tools should be involved in all scales, interfaces, variables, standards, equipment, data (collection, transmittal, storage), ownership, liability, reporting, enforcement, and costs perspectives.

Maintenance & Operation Responsibility: Who should be responsible for constructing, inspecting, and maintaining green roofs in private properties? What is the operation procedure (i.e. inspection procedure, maintenance frequency, responsible parties, etc.)? Which parties are in charge of the operation reporting duties or report assessment?

Equity: Will there be various compliance mechanisms for different types of private properties (i.e. single-family homes, townhouses, medium-rise residential, and high-rise buildings)? If so, how does the City of Vancouver ensure standards are applied equitably across the private realm?

Cost: Who pays for green roofs' construction, operation and maintenance? How to minimax the stuff and cost? Will the responsible parties receive credits in different forms (i.e. property tax refund, penalty, etc.)

Those six aspects above are the fundamental research fields for this project. Through online research and interviews with selected governments, this project analyzes established programs similar to the City of Vancouver program for furthering the City's development strategies and avoiding problems. The minimum criteria for all aspects will be presented, including cost, labour, scale, etc. Ultimately, the conclusion and recommendation will provide references on the policy-making process and considerations for the next step of rainwater management.

Chapter 2: Background

2.1 City of Vancouver Context

Vancouver is famous for its rain, and it has become an inherent part of the city's culture and identity. On average, Vancouver has over 160 rainy days and between 1200 – 1600 millimetres a year. Around 70% of the perception is light showers (less than 24 mm per day), and another 20% arrives as rainstorms (between 24-48 mm per day). The last 10% of the annual rainfall volume arrives as extreme rainstorms (greater than 48 mm per day) (Metro Vancouver, 2016). Although the large rainstorms are predicted to increase in intensity and frequency due to climate change, especially in fall and winter. Specifically, the predicted increment shows 12% in fall, 5% in winter and 7% in spring precipitation (Pacific Climate Impacts Consortium, 2016). The average precipitation from each of these events is also predicted to increase, with 33% more rainwater on very wet days and 63% more on extremely wet days. The less frequent events, normally 1-in-20 year events are projected to increase in intensity by 36%, indicating a potential for increased flooding (Pacific Climate Impacts Consortium, 2016).

To address the future rainwater issue, the City of Vancouver established Rain City Strategy which reaffirms the City's aspirational target to capture and treat 90% of Vancouver's average annual rainfall, close to where it lands. The strategy aims to capture (infiltrate, evapotranspiration, or reuse) and clean 48 mm of rainfall per day by amending the associated rainwater management design standard for GRI assets and site plan (City of Vancouver, 2019). In future envision, the strategy sets an implementation goal for capturing and cleaning rainwater from 40% of Vancouver's impervious areas by 2050. The 30% of the rainwater would be achieved by including rainwater management, where feasible, as a standard practice in new projects in both public realm and private realm. The remaining 10% would be achieved through targeted retrofits in both realms as well (City of Vancouver, 2019).

By far, the City of Vancouver has achieved great accomplishment in the public realm. From 2017 to 2019, the City has designed and constructed 38 new GRI practices in the public realm, which manage rainwater volume and water quality for an estimate 15.7 hectares of impervious areas on streets and lanes, bring the total number of assets in the public realm to 238 (City of Vancouver, 2019). Meanwhile, the rainwater management in private sites is still in developing process and the City has been passively updated policies accordingly. Since 2018, the City has updated Sustainable

Large Sites Rezoning Policy, Green Buildings Rezoning Policy, Vancouver Building By-law, etc. (City of Vancouver, 2019). A variety of GRI tools including bioretention, absorbent landscapes and green roofs are suggested and required in new construction permit with technical guidelines. Since the new policies came into effect, the City has reviewed approximately 264 rezoning and development permit applications pertaining to rainwater management across the city by 2018, which represent approximately 170 unique sites at various stages of the permitting process (City of Vancouver, 2019). While much more work needs to be done in terms of advancing rainwater management on private sites in future, there are significantly more Green Rainwater Infrastructure (GRI) assets being created now than a few years ago. Some of the challenges that have been encountered to date are mainly the operation and maintenance on private assets, which ensure the most GRI tools are functioning effectively.

2.2 Green Roof introduction and Benefits

Green roof, also named as ecoroof or vegetated roof, is a lightweight vegetated system planted on top of a human-made structure which could be below, at, or above grade. It's an innovative approach to make urban landscape more sustainable, environmental, and livable using vegetation. Green roof is categorized in GRI, and it is a very well-established infrastructure in many countries with government legislation and financial support. Green roof system consists of at a minimum, high quality waterproofing, root repellent system, drainage system, filter cloth, a lightweight growing medium, and plants (About Green Roofs, 2022). In the past 1 to 2 decades, Dunnett and Kingsbury (2004) found 2 major approaches to categorize green roof: extensive and intensive. The soil layer of extensive green roof is normally less than six inches with a modest roof load, limited plant diversity, minimal watering requirements and limited access. Intensive green roofs contain deeper substrate layer, more diverse growing medium including trees and shrubs, and generally require more effort for the tending of plants. Intensive green roofs also emphasize space usage, and therefore has higher expectations of performance and aesthetic than extensive green roofs (Nigel Dunnett, Noël Kingsbury, 2004). Green roof offers a wide range of public and private benefits in addition to enhancing its aesthetic value:

2.2.1 Stormwater Pollutant Reduction

Stormwater and snowmelt in urban areas are more contaminated than natural environment. Under natural environment, rainfall is collected by vegetation and soil near where it lands and the rest portion merge into the underground water system. The retained water contributes to the replenishment of soil moisture and groundwater. In urban area, most of the landscape are impervious and stormwater will accumulate on land surface then became urban rainwater runoff, which is a major cause of water pollution in urban areas (N. Winters, K. Graunke, 2014) (Julann A. Spromberg, 2015). When rain falls on the roofs, streets, parking lots and other hard surfaces, the rainwater picks up pollutants while flowing over these surfaces and the untreated rainwater is conveyed through pipes to the treatment plant or directly into local waterbodies. The common pollutants found in urban rainwater runoff are litter (e.g. cigarette butts), bacteria (e.g. animal waste), heavy metals, chemical compounds in tire dust, hydrocarbons (e.g. oils and gasoline), nutrients, micro-plastics (e.g. vehicle and building material wear), and Sediment (City of Vancouver, 2019).

Green roofs provide the permeable area in urban landscape, and collet rainfall close to where it lands to avoid contamination. The rainwater could be directed into water reuse system, wastewater plants, or watersheds as water resource. In high level, green roofs use soils, microbes, plants and sediment traps to retain and metabolize pollutants from urban rainwater runoff.

2.2.2 Rainwater Quantity Management

Green roofs can capture rainwater at the source, reducing the volume of rainwater entering the sewer and drainage system and lowering the possibility of combined sewer overflows (CSO) events and their overall volume. There are many studies that investigated and proved the hydrological benefits of green roofs. For example, Carter and Rasmussen from the University of Georgia conducted a green roof precipitation test with a black roof as the control group (Carter TL, Rasmussen TC, 2006). The results showed that green roof precipitation retention is around 90% for small storms and 50% for larger storms. Teemusk and Mander also researched the stormwater retention capacity, and 85.7% of light rain could be retained, and the runoff peak of a heavy rainstorm could be delayed by half an hour, although the runoff cannot be fully retained (Teemusk A, Mander Ü, 2007). For the long-term performance, Voyde et al. found that an average of 82% of rainfall amount could be retained, and about 93% peak flow could be reduced from a field-scale living roof in New Zealand (Voyde E, Fassman E, Simcock R, 2010). Stovin et al. also concluded that green roof provides 50.2% cumulative annual rainfall retention based on an extensive set of 29-month rainfall-runoff data from a green roof test bed in the United Kingdom.

