Application of Stormwater Tree Trenches in the City of Vancouver

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The author and mentor acknowledge that all the work in this report was completed on the unceded and ancestral territories of the Coast Salish Peoples (Vancouver, British Columbia, Canada)

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Executive Summary

Vancouver is growing at a fast pace. Consequently, Vancouver's growth will be tied with a higher incidence of impervious surface to accommodate the incoming population. The increase in urbanization adds pressure on available space, further limiting areas where rainwater can be absorbed into the ground. As of 2016, it is estimated that 56% of Vancouver's land is covered by impervious surfaces [1]. Impervious surfaces hinder the natural rainwater infiltration cycle. Since water cannot infiltrate into the underlying soils, it becomes runoff. The runoff is collected and piped to the stormwater system. Current climate models project that climate change will make rainfall more intense [2], increasing the amount of runoff generated and overwhelming piped systems leading to increased flooding and combined sewer overflows.

Stormwater Tree Trenches (STT) are a versatile green infrastructure (GI) technology that shows promising application in Vancouver's highly dense urban environment. Soil cells or structural soil can be used as STT. This form of GI practice addresses many of Vancouver's strategic plans. In particular, STT align with the targets set by the Citywide Integrated Rainwater Management Plan (IRMP) as it can:

- Capture rainwater by letting it infiltrate into the native soils.
- Filter pollutants found in street runoff, sending cleaner rainwater to the stormwater system. If a STT is saturated, the excess rainwater is collected at the bottom of the practices with an underdrain connected to the stormwater sewer.
- Provide street trees with additional rooting volume, nutrients and water. These support the tree's survival by allowing them to grow healthier and have bigger canopies. In turn, the healthier urban forest and canopy will intercept more rainfall, reduce urban heat island effect, and contribute to biodiversity.

The literature review conducted in the study revealed that STT were used in the Lower Mainland of B.C., across North America, and Europe. However, only a few systems, which were in other climate regions, have been monitored for performance. Those studies found the following:

- **Rainwater Volume Reductions to Stormwater System–** Rainwater was allowed to infiltrate naturally. In some cases up to 98% volume reduction was found [3].
- **Peak Flows –** Rainwater runoff was slowed and detained successfully within the STT. This resulted in smaller flows to the sewer system. It was reported that rainwater could be delayed up to two hours from entering the stormwater system [4].
- **Water Quality –** Soil cell STT are effective in removing heavy metals such as copper, aluminum, zinc and iron with efficiencies over 86%. In addition, total suspended solids and phosphorus can be reduced with at least 70% efficiency [5].
- **Tree Health –** All STT methods were successful in preserving tree health. However, STT experts recommend the installation of trees naturally resilient to changes in soil pH, drought and saturated soil conditions [6].

The Vancouver STT Monitoring Plan will evaluate the performance of four STT designs in Vancouver and compare the performance to that found in other climate regions. In addition, the literature review identified a gap in knowledge of water quality performance for structural soil STT practices that the Vancouver STT Monitoring Plan will address.

This report also examined the life cycle cost of a boulevard reconstruction project. When comparing the boulevard reconstruction scenarios, the green infrastructure options were 28%-59% more costly over the life cycle of the boulevard than the conventional pave-only approach. However, the conventional approach doesn't meet many of the City's sustainability goals including stormwater management and tree soil volume targets. When comparing only the green infrastructure scenarios, the STT options were between 20-30% cheaper than the bioswale option or a conventional design with a manufactured water quality device.

The following implementation recommendations for STT implementation were derived through this study:

- **STT configuration –** Liners and gravel storage areas bellow the STT should be avoided in order to support tree health. This will allow the tree roots to access subsoils and allow groundwater moisture to percolate up through the soil during dry periods.
- **STT Type** - When choosing between structural soil and soil cells, designers must:
    - **Weigh soil volume goals –** Easier to achieve with soil cell STT.
    - **Consider space constraints** – Available subsurface areas that are non-uniform and constrained by utilities may favor the use of structural soil which can easily fill unusually shaped spaces.
- **STT design components** remain to be optimized and tested, including:
    - **Pre-treatment** - CB sumps are the most common form of pre-treatment, but they fail to effectively remove fine sediment which may reduce the STT performance over time.
    - **Soil mixes in STT** – Soils used in the soils cells and structural soils must balance drainage needs, filter requirements, and tree needs such as moisture retention and nutrients. The soils used for non-stormwater soil cell and structural soil applications may not be ideal for STT applications.
    - **Distribution and sub-drain pipes** – The location of the distribution pipe and the orientation of the perforations impacts how well stormwater is distributed throughout the trench and maximizes the storage volume. To enhance volume control performance, the sub-drain pipes can be raised from the bottom, include elbow bends or have slow release orifice controls.
- **Tree Health –** Research has shown that both soil cell STT and structural soils STT can successfully support trees, but the following must be considered:
    - **Soil moisture conditions –** Tree species that are resistant to dry and saturated soil conditions are recommended.
    - **Soil pH –** The tree selected needs to be able to withstand changes in soil pH. The soil pH may vary due to the pH of the stormwater, the STT soil medium, and the use of road salts in the winter, among other factors.
    - **Tree growth –** The final growth of the trees species is another important factor to be considered. The STT, as well as the street tree pits, have a determined amount of available soil volume and space. The designer must ensure that in the future, the tree will not outgrow the allotted space and soil volumes.
- **Maintenance and Asset Management**
    - **Onsite utility mapping –** Utility cuts must be considered in the design of these linear right-of-way facilities. The design must be kept simple for easy restoration. Consider the use of tracing wire through distribution pipes and sub drains so that they can be identified with M-scope utility line detectors.
    - **Short term maintenance –** While STT may have less maintenance than a bioswale or bioretention rain garden, they still require regular maintenance. The frequency of vacuum truck cleanouts of pre-treatment CBs will depend on the street's uses, traffic volumes, and leaf drop. At a minimum, CB sumps should be vacuumed at least once a year. A monitoring program should be implemented to evaluate the accumulation rate of sediment in CBs critical to GI and stormwater management functions.
    - **Inspection and maintenance access points –** Access for inspections and maintenance must also be considered. Sub drains and distribution pipes need cleanout access points, and pipe bends need to be limited to 135 deg to allow pipe cleaning equipment to access the full length of pipe. Monitoring wells should be installed to monitor water levels in the STTs.

STT are a cost effective green infrastructure approach well suited to the denser urban redevelopment happening in the City of Vancouver. They are a compliment to active transportation improvements and achieve tree soil volume goals in addition to meeting rainwater management objectives. Fitting with the City's reputation as a leader in sustainable design, there are also many opportunities to innovate on the STT design.

Soil Cells – Olympic Village, Vancouver
Image by DeepRoot

1.0 Introduction

Green Infrastructure (GI) is a set of sustainable rainwater management tools. GI mimics natural processes to filter and return stormwater to the ecosystem through the use of plants and soils. The US EPA [7] defines GI as a: "Cost-effective, resilient approach to managing wet weather impacts that provide many community benefits … [G]reen infrastructure reduces and treats stormwater at its source while delivering environmental, social, and economic benefits."

Under natural conditions, rainwater lands on pervious surfaces. Close to 50% of the rainwater is absorbed, about 40% is returned to the atmosphere and a small portion (~10%) runs off to water bodies [8]. In urban conditions, between 30 to 50% of the rainwater runs off rapidly to the water bodies or sewers, picking up urban pollutants and increasing the rainwater volume to the sewer system in the process [9].

Excess urban runoff poses a threat to the environment. This issue is expected to become worse with climate change. The BC government projects that winter precipitation is expected to increase by 23% in the province by 2080 when compared to 1961-1990 historical averages [2]. The increased rainfall is expected to trigger combined sewer overflows (CSO) more often in areas where the sewer system has not been separated yet. In 2016, Environment Canada estimated that British Columbia discharged more than 45 million m^3 of untreated sewage into BC waters, where approximately 71% came from the Lower Mainland [10].

As Vancouver continues efforts to separate combined sewers and reduce sewer overflows of untreated sewage, more urban rainwater runoff will be flowing directly to the City's receiving waters leading to environmental impacts if not adequately treated prior to release. It is important to recognize that urban rainwater runoff is harmful to aquatic life and the recreational use of local waters. Typical pollutants found in urban landscapes include: pathogens; fine sediment; heavy metals from brake pads and tires; excessive nutrients such as nitrogen and phosphorus from landscaping practices and urban agricultural; and hydrocarbons in the form of oil and grease [11]. The Washington State Stormwater Center (WSSC) researches the impacts of urban rainwater runoff on the Salish Sea's aquatic life, with a focus on salmon. Their studies determined that the exposure of salmon to untreated stormwater is fatal [12] [13]. Among the symptoms the salmon experience are loss of orientation, gaping, loss of equilibrium and pectoral fin splaying [12]. In addition, a 2018 study by WSSC concluded that fish embryos that develop in sub-lethal doses of untreated stormwater runoff negatively impacts the embryo's sensory system development. The researchers theorize that this could have negative consequences in the fish's survival [14].

Stormwater Tree Trenches (STT) are an emerging GI technology that shows promising application in the City of Vancouver's high density urban development. This report will focus on STT and how they address water quantity and water quality issues. Rainwater runoff is directed into the trenches, where it can be treated and infiltrated by the trench soil medium. Figure 1 shows the schematic of a STT design and it illustrates the rainwater capture and distribution process within the practice. Moreover, the STT provide street trees with additional soil for root volume and access to water.