2.2.3 Environmental Benefits

The elements of extensive and intensive green roofs, like trees, plants and in particular soil, can play a critical role in absorbing and sequestering carbon dioxide, which is a significant greenhouse gas produced by burning fossil fuels like gasoline, diesel and natural gas (J. Satzewich, D. Straker, 2019). Additionally, green roofs also have an impact on air quality improvement. Researchers discovered that the vegetation on green roofs could trap particulates and dissolve gaseous pollutants through the stomata of their leaves. Yok and Sia reported that their pilot green roof project in Singapore reduced 37% sulphur dioxide and 21% nitrous acid (Tan Puay Yok, Angelia Sia, 2005). Green roofs can contribute the urban heat island (UHI) effect due to heat absorption, shading, and evapotranspiration (About Green Roofs, 2022). Depending on the design and local climate, green roofs potentially save building heating and cooling energy. Green roofs also preserve habitat for displaced creatures by providing a safe, natural space in the urban area for birds, spiders, beetles, butterflies, and other invertebrates to live, nest, and have food (Brenneisen, 2003).

Chapter 3: Major Factors Affecting Green Roof Performance

3.1 Green Roof Requirements

The green roof requirements are mainly developed in Europe with the rating system and are contained in jurisdiction green roof construction standards in various projects. The requirements help the government ensure green roof-designed performance goals over short and long periods. In 1998, the Landscape Construction and Development Research Society (FLL) in Germany published a system for rating green roods in land-use planning, building permit application, and construction approval (Ngan, 2004). There are four major categories of green roof construction growing medium water retention capacity, drainage layer water retention capacity, number of plant species (extensive green roofs), and plant biomass or volume (intensive green roofs).

Another well-known green roof performance rating system is the Karlsruhe Performance Rating System, which rates five natural functions of green roofs. The five functions are assigned with weight in percentage according to their importance (Doug Banting, 2005). The five functions are:

- Soil type and depth (15%)
- Impact on climate due to evapotranspiration (15%)
- Type and variety of vegetation (30%)
- Impact on zoological biodiversity (30%)
- Average annual stormwater retention (10%)

The well-defined rating systems need to ensure green roofs are properly designed and constructed, as the performances are full of uncertainties without complex monitoring equipment setup. Many factors will still affect green roof performance even if it has been well-designed and constructed.

3.2 Factors Affecting Green Roofs

3.2.1 Green Roof Operation & Maintenance

A green roof is a complex "living" system with the same functions as a conventional roof and contains a vegetation ecological system. A successful green roof requires design, construction, establishment, O&M plan, and O&M implementation all work well. Missing any element will fail the project. Operation and maintenance(O&M) is a significant human factor in keeping green roofs' ideal performance in the long term. The purpose of O&M is to provide ideal conditions for all vegetation, find issues in the earliest stage, and prevent structural damage on the roof. A well-performed green roof should be self-sustaining with the balance of soil, plantings, and water and minimal O&M needs. O&M plan should include vegetation care, weed and pest control, proper irrigation (frequency and water quantity), and frequent inspection (City of Portland, 2009).

Ideally, O&M doesn't require many garden care techniques, including trimming, edging, or fertilizing the plant. It only needs frequent inspection of vegetation health and coverage. Most plant problems are caused by pests, too much or less irrigation, fertilization, air vent flow damage, HVAC condensation, or people. Weeding and mulching may be required depending on the planting method. The drains are important for any type of roof and should be cleared annually. Erosion is another common concern of green roofs and needs to be corrected with gravel mulch and sedum cuttings (City of Portland, 2009).

3.2.2 Low-Return-Period Weather Events

Low-return-period weather events like light rain and snow events do not occur soon after one another if the substrate layer is not fully saturated, are common in most moderate climates. Teemusk and Mander compared stormwater retention potential and runoff water quality of an extensive green roof and a modified bituminous membrane roof in three rainfall events and snow cover melting (AlarTeemusk,U¨lo Mander, 2007). Two light rain events continue for two days, each with 2.1 mm and 2.4 mm of rainfall, and one heavy rainfall event continues for six days with 18.2 mm of rainfall. The results showed that the green roof effectively retained 85.7% of light rainfall. For heavy rainfall (12.1mm), the green roof is able to delay the runoff for up to half an hour but cannot fully retain it. The final runoff volume was the same as the reference roof. Snow melting events have two processes in the green roof: the melting of the snow cover and then the melting of the frozen water in the substrate layer. Snow cover melted quickly, but the green roof extended the water runoff time compared to the reference roof. The runoff water quality mainly depends on the character of the runoff and the pollutants accumulated on the roof. The values of COD, BOD7, and concentrations of total N and total P were higher on the bituminous roof compared to the green roof in light rain events. In heavy rain events, the components' concentration was low as the rain washed more phosphates and nitrates off the green roof. In conclusion, low return period rain and snow events will not affect green roofs' performance, and heavy weather events will reduce the difference between a green roof and normal roof.

3.2.3 Green Roof Age

There might be some concerns for those green roofs that have been constructed for a long time. A research team in Manchester, UK, selected a 43-years old intensive green roof as an experiment target and collected runoff quantities data of 69 rainfall events compared to an adjacent paved roof (A.F. Speak, J.J. Rothwell, S.J. Lindley, C.L. Smith, 2013). The aged green roof performed an average of 65.7% rainfall runoff retention in all rainfall events, while the bare roof only achieved 33.6%. During high rainfall events and continuous above-average rainfall events, green roofs' retention rate is significantly lower. The research found that the organic matter content in the aged roof's substrate layer is relatively high, directly increasing the green roof's retention capacity. The performance of an aged green roof does not show a significant difference as long as it is in well-functional condition, especially the substrate layer.

3.2.4 Climate Conditions

The local climate conditions, mainly temperature and moisture, are major elements affecting green roof performance. The research team in Northern Europe evaluated the effects of maximum green roof storage capacities and evapotranspiration on stormwater retention along local climate conditions by analyzing historical data of daily temperature and precipitation in a green roof water balance model (Birgitte Gisvold Johannessen, Hans Martin Hanslin, Tone Merete Muthanna, 2017). The data showed that potential annual stormwater retention is different between locations, caused of temperature and precipitation differences. The wettest locations have the highest absolute retention values, and the warmest and driest locations have the highest retention in the percentage of annual precipitation with up to 58% compared to 17% for the lower range. Despite green roof locations, all green roofs have high rainwater retention capacity ranging from 52% to 91% during summer. The green roofs in cold and wet locations experience drought season once every 3.3–3.9 years and have around 25mm storage capacity, while the green roofs in warmer and drier locations have a 40-50 mm storage capacity, around 1.5 times increment. The research found that evapotranspiration was the limiting factor for green roof retention capacity in cold and wet locations. However, there have to be relatively large changes in evapotranspiration to affect the retention capacity (Birgitte Gisvold Johannessen, Hans Martin Hanslin, Tone Merete Muthanna, 2017).

Chapter 4: Case Studies: Toronto and Portland

4.1 City of Vancouver Overview

Understanding the context of the City of Vancouver's current stormwater management in the private realm, including rainwater management background, requirements on private property, major development review process phases, and rainwater management QA practices, is the first and important step in this Research. It will set the baseline for other cities in the case study to compare and summarize the most valuable and accurate recommendations based on Vancouver's rainwater management stages. The similarity and differences between Vancouver and other case study cities need to be highlighted, and lessons learned from other cities will be categorized into various aspects of Vancouver's rainwater management program. The following section comprehensively summarises the City of Vancouver's rainwater management program, from the background and motivation to the reviewing process and best practices in the private realm.

4.1.1 Background

Vancouver is located on the western half of the Burrard Peninsula, bordered by English Bay and Burrard Inlet to the north and the Fraser River to the south. The City of Vancouver is a coastal seaport city and the largest city in British Columbia. The City of Vancouver has 114 square kilometres (44 square miles) of land serving 631,486 (according to the 2016 census) people. With the protection of mountains and warmth from Pacific Ocean currents, Vancouver has a moderate oceanic climate. Vancouver's wettest months are November and December, with an average precipitation of 182mm. July and August are the driest months in Vancouver, normally with an average of just 41mm of precipitation (City of Vancouver). In 2021, Vancouver's total precipitation is 116 cm (Environment and Climate Change Canada).

The City of Vancouver faces several challenges with respect to rainwater management. Population growth and climate change are straining the city's aging sewer system, leading to water quality impacts on receiving waters such as False Creek and the Fraser River. Urban rainwater runoff discharges directly to the sewer and drainage system and contributes to pollutants that are known to be toxic to fish and other aquatic species. Vancouver's prevalence of combined sewers and associated combined sewer overflows (CSO's) only exacerbate this issue, as does climate change causing more frequent, intense rainstorms.

In response to these issues, the City of Vancouver's Citywide Integrated Rainwater Management Plan (IRMP) and the Rain City Strategy (RCS) call for a shift in urban water management strategies to include a more holistic and integrated approach to realizing sustainable rainwater management across the city and achieving the goals of improved water quality, increased resilience, and enhanced livability. With the vision of embracing rainwater as a valued resource for local communities and natural ecosystems, the RCS aims to mimic the natural hydrological cycle by managing rainwater where it falls using green rainwater infrastructure (GRI) such as green roof systems, water infiltration systems, and water reuse systems. The RCS seeks to remove pollutants from water and air, increase managed impermeable area, reduce the volume of rainwater entering the pipe system, improve water use efficiency, mitigate the urban heat island effect, and increase total green area. Over the coming three decades, the RCS will be the guideline for Vancouver's transfer to a water-sensitive city on both public and private properties. Green roof systems and infiltration systems are expected to play an important part in Vancouver's rainwater management strategy as the city grows and density increases in the decades to come.

The RCS affirms the City's rainwater management target to capture and clean at least 90% of Vancouver's average annual precipitation near where it lands. In 2019, RCS required public properties to design a rainwater management plan to capture and clean 48 mm of rainfall per day in streets, public spaces, civil facilities, and parks. The current design standard for private property is to capture and clean from a minimum of 24 mm rainfall per day, and it will be the same as public properties in the near future. The design standard is applied at the project, site or district scale whenever rainwater management objectives are included as part of a project scope. The RCS also establishes an ambitious implementation target to manage 40% of Vancouver's impervious areas' rainwater runoff quantitively and qualitatively by 2050 through new development, capital projects and strategic retrofits. It is estimated that 30% of this total would be achieved by including rainwater management, where feasible, as a standard practice in new capital projects in the public realm and through regulation for new developments in the private realm. The remaining 10% of the total would be achieved through targeted retrofits in the public and private realm (City of Vancouver, 2019).

4.1.2 Vancouver's Private Realm Rainwater Management

In the private realm, the City of Vancouver has established a rainwater management program focusing on water-sensitive site design and green rainwater infrastructure practices to regulate and guide property owners to treat rainwater in the correct ways. The new or redeveloped sites will increase pervious surfaces that allow rainwater to infiltrate, use landscape systems which allow rainwater to irrigate and evaporate, and capture and use rainwater (City of Vancouver). The city will review applications in the private realm to ensure new and redeveloped projects meet the standards. There are four stages with separate intake streams for starting the rainwater management review process. Each stream will be triggered by different requirements and require submittals. The four stages are:

- Rezoning Stage;
- Development Permit Stage;
- Building Permit Stage; and
- Occupancy Permit Stage.

The reviewing process will start on the rezoning stage if the Green Building Policy for Rezoning or the Rezoning Policy for Sustainable Large Developments is triggered. If the development is located in an area of concern for rainwater management or adequate drainage is unclear or not available according to Section 4 of the Zoning and Development By-law, then the review process will skip the rezoning stage and begin at the development permit stage. The building permit and occupancy permit stages are required for all applicants. The Rainwater Management Bulletin (RMB), published by the city, provides information on the process and submission requirements related to rainwater management throughout the development process to the permit applicants.

Rezoning Stage

Sites with CD-1 zoning require a Preliminary Rainwater Management Plan (RWMP) and Rainwater Management Project Summary Form. The Rainwater Management Plan (RWMP) explains how a proposed rainwater management system meets the requirements of Section 4 of the Zoning and Development By-law in detail, and it is required in all rezoning, development permit and building permit stages with different standards. The Preliminary RWMP only outlines the proposed rainwater management system and how the project will meet the requirements for volume reduction, rate control, and water quality required in the Rezoning stage in a high-level approach.

Development Permit Stage

Registration of Rainwater Legal Agreement, acceptable to the General Manager of Engineering Services and the Director of Legal Services, is required prior to the development permit issuance. The agreement prevents construction until the final RWM design is accepted, requires that the RWM systems be built as per the accepted design, and requires that these systems be maintained by the owner indefinitely. A Complete RWMP report and Rainwater Management Project Summary Form are also required. The Complete RWMP should outline the near-finalized rainwater management system with some relevant design details, while some information may be missing or to be confirmed at the building permit stage.

Building Permit Stage

The Final RWMP and Rainwater Management Project Summary Form are required in this stage. The Final RWMP needs to outline the final rainwater management system to be constructed, including Best Management Practices located within the building footprint and final internal building mechanical designs. The Final RWMP can deviate from the accepted Complete RWMP as long as they satisfy the requirements. A standalone Operation & Maintenance Manual is also required with information on the rainwater management system maintenance program for its future upkeep and performance. The Building Permit Stage is the last stage of reviewing process prior to construction.

Occupancy Permit Stage

A sealed letter from a registered professional confirming that the rainwater management system has been constructed in accordance with the accepted Final RWMP is required.

Post-Occupancy Maintenance Reporting

Post-Occupancy is not a stage in the City of Vancouver's Rainwater Management Plan reviewing process. The property owner must submit a report after the period of time defined in the legal agreement passes that demonstrates the on-site rainwater management systems have been maintained well after the period of time defined in the legal agreement passes.

4.2 City of Portland Private Realm Rainwater Overview

4.2.1 Background

Portland is a large port city located in northwest Oregon, US and has 641,162 people living there. Similar to Vancouver, the City of Portland is also in a moderate climate zone, generally warm and temperate, and well known for its rainy weather with 48’’ average annual precipitation with rainier winter (Bureau of Environmental Services, 2022). Portland has five major watersheds: Columbia Slough, Fanno Creek, Johnson Creek, Tryon Creek, and Willamette River, which are part of two larger drainage basins: Willamette River Basin and Columbia River Basin (Bureau Environmental Services, 2022). Many species of birds, salmon, and other wildlife species are found in the ecosystem of the Columbia and Willamette Rivers.

For years, Portland has been a municipal leader in stormwater management with a complex network of engineered and natural assets. In addition to hundreds of miles of pipes and ditches, Portland works with property owners and community organizations to tackle urban challenges with green street planters, trees, and natural area restoration (Bureau Environmental Services, 2022). One of the reasons for the city's success in stormwater management is its promotion of green infrastructures, including green roofs, rain gardens, sustainable street design, and infiltration planters through educational, funding, and incentive programs (Noah Garrison, New York). As with many cities, Portland has a history of pollution and a desire to repair local ecosystems, which became the motivation to develop its stormwater strategies. The overflows from city’s combined sewer system are one of Portland’s ecological concerns as they caused industrial and urban pollution to the Willamette River.

US Congress passed the Clean Water Act (CWA) in 1972, which “prohibits the discharge of pollutants into waters of the United States unless the discharge complies with a National Pollutant Discharge Elimination System (NPDES) permit” (Bureau of Environment service, 2020). The City has NPDES Municipal Separate Storm Sewer System (MS4) permit for stormwater and the separated collection system and NPDES Waste Discharge Permit that manages the combined sewer collection system and the wastewater treatment plant (Bureau of Environment service, 2020). In 1999, Portland adopted its first Stormwater Management Manual (SWMM) city widely to protect watershed resources and infrastructure investments in both public and private realms. The SWMM has been updated regularly and contains retention, water quality, and flow control design standards for stormwater management facilities (Bureau of Environment service, 2020).