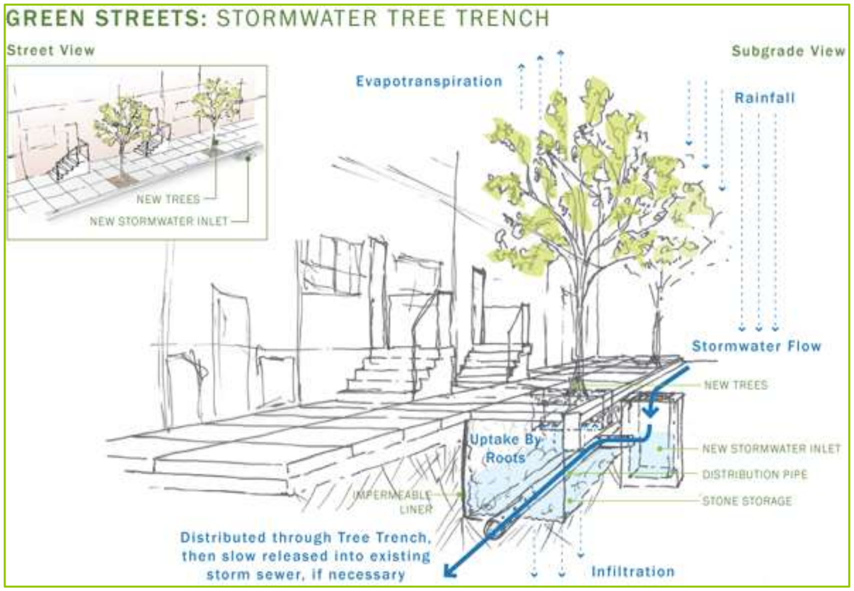

Figure 1: Stormwater Tree Trench Schematic. Image source: PWD [13]

1.1 City of Vancouver Context

Vancouver is a fast growing city that is expected to increase in population at a rate of 1.8% annually beyond 2019 [15]. Increased urbanization is tied to increases in sewage volumes and stormwater runoff which will worsen combined sewer overflows. As of 2016, only 44% of the City of Vancouver (CoV) is permeable green spaces in the form of open spaces, parks, and golf courses. This leaves a 56% of land dominated by impervious and compacted landscapes. The breakdown of the impervious land use is comprised of streets (30%) and private property (55%). The City of Vancouver has direct influence on the design and operations of streets. On private property, the City has indirect influence in the form of municipal regulations such as "by-laws, standards and guidelines" [1].

In 2017, the City of Vancouver Council adopted and updated vision and goals for the Citywide Integrated Rainwater Management Plan (IRMP):

Vision: *Vancouver's rainwater is embraced as a valued resource for our communities and natural ecosystems.*

Goals:

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

With this vision in mind, the City has moved to incorporate GI into city projects and new development. GI not only aligns with the Citywide IRMP, but it also supports the targets set by the City's Greenest City Action plan and Healthy City Strategy which aim to: increase the access to nature, reduce urban heat island effects, increase pedestrian safety by reducing sidewalk buckling, and conserve potable water, among other objectives [15] [16] [17]. Green infrastructure practices installed in Vancouver include bioretention or rain gardens, green roofs, stormwater treatment wetlands, underground infiltration systems, permeable pavement, and rainwater harvesting.

Stormwater Tree Trenches fit well in many of the developments and transportation projects on the horizon for the City of Vancouver. Over the next 10 years, STT will potentially be used in the Northeast False Creek Redevelopment, Riverview District, Cambie Corridor, and various other greenway and complete street projects. Lessons learned and performance monitoring of small scale STT demonstration projects installed in 2017 and 2018 on 10th Ave, Quebec St, Smithe Street, and Vancouver Art Gallery North Plaza will be used to improve on designs for future larger scale applications.

Figure 2: Trees growing in soil cells at Vancouver's Olympic Village. Image source: Deeproot [79]

Soil Cell – The Quarters in Downtown Edmonton
Image from City of Edmonton

1.2 Method

This report was compiled from mid-April to early August of 2018. The two primary components of this report are the STT literature review and the preliminary monitoring plan for the four GI practices to be monitored in Vancouver. The main goal of the literature review was to document the performance and experiences of other cities across North America and Europe that have implemented STT. The literature review is organized by cities with similar climate as Vancouver, BC and then expanding beyond.

Initially, a traditional literature review was conducted. The literature included in this report encompasses: thesis, dissertations, journal papers, articles, conference presentation proceedings, and reports. However, STT are a new area of research that is slowly increasing in content. The amount of information publicly available is still limited as of 2018. With a few exceptions, all of the studies and project documentation found were on structural soil and soil cell performance as used solely for increasing root volume and not for treating and retaining stormwater runoff.