4.2.2 Stormwater Management Requirements

The SWMM sets stormwater management requirements applying to new development or redevelopment projects involving 500 square feet or more of impervious area. The requirement prioritizes on-site infiltration using vegetation as the most possible standard to maximize environmental and urban design benefits, but it would be impossible for some sites because of technical issues or competing requirements. Thus, SWMM established the Infiltration, and Discharge Hierarchy ranks discharge systems in three levels. Level 1 requires full on-site infiltration of the 10-year design storm with design infiltration rates of 2 in/hr or more. The only exception is for a project with an green roof (also known as green roof) covering 60% or more of the roof area and conforming to the latest SWMM manual design standards. Level 1 is always prioritized, and level 2 and 3 (offsite discharge) can be applied only if full on-site infiltration is not feasible. Level 2 requires the project to use surface water systems or separated storm systems that ultimately drain to surface water as primary disposal and conveyance for stormwater receiving systems. Level 2 contains water quality treatment standards for all projects and flow control standards in most situations. Level 3 requires projects discharging offsite to combined sewers that convey water to the wastewater treatment plant with flow control standards (Bureau of Environment service, 2020). The full requirement is shown below:

Table 1: City of Portland Infiltration and Discharge Hierarchy Stormwater Management Requirements (Bureau of Environment service, 2020)

Level 1: Full Onsite Infiltration
Fully infiltrate the 10-year design storm (sites containing green roof covering over 60% and conform to SWMM manual design standards will be excepted).
Level 2: Offsite Discharge to the Separated Stormwater System
• Pollution reduction (remove 70% TSS from at least 90% rainfall and reduce pollutants) • Flow control (limit post-development peak runoff rates)
Level 3: Offsite Discharge to the Combined Sewer System
Flow control (limit post-development peak runoff rates)

The Bureau of Development Services (BDS) oversees development reviews, including land use reviews and building and trade permits for private improvements. The Bureau of Environment Services (BES) oversees the private realm’s stormwater facilities within the development permit reviewing process. All Infiltration and Discharge Hierarchy applications need to be reviewed and approved by BES on a site-by-site basis. Suppose the project cannot meet any levels because of technical issues. In that case, the project designer can submit a Special Circumstances Request and pay the Offsite Stormwater Management Fee instead of designing stormwater management facilities. The amount of charge fee depends on the total area of unmanaged impervious area, and the unit price is calculated according to City's construction costs for installing stormwater management facilities through retrofitting existing impervious area.

4.2.3 Portland Submittal Requirements

Portland allows three approaches to designing stormwater facilities: Simplified, Presumptive, and Performance Approach. The Simplified Approach can be used for new or redeveloped projects has less than 10,000 ft^2 (0.23 acre) impervious area, and it is applied to mostly residential development, including roofs, patios, parking areas, driveways, etc. The Simplified Approach requires a site plan, landscape plan, O&M plan, hierarchy level justification, and SIM form with infiltration test (Bureau of Environment service, 2020).

4.2.4 Operations and Maintenance for Private Properties

Stormwater infrastructures and facilities require regular maintenance to ensure performance and limit environmental impacts. In Portland, property owners or the designated responsible party are responsible for the operation and maintenance of its own facilities. The owner includes all current and future owners of the property. The current owners are responsible for informing the city to update the responsible party whenever it changes. The O&M Plan and O&M Form submitted in the reviewing stage will be the standards of inspection and enforcement. The standard O&M Plan and O&M Form are available on Portland websites. They are categorized into infrastructure types, including green roof, permeable pavement, rain garden, basin, planter, filter strip, drywells and soakage trenches, surface sand filter.

4.2.5 Inspection

The BES oversees post-construction inspections of stormwater facilities and drainage reserves on private property. To the extent permitted by law, BES can enter all private realms at any time to inspect potential violations or connections or for any other lawful purpose required by or authorized under City 17.38.043 Code or ordinances of the City, the Charter, or state or federal law (City of Portland, 2020c). The Inspection program follows the Maintenance Inspection

Program Administrative Rules as administrative rules. BES provides post-construction inspections of stormwater facilities and drainage reserves on private property. To the extent permitted by law, BES may enter all private and public premises at any time for the purpose of inspecting for potential violations or connections or for any other lawful purpose required by or authorized under this Code or ordinances of the City, the Charter, or state or federal law (City of Portland, 2020c). The BES staff have authorization including but not limited to inspection, sampling, testing, photographic documentation, record examination, copying, and installation of devices to verify if the property owner maintains stormwater management facilities properly. If the property has been inspected, the inspector will provide property owners with a report outlining any required corrective action, the deadline to correct, and City notification (if needed).

We conducted an interview with Portland BES staff. They implemented inspections based on stormwater facility categories, previous inspecting time, and private property type. Due to limited staff resources, the single-family units are not on the inspection list anymore as they are low risk. Instead, they mail letters to single-family units annually explaining the importance and benefits of operation and maintenance. The single-family units are around 60% of Portland's total private properties. For new developments, BES will try to inspect in the first year after the project is finished. Then the following inspection depends on the previous inspection date and stormwater management facility type. The green roof is prioritized as the system complexity and huge failure cost, and the set inspection time is within two years after the previous inspection.

4.2.6 Enforcement

Enforcement will be triggered if the property owners or the designated responsible party don't comply with the operation or maintenance of the stormwater management facility based on the O&M Plan. The enforcement will not be triggered entirely right after an inspection. The city will give a certain time to property owners to fix the issue, then apply smaller bills until the full-amount bill is issued. Based on the BES Enforcement Program Administrative Rules, civil penalties can be up to $10,000 per day per violation. The enforcement-triggered conditions include but are not limited to (City of Portland, 2020c):

- *Failure to construct stormwater management or source control facilities to the standards of the City's Stormwater Management Manual, Source Control Manual or Section 17.38.035;*
- *Failure to comply with a written order of the Director, made under authority of this*

Chapter, within the specified time;

- *Failure to comply with any condition of an O&M plan or agreement issued under the authority of this Chapter or rules within a specified time;*
- *Failure to maintain a stormwater management or source control facility leading to a potential or actual operating deficiency of the facility;*
- *Failure to have a properly recorded, accurate O&M form or plan, as appropriate, on file with BES;*
- *Failure to comply with enforcement actions as identified in the BES Enforcement Program Administrative Rules;*
- *Failure to comply with drainage reserve rules in the City's Stormwater Management Manual.*

4.2.7 Funding Mechanisms

The Bureau of Environmental Services (BES) is in charge of Portland's wastewater and stormwater infrastructure to protect the environment and residents' health. The bureau's funding is primarily from retail sewer and stormwater charges, wholesale contract revenues from surrounding jurisdictions, system development charges, permit-related fees, and reimbursements for services provided to other bureaus (City of Portland, 2019). From 2020 to 2021, the bureau has $351.8 million (US Dollar) adopted budget for operating and capital expenditures, and the operation portion is $181.2 million (US Dollar). A certain portion of this funding is from residents. In 2020-21, a typical residential family's sewer and stormwater bill was anticipated to increase by $2.16 per month (2.85%) to support the bureaus' budget and the long-term forecast.

4.3 City of Toronto Overview

4.3.1 Background

Toronto is Ontario's capital city and the largest city in Canada. Around 3 million people live in this 640 km^2 land, making the city have a high population density and extensive sewer infrastructures network (Government of Canada, 2021). As Toronto is in a different climate zone, the weather is more extreme compared to Vancouver. The warmest months are July and August, averaging over 20°C and frequently rising above 30°C in the daytime. In winter, Toronto has snowfall and the coldest temperature below -25°C in January and February (City of Toronto, 2023). The average annual precipitation in Toronto is around 30 inches, and the average snowfall is 4 inches (Environment and Climate Change Canada, 2023).

As motioned above, the city has a very complex sewer system, including 2,800 miles of storm sewers with more than 2,600 outfalls and 807 miles of combined sewers with 79 CSOs due to high population density (Christopher Kloss, Crystal Calarusse, 2006). In its long history, Toronto had serious water pollution issues in Lake Ontario and its tributaries, which motivated Toronto to achieve successful stormwater management. In 1972, Toronto was identified as an Area of Concern for the Great Lakes by the bilateral Canada-U.S. Great Lakes Water Quality Agreement. In response to this issue, the city established Remedial Action Plan (RAP) in 1987 and developed an approach to restore drinkable, fishable, swimmable, and aesthetically pleasing water and make the city and surrounding watersheds become habitat areas (Noah Garrison, Karen Hobbs, 2011). The complex sewer system is one of the major sources of water pollution in Lake Ontario and city watersheds. Toronto also established a sewer bylaw to control sewer water quantities and qualities. After three years, Toronto's City Council approved the Wet Weather Flow Master Plan (WWFMP). WWFMP is a 25-year plan costing $1.03 billion utilizing both traditional and green stormwater methods to improve surface water quality and quantity, solve sewage overflows issues, and protect habitat and wildlife by prioritizing rainwater management near falling location (Noah Garrison, Karen Hobbs, 2011). In the high-level approach, Toronto approaches to improve the wet weather flows and watershed ecosystem. The strategy adopts a comprehensive approach of using any innovative methods that can achieve the set performance objectives with respect to controls for peak flows, flood management, water quality, and annual runoff volume (City of Toronto, 2006).

4.3.2 Stormwater Management Requirements

In 2010, Toronto adopted Toronto Green Standard (TGS) in its policy frame to standardize new private and city-owned developing projects' performance and sustainable design. The TGS has been updated many times since then, and the city council accelerated the implementation dates of TGS to achieve a near-zero emission target. The latest TGS is Version 4, which has been effective since 2022 May 1st, and the V4 developments are estimated to save over 1MT CO_2e cumulative greenhouse gas emissions by 2050, or taking more than 300,000 cars off the road each year (City of Toronto, 2023) TGS has four tires, and only tier 1 is mandatory and needs to be applied through the planning approval process. Tier 2-4 are volunteer, and various Development Charge Refund Programs offer financial incentives to eligible projects. TGS set requirements based on the Wet Weather Flow Management Guidelines in six aspects, including checklists & templates, air quality, building energy & emission, water quality & efficiency, ecology & biodiversity, and water and the circular economy. The targeting projects are categorized by building type: low-rise residential buildings, mid to high-residential & non-residential buildings, city agencies, and corporation & division-owned facilities. Low-rise residential buildings are less than four stories with a minimum of 5 dwelling units, and mid-to-high-residential buildings are higher than four stories. Under the water quality & efficiency section, TGS required the private properties, including both low-residential and mid-to-high-residential buildings, to have water balance, quality and quantity control with priority on on-site green infrastructures. The detailed requirements are shown in table 3 (City of Toronto, 2023).

Table 2: TGS Standards for Private Realm

	Water Balance, Quality & Quantity Control
TIER 1	**Water Balance**: Retain a minimum of 50% of the total average annual rainfall volume (or equivalent 5 mm from each rainfall event) generated from all site surfaces through infiltration, evapotranspiration, water harvesting and/or reuse, in accordance with the Wet Weather Flow Management Guidelines. **Water Quality**: Provide an enhanced level of protection for water quality through the long-term average removal of 80% of Total Suspended Solids (TSS) on an annual loading basis from all runoffs leaving the site, in accordance with the Wet Weather Flow Management Guidelines. Provide E.coli control for direct discharges to Lake Ontario or for discharges

	generated from waterfront sites, where deemed necessary and in accordance with the Wet Weather Flow Management Guidelines. **Water Quantity:** Provide peak flow control following applicable Wet Weather Flow Management Guideline requirements for flood flow management, erosion control and discharge to municipal sewers.
	On-site Green Infrastructure
	Ensure that the total landscaped site area, located at and above grade, includes at least one of the following features: • A Green Roof covering at least 80% of Available Roof Space; • An Intensive Green Roof for 80% of the Green Roof Area provided; • Biodiverse green roof to support pollinator species covering a minimum of 50% Green Roof Area; • 25% of the Lot Area at or above-grade, planted with native flowering/pollinator species; • At-grade Bioretention facilities provided to capture and control 75% of runoff from on-site hardscape surfaces; or • Reforestation of a portion of the site (beyond the limit of a stewardship plan).
TIER 2	Water-Efficient Fixtures
	Install water fixtures or use non-potable water sources that achieve at least a 40% reduction in potable water consumption for the building (not including irrigation) over the baseline water fixtures.
	Efficient Irrigation
	Where soft landscaping exists on the site, reduce potable water use for irrigation by 60%.

4.3.3 Toronto Green Roof

Research

Toronto has investigated the benefits of green roofs since 1990 and has been at the forefront of promoting green roofs in the city's developments to address environmental challenges. In 2003, the city formed a Green Roof Task Force to investigate and promote the benefits of green roofs. 2 years later, the city, in partnership with Ontario Centres of Excellence - Earth and Environmental Technologies (OCE-ETech), collaborated with the Ryerson University to conduct research on Toronto's potential environmental benefits and costs of green roof technology. The research includes a study of available green roof technology, the measurable benefits of green roofs to Toronto's environment, potential monetary savings to the municipality through the use of green roofs, and minimum thresholds of green roofs that could be used for part of any incentives or programs (Doug Banting, 2005). The research simulated characteristics and distributions of the city's rooftops in 2005 using GIS database, which contains landscape features (buildings, streets, stormwater infrastructure) and watersheds' geographic information. It determined the benefits based on the aggregation of building distribution and land use in scenarios setting. The GIS data was provided by the City of Toronto's Works and Emergency Services Department, which was part of the Toronto Wet Weather Flow Management Master Plan Study, and it is the foundation of this research.

The green roof area in this study is based on 100% of the available green roof area. The green roof has restrictions in design, construction, operation and maintenance. The research team considered that and set 4 requirements for simulating green roofs on city rooftops:

- The rooftop must have less than 2% slope.
- The area of the rooftop must be larger than 350 square meters.
- Green roof has to be larger or equal to 75% of the roof footprint when constructed on a building.
- Greenery over underground parking garages and non-conditioned enclosed spaces at grade level are not included in green roof statistics.

The total estimated Toronto land area is 631.75 km^2, and 21% of the total land area is building roof area. With the boundary setting, only 37% of building roof area can be constructed as green roof. Detailed data is shown in Table 4.

Table 3: Toronto Land Use Statistics (Doug Banting, 2005)

Land Use	Area in km^2 (percentage of total land area)
Toronto total estimated land area	631.75
Toronto total building rooftop area	134.78(21%)
Toronto total building rooftop available for green roof installation	49.85(8%)

With the land data, the research team applied monetary analysis to estimate the basic cost of green roofs, then compared it with the estimated municipal level saving in stormwater management, combined sewer system, air quality, building energy, and urban heat island effect. Compared to a traditional roof, a green roof has a higher cost for construction and maintenance, which are primarily private property owners' responsibilities. The researcher studied some City of

Waterloo's projects and concluded that reroofing a building with an extensive green roofing system will cost $75 to $90 per square metre more compared with a traditional roof. The major cost at the municipal level will be establishing programs to promote green roofs, like incentive programs, educational programs, etc. Otherwise, no other costs need to be considered and included in this study.

Green roofs will have benefits for stormwater management cost saving due to pollutant reduction, prevention of receiving stream erosion, and stormwater management practices replacement. The best management practices defined in Toronto Wet Weather Study include pervious pavements in residential high-rise and commercial areas, and underground storage in commercial areas. Green roofs can replace those three types of stormwater management practices to save costs, varying between $2.8 and $79 million. The pollutant reduction will save around $14 million, and erosion control will save $25 million. The combine sewer overflow (CSO) is a major concern for most urban cities with frequent rain, large impervious land areas, and high population density. Green roofs can provide more permeable land to collect precipitation and prevent it from merging into sewer pipes and postpone rainwater discharging rate to reduce sewer peak volume. The research team estimated that 5%-15% of Toronto's impervious area in the combined sewer area could be replaced by green roofs, which will save $15.7 million and $46.6 million on infrastructures respectively. Besides that, CSO reduction will also minimize beach closure and bring $750,000 saving annually. By implementing various classes of vegetation and green area restoration, green roofs can absorb the detrimental air pollutants, including O_3, SO_2, NO_2, CO, PM_{10} and bring US$1,970,000 benefits annually, which is equal to $2.5 million Canadian dollars in 2005. Building with green roofs can save energy usage as the roof can prevent heating energy from leaking from the building or getting into the building depending on the weather and improve the energy efficiency of the HVAC system. In this way, green roofs are able to reduce the energy peak demand and save CO_2 produced by those saved energy. The urban heat island effect will be reduced by green roofs, similar to building energy, if the green roofs are fairly widely implemented. Urban heat island is caused by heat gathering due to dense and high-rise buildings. Green roofs can absorb the heat in the local area to reduce temperature. Building energy and urban heat island reduction will both bring initial and annual savings. The total cost saving of green roof implementation in Toronto is estimated to be $313.1 million initially and $37.13 million annually. The estimated green roof implementation savings is shown in table 5.

Table 4: Summary of municipal level environmental benefits of green roof implementation in the City of Toronto (Doug Banting, 2005)

Category of Cost Saving	Initial Cost Saving	Annual Cost Saving
Stormwater	$118 million	$0
Combined Sewer Overflow (CSO)	$46.6 million	$750,000
Air Quality	$0	$2.5 million
Building Energy	$68.7 million	$21.6 million
Urban Heat Island	$79.8 million	$12.3 million
TOTAL	**$313.1 million**	**$37.13 million**

Green Roof Bylaw

The city was convinced by the research collaborated between the city and Ryerson University and realized that the wide implementation of green roofs would bring Toronto significant environmental and economic benefits involved in stormwater management, CSO control, air quality improvement, building energy efficiency improvement and urban heat island reduction. After the study finished, the City of Toronto organized two stakeholder workshops to get the support of defining green roof's criteria, identifying barriers to green roof implementation, and finding ways to prompt green roof implementation. Lots of stakeholder consultation was involved during this process, and finally, the city proposed the Green Roof Strategy with four major initiatives (City of Toronto, 2023):

- Green roof pilot incentive program;
- Installation of green roofs on the City and its Agencies, Boards and Commissions buildings;
- Use of the development approval process to encourage green roofs; and
- Publicity and education.

In 2006, Toronto City Council adopted the Toronto's Green Roof Strategy "Making Green Roofs Happen" in its policy frame and developed incentive programs, public education, and development approval process to encourage the City building and private property owners to build green roofs.

As one of the Green Roof Strategy, the Green Roof Pilot Program was created for private property owners. In 2006, the pilot incentive program offered $10/m^2$, which is funded by Toronto Water.

The program was very successful after its establishment and prompted the construction of 3,000 m^2 green roofs with 16 rewarded applications just in 2006. The green roof incentive program still exists now and became the Eco-Roof Incentive Program which raised funds to $100/$m^2$ and included cool roofs in incentive categories (City of Toronto, 2023). For City and City's Agencies, Boards and Commissions, the policy requires new buildings constructed by them to provide a green roof covering at least 50% of available roof space. To promote green roofs, the city established a green roof web page, organized technical workshops, and held two in-depth 'Green Roof 101' training sessions for city staff across sessions to educate green roof benefits, design and construction standards.

In 2009, City Council adopted the Green Roof Bylaw, which makes Toronto the first city in North America that have a bylaw requiring and governing the construction of green roofs (City of Toronto, 2023). The bylaw sets 20-60% of the available roof space of a building, except residential buildings that are less than six stories or 20 m in height, need to be green roof applied to (City of Toronto, 2021):

- New commercial, institutional and residential development with a minimum gross floor area of 2,000 m^2;
- New additions to commercial, institutional and residential development where the new gross floor area added is greater than 2,000 m^2; and
- Industrial buildings greater than 2,000 m^2 gross floor area.

The Available Roof Space is defined by the bylaw, and it excludes areas that are designated for renewable energy, residential private terraces, residential outdoor amenity space which is less than 2m^2 per unit, and tower roof on a building with a floor plate less than 750m^2. The green roof area is defined in the bylaw as well (City of Toronto, 2021):

Table 5: Green Roof Area Standard

Gross Floor Area (Size of Building)	Coverage of Available Roof Space (Size of Green Roof)
2,000 - 4,999 m^2	20%
5,000 - 9,999 m^2	30%
10,000 - 14,999 m^2	40%
15,000 - 19,999 m^2	50%
Larger than 20,000 m^2	60%

Chapter 5: Green Roof on-site Monitoring Analysis

Another approach to ensure the performance of green roofs is on-site monitoring, which has been used widely in experiments and academic research mentioned in previous literature reviews. The on-site monitoring requires a combination of sensors to monitor water input (precipitation), soil moisture, water outflow, surrounding environment, and irrigation (if applicable). By analyzing the collected data, a simulated green roof water flow model can be presented to calculate the water retention capacity within different weather conditions. One of the major concerns of on-site monitoring is the labour intensity of recording data. Through research, the wireless data logger can be included in equipment combinations to reduce labour intensity. Normally, the monitoring program requires sensors and flow meters to be controlled by two dataloggers programmed to measure and record data. One data logger recorded the rate of runoff, weather conditions, and irrigation, while the second logger recorded the soil temperature and moisture. All data loggers can be wireless with WIFI and power available on the site. The equipment set-up highly depends on the green roof structure. Some recommended set-ups are concluded:

5.1 Flow Monitoring

Flow Monitoring will monitor the water outflow from the green roof, and the equipment setup highly depends on the water pipe design. The monitoring equipment could be set up in the pipe if all outflow merges in one pipe. Otherwise, individual monitoring equipment needs to be installed on all drainage pipes.

Senix ToughSonic Ultrasonic Distance Sensor - TSPC-30S1

The common issue of green roof monitoring in the post-construction stage is the inability to access downspouts, and it restricted the type and variety of flow monitoring equipment. Some studies during research used flumes to monitor the outflow from the green roof. However, the flume has the potential to backup water onto the roof and is inaccurate at the very low end (0.1 gpm or less), which might cause a tendency to overestimate retention and underestimate runoff (Cardno TEC Inc., 2012). The Senix TSPC-30S1 ultrasonic sensor is an ultrasonic depth sensor, and it can be placed in a runoff chamber as a drainage pipe weir device with an outlet weir to measure the runoff volume from the green roof. The ultrasonic depth sensor measures water depth behind the weir face as water discharges with a 3 ml/min resolution. As flow increases, the water level behind the weir's face rises. The ultrasonic sensor detects the rise in water height and adjusts its output voltage accordingly. The drainage pipe weir device can be used between 0° to 70°C and is applicative to most drainage pipes. A data logger connects to the ultrasonic sensor and records the output voltage, which can be transferred to the flow rate. The weir devices can accommodate saturated substrate conditions based on the drainage area (normally 50 mm/hr of rainfall). If the flow rate exceeds the upper limit, water will overflow weir into the roof drain to prevent backup and ponding of water on the roofs (Patricia Culligan, 2014).

Unimag Electromagnetic Flow Meter -- DP03ECTERPAA Dual Sensor

The flow meter will be an outstanding option If the green roof has a leader pipe for drainage with easy access. The Unimag Electromagnetic Flow Meter uses a magnetic field to generate and channel liquid flow through a pipe. A voltage signal will be created and sent to the electronic transmitter when liquid flows through the flowmeter's magnetic field. Then the signal can be processed to the liquid flow rate. The faster the flow of the fluid, the greater the voltage signal generated. The flowmeter will generally not work with hydrocarbons, distilled water, and many non-aqueous solutions. There are studies showing that the flow meter will not work properly for water flow lower than 1.5 gallons per minute and requires a tipping bucket flow meter to present accurate results. (Cardno TEC Inc., 2012). The Unidata 6506H Tipping Bucket flow Gauge is an outstanding tipping bucket flow meter. It is a simple two-wire connected device constructed from stainless steel requiring no power supply (Streamline Measurement Ltd, 2021). This device could be combined with Electromagnetic Flow Meter to monitor flow in all ranges. The unit varies from $2000 to $3000, depending on the pipe size.

Table 6: Flow Meter Summary

	Senix ToughSonic Ultrasonic Distance Sensor	**Unimag Electromagnetic Flow Meter**
Price	$800	$2000 to $3000
Green Roof Requirement	No additional require	Easy access to leader flow pipe
Maintenance	Might require more maintenance	Less maintenance
Monitoring Flow	All flow-range monitoring	Higher flow monitoring, need combine with Unidata 6506H Tipping Bucket Flow Meter to achieve all flow-range monitoring

Limitation	Maximum flow depends on the drainage pipe size	No restriction
Installation	Need construction team to install, require high-knowledge people to initialize devices before installation	Need construction team to install
Monitoring Set	One unit per drainage pipe. One green roof might require multiple units to monitor total flow	One unit per leader pipe. Normally one green roof requires only one unit

5.2 Weather Monitoring

HOBO Weather Station Rain Gauge Smart Sensor

A weather station that monitors wind speed, air temperature, relative humidity, and solar radiation needs to be set up on-site. The data collected, which are assumed to represent hydrologic input (rainfall) and output (evapotranspiration) conditions on the green roof, provide a basis for calibrating these processes within the hydrologic model. The Hobo Weather Station Rain Gauge Smart Sensor (tipping bucket rain gauge) will obtain site-specific rain data. The rain gauge should be mounted to a weather mast, ideally located on the roof of a building, with a barometric pressure meter. The rain gauge and barometric pressure meter can be configured to record data on a given period. It should be noted that tipping bucket rain gauges tend to underestimate the amount of snowfall. The Data Logging Rain Gauge system is battery-powered, and ideally, it should be maintained each year (changing battery). The cost of the device itself is around $600.

5.3 Soil Moisture Monitoring

Soil moisture and temperature should also be monitored, and collected data as supplemental measurements.

HOBO S-SMC-M005 EC5 Soil Moisture Smart Sensor

Soil moisture smart sensors are used for measuring soil water content and are designed to work with smart sensor-compatible HOBO stations. Data will be stored in a data logger, and the monitoring method will vary on the data logger (manual or wireless). The unit costs around $250.

HOBO S-TMB-M002 Temperature Smart Sensor

This 12-bit sensor has a measurement range of -40 to 100°C (-40 to 212°F) and a selectable measurement-averaging feature. The smart sensor has a plug-in modular connector that allows it to be added easily to a HOBO station. All sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the station without any programming or extensive user setup. The unit costs around $150.

5.4 Data Logger

The data logger will be used with all the devices. Sensors' data will be transmitted into a data logger to store. The data logger can upload the data to cloud service or store it in unified memory.

HOBO U30 Wi-Fi Data Logger - WIFI

The HOBO U30-WIF is a web-based, 15-channel data logging system for a broad range of energy and weather monitoring applications using WIFI for easy access from internet-enabled devices. In addition, alarms can be configured to generate text messages and emails when data goes out of range. This device has a rechargeable battery and typically has a lifetime of around 3–5 years, depending upon the conditions of use. The unit costs around $250 each and operate between -20°C to 40°C.

Campbell Scientific Data Logger (CR3000-ST-SW-RC-NC) - Manual

The CR3000 data logger can be charged by a battery or rechargeable power source. The data logger can operate for extended time periods with low power consumption and solar panel.

It has 28 single-ended or 14 differential (individually configured) analog inputs available. The unit costs around $150 each and operate between -25°C to 50°C.

Chapter 6: Discussion and Recommendations

6.1 Case Study Gap Summarization

Table 7: Case Study Comparison Table

	Vancouver	Portland	Toronto
Population	631,486	641,162	2,956,024
Location	Coastal seaport city in southwest coast of Canada	Northwest Oregon, US	In south-central Canada, near the east coast
Average Precipitation	116 cm	122 cm	76.2 cm
Motivation	Aging sewer system; Population growth; Climate change; Water quality; CSO	Watersheds pollution; Damage to the ecology of plants and animals; MS4 permit compliance; CSO; System capacity	Population growth; CSO; System capacity; Economic benefits; Aging sewer system; Water quality
GRI Reviewing Authorization (Private Realm)	City of Vancouver	City of Portland, Bureau of Environmental Service	City of Toronto, Environmental Planning and Toronto Water
Central Policy Document	Rain City Strategy	Stormwater Management Manual	Wet Weather Flow Management Guidelines
Private Realm Rainwater Management Objective	Capture and clean rainwater from a minimum of 24 mm per day (established in 2019, will be 48mm in near future)	Full Onsite Infiltration (fully infiltrate the 10-year design storm), Offsite Discharge to the Separated Stormwater System with pollution reduction and flow control requirement, or Offsite Discharge to the Combined Sewer System with only flow control requirement	Mandatory: Retain a minimum of 50% of the total average annual rainfall volume, remove 80% of Total Suspended Solids (TSS) on an annual loading basis from runoff, peak flow control following and apply on-site green infrastructure Voluntary: Water-Efficient Fixtures and Efficient Irrigation
Applicable Site	New and redeveloped projects; Applications for rezoning permits and development permits	New development or redevelopment projects involving 500 square feet or more of impervious area (green roof has exception)	New and redeveloped projects

Rainwater Management Requirement	Rainwater Management Plan (preliminary, complete, and final version); Registration of Rainwater Legal Agreement; Rainwater Management Project Summary Form; Operation & Maintenance Manual; a sealed letter from a registered professional; on-going report proving GRI performance.	Site Plan; Landscape Plan; Operation and Maintenance Plan; Operation and Maintenance Form; Hierarchy Level Justification; SIM Form	N/A
Operation & Maintenance Responsibilities	Current private owner's or property manager's responsibilities	Current private owner's or property manager's responsibilities	Current private owner's or property manager's responsibilities
Monitoring	An on-going report to prove rainwater management performance is required in 2 years after project finished.	The BES oversees post-construction inspections of stormwater facilities and drainage reserves on private property. Enforcement will be triggered if the property owners or the designated responsible party don't comply with the operation or maintenance of the stormwater management facility based on the O&M Plan.	The city monitors sewer system in the end area. The Bylaw allows city to track back to origin area if pollution is found.
Cost	The property owner pays for operation and maintenance of GRI tools. If the GRI tools needs to be replaced, it's also	The property owner pays for operation and maintenance of GRI tools. If the GRI tools needs to be replaced, it's also private owner's responsibility. If the	The property owner pays for operation and maintenance of GRI tools. If the GRI tools needs to be replaced, it's also private owner's responsibility.

	private owner's responsibility.	rainwater management fails, civil penalties can be up to $10,000 per day per violation based on the BES Enforcement Program Administrative Rules.	
GRI Encourageme nt	Education sectors through public documents	Incentive programs; Public education; Mails to single-family owners	Mandatory Downspout Disconnection; Intensive research on green roof; Green roof GIS simulating model

6.2 Conclusion

The benefits of green rainwater infrastructure (GRI) are well recognized in our research through published papers and institutions of government. As a well-known and outstanding GRI tool, the green roof brings many more benefits besides rainwater management. Proven by researchers and experiments, green roofs ensure the quality and quantity of collected rainwater, improve building energy efficiency, absorb air pollutants, reduce urban heat island effect and gas house emission, bring aesthetic benefits, and preserve habitat for displaced creatures. The ongoing green roof performance has restrictions on many factors: substrate layer depth, temperature, moisture condition, weather events intensity and period, and proper operation and maintenance. All researched cities prioritized on-site infiltration by green rainwater infrastructure in their rainwater management strategies and policies, although their approaches and requirements may differ. A comprehensive advanced GRI program should contain application process, available, O&M manual and regular post-occupancy inspection. The fully green roof on-site monitoring is possible based on the research equipment combination, but it might not be applicable for every green roof in city as the high cost and complex installation.

Portland and Toronto both have an independent green roof standard in addition to their rainwater management strategy. The Portland refers to the green roof as ecoroof and exempts the buildings with green roof from mandatory level 1 full on-site infiltration requirement as long as the green roof is qualified by Stormwater Management Manual (SWMM). SWMM is the core document for Portland rainwater management, and it has been continuously updated every several years. The manual contains all the rainwater management requirements and benefits, recommended approaches, the application process, necessary forms, and operation and maintenance. It gives property owners a clear and full understanding of the necessity of GRI and minimum efforts to plan their projects. In Portland's post-occupancy inspection program, green roof is also prioritized and most green roof will be inspected less than every two years.

Toronto adopted the Green Roof Bylaw in the policy frame back in 2009, and it makes them the first city in North America to have a bylaw requiring green roofs. The bylaw was pushed by published research conducted with Ryerson University on Toronto's potential environmental benefits and costs of green roof technology. The research reviewed published papers and reports to explain green roof benefits in all fields with proven and available green roof systems with established standards established in Europe. To estimate the potential benefits green roofs could bring to Toronto, the research team used a GIS geographical model collected by the city of Toronto to simulate a future city with green roofs on all qualified buildings. The results showed monetary benefits in stormwater management, combined sewer system control, air quality improvement, building energy and urban heat island reduction, which proves the necessity of applying green roofs in Toronto. Although the simulation boundary might not be exactly the same as realistic conditions as its simplicity, the results are compliant with Toronto geographical information and convinced stakeholders.

6.3 Recommendations

It was found that city administrations had similar water difficulties during the research, including combined sewer system overflows, local watershed pollutants and infrastructure capacity limitation, which became the motivation to develop their rainwater management programs. Portland, Toronto and Vancouver all prioritized GRI in rainwater management strategies with different standards and approaches to ensure proper performance. By comparing cities' management programs and policy frames, valuable lessons of city-scale performance ensure programs are learned.

As described in section 4.3.3, the extensive research played a significant role in perusing stakeholders and the city council to adopt the Green Roof bylaw enhancing GRI implementation. The data analysis can be used to estimate incentive programs educating and encouraging private owners to take the initiative to construct GRI tools. With foundation research, jurisdictions can develop realistic strategies in the long term and prove the further estimated achievement. The research can be in different forms, including literature, planning, and modelling, as long as it complies with local reality.

6.3.1 Rainwater Management Requirement

The City of Vancouver has a specific rainwater management requirement "capture and clean minimum 24 mm rainfall per day" in the private realm. The rainwater management requirements of Portland and Toronto are in a more complex system. Portland applies a hierarchy-level ranking system to projects in the private realm. It includes different objects in three levels, and the project has to comply with level 1 unless any technical difficulties exist, and the city reviewing office has to prove it to apply level 2 or 3. Level 1 is fully onsite infiltration, and level 2 gives allowance to sites that have difficulty discharging rainwater offsite with pollutant and flow control. Then level 3 only contains flow control. Each case will be approved individually, and the sites cannot comply with any levels that need to pay offsite stormwater management fees depending on the unmanaged area to the city. The Bureau of Environment Service told us that most of the sites paying an offsite fee only for a small portion of projects, while most of the site is normal. New and re-develop projects are different, and one standard might be hard to comply with all sites with equity. The various level system can ensure every project achieves the best effort of rainwater management without struggling to meet objects in uncommon situations.

Similar to Portland, Toronto has Tier performance standards in their board policy Toronto Green Standard. Tier 1 is mandatory, and Tier 2-4 is voluntary. Tier 1 is well-defined in rainwater balance, quality, and quantity control with onsite green infrastructure. Tier 2 has additional requirements for water and irrigation efficiency. The sites that complied with Tier 2 may have rewards or incentives from the city (Development Charge Refund Program). In addition to mandatory and voluntary standards, the city also has different requirements for building types, including low-rise residential buildings (less than 4 stories with a minimum of 5 dwelling units) and mid to high-rise residential buildings (over 4 stories) in the private realm. Although the Toronto Green Standard Version 4 published in May 2022, has the same rainwater management standards for both types of buildings, the initiative to differ building types is important.

A comprehensive rainwater management requirement, including different levels, is developed in both researched cities and proves its effectiveness. The best rainwater management requirement from research contains basic standards, voluntary standards with rewarding programs, and monetary solutions for impossible conditions.

6.3.2 Required Documents in Reviewing Process

The required documents in permits application are similar in all cities. The core documents include a site plan, rainwater management plan, legal agreement and operation and maintenance plan. The City of Vancouver requires an on-time GRI report after 2 years of construction as defined in the legal agreement and does not limit and differ GRI varieties. Portland is similar, and it contains an additional portion of the standard O&M plan categorized by GRI type submission requirement. The standard O&M plan has different forms for green roofs (also known as green roofs), permeable pavement, rain gardens, basins, planters, filter strips, dry wells and soakage trenches, and surface sand filters. Each form includes specific caring instructions, maintenance indicators with corrective action, and an annual maintenance schedule with the procedure. The forms need to be submitted in the permitted development process. The forms regulate owners' operation and maintenance procedures and give them instructions, as many property owners have limited knowledge. It also helps new property owners know the existing GRI in the property as the responsibility of taking care of GRI transfers to current property owners even if they didn't construct them. If the existing GRI tools are different from the owners' previous property, the O&M plan prevents damage from the inappropriate procedure. After construction, the O&M needs to be kept for at least the first two years to present for the inspection. Thus, specific requirements or O&M instructions for some common GRI tools will be beneficial compared to general information complying with all kinds of GRI. In addition, Portland has inspection in the building permit stage to ensure requirements are satisfied, which is a valuable lesson for other jurisdictions.

6.3.3 Policy Frame

The post-occupancy inspection and enforcement are supported by City Code 17.38. Toronto Sewer Bylaw also defines Toronto's water quality monitoring in the city sewer system. The policy framework is the foundation for the rainwater management program. A bylaw must be established first to explore the possibility and new programs in the post-occupancy stage. Besides supporting programs, bylaws could also be used to encourage a specific type of GRI tool implementation. A good example is Toronto Green Roof Bylaw. The green roof bylaw regulates the implementation of green roofs in all buildings with a gross floor area of over 2,000 m^2. The green roof is pushed forward in rainwater management compared to other green infrastructures as its obvious benefits.

6.3.4 Post-Occupancy Monitoring

The City of Vancouver requires property owners to declare GRI status after two years of construction to monitor GRI performance. There isn't a post-occupancy monitoring or inspection program. Portland's City Code 17.38.043 gives BES the right of entry to enter all private premises at any time to inspect any potential violations with proper protocols. The inspectors are authorized to take samples, test, record examinations, install devices and make photographic documentation. From our interview with Portland BES, the inspection program is an outstanding way to ensure GRI's ongoing performance in the long-time period after construction. If the sites fail to comply with the proposed initial O&M plan, the city can apply civil penalties of up to $10,000 per day per violation. In a realistic situation, the penalty will start with a reasonable amount from a couple of hundred dollars in a certain time for the owner to solve the issue. Due to limited resources, BES is not able to inspect all sites at the ideal time. The BES now stops inspecting single-family properties as the applicable GRI tools are uncommon to fail and obvious to notice. Instead, BES mailed out information sheets annually, reminding owners to maintain the GRI. Inspecting standards are also different by GRI type. The more complex GRI with higher failing risk or more cost to fix is prioritized for inspection. Normally, green roofs are the priority and will be inspected every two years. The inspection date depends on the project's previous inspecting time. Thus, a comprehensive post-occupancy inspection program should be established to ensure the ongoing performance of GRI. The inspection program can be downsized with the limited resource focusing on certain GRI depending on the inspecting frequency and risk.

6.3.5 Incentive Program

During interviews, both cities mentioned their incentive programs. Portland had Ecoroof Incentive previously, and it has achieved increment in green roof implement over city's inspection according to city staff. As mentioned in section 4.3.3, Toronto has established EcoRoof Incentive Program to encourage green roof implementation since 2006. The incentive program has been proven to be an outstanding method to encourage comprehensive rainwater management. Currently, both Portland and Toronto still have multiple incentive programs and prioritize them in their strategy. The City of Vancouver could establish incentive programs to encourage a specific type of GRI, like green roofs, or push the implementation of GRI in private realms.

6.4 Recommended additional studies

This research includes green roof benefits, major factors that affect green roof performance, and the city-scale green rainwater infrastructure management programs of Vancouver, Portland, and Toronto. The recommended future works are:

- Case studies on other cities with advanced rainwater management programs;
- Green roof construction standards and barriers;
- Green roof implementing models in the City of Vancouver;
- Post-occupancy inspection program establishment process and cost;
- Operation and maintenance based on infrastructure categories; and
- Incentive programs for perusing private property owners choosing GRI.

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