To expand the literature review, the mentor and author reached out to municipalities with experience in design and construction of STTs. Working through professional associations, over a dozen cities were identified as having installed STT. The interviews with the municipal staff from the cities identified were structured around the municipality's experience integrating STTs in city projects, the challenges faced, and the lessons learned. Figure 3 pinpoints the geographic location of the cities covered in the literature review.

The other components of the report consist of a life cycle cost analysis (LCCA) for STT, STT case studies, and the monitoring plan for Vancouver STT.

1.3 Limitations

The following limitations were identified during the production of this report.

An important limitation was the project timeframe. The literature review and monitoring program research and compiling process were completed during the allotted time by the Greenest City Scholar (GCS) program. A total of 500 hours were used to complete all tasks. The scope of the research was narrowed to the cities identified in Figure 3. This allowed the timely completion of this study. The author and mentor recognize that there are many examples around the globe that were not covered in this GCS report due the project timeframe constraint.

The monitoring plan was developed simultaneous to the construction of the GI practices that will be monitored. The major benefit of this is that the design of the practices incorporates modifications that allow the incorporation of monitoring equipment. Unfortunately, space, resources and timing were limited. Hence not all desired modifications were feasible to be integrated in the designs. The monitoring plan included in this report is at a draft stage as of August 2018. The plan will be progressively modified as the monitoring equipment is confirmed and construction of the practices concludes.

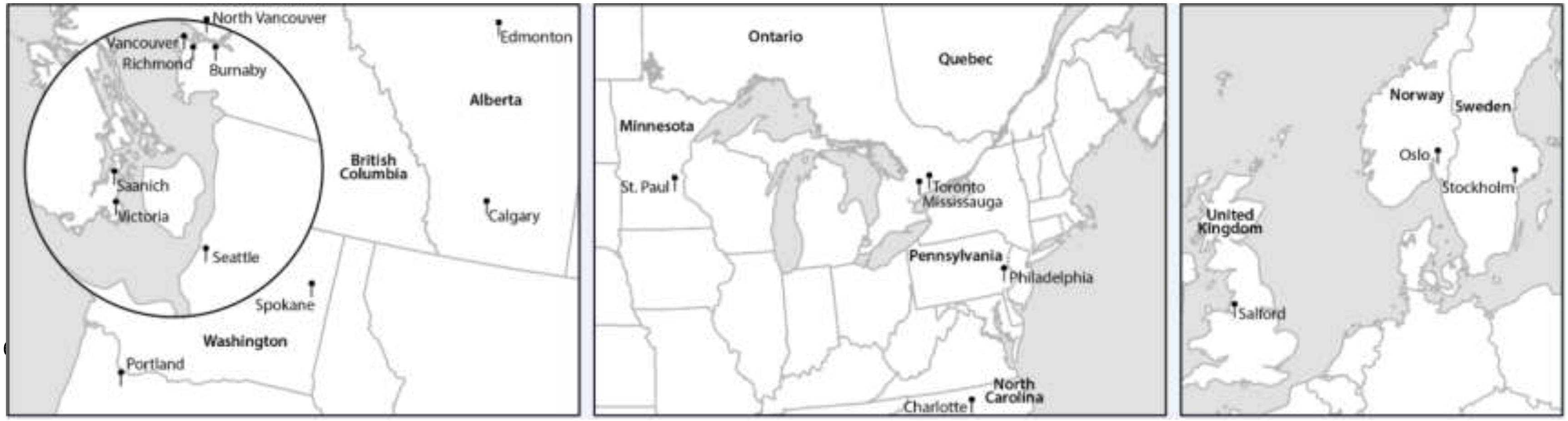

Figure 3: Cities included in literature review research. Image Source: GI Branch

2.0 Literature Review

2.1 Tree Trenches

Tree trenches can be grouped in two main categories:

- **Soil cells**. This practice uses a plastic module structure that bears the loadings from the surface. Soil fills voids left in the plastic module. The volume of soil contained in the plastic matrix varies between soil cell manufacturers. Up to 92% void space can be achieved [18].
- **Structural soil.** These practices use open grade crushed stone to bear the loadings of the surface. Depending on the designer, structural soil can be mixed with soil and a stabilizer or consist solely of crushed stone. Up to 30% void space within the stone to be filled with loam soil [18].

Both systems achieve the goal of providing trees with extra rooting volume that conventional urban tree pits fail to provide. Yet, both systems have advantages and disadvantages.

Tree Health

There is a strong correlation between tree health and soil volume as demonstrated by a study lead by Dr. T. Smiley. The study began in 2004 at the Bartlett Tree Experts labs in North Carolina. The experiment, which is still ongoing, compares the tree health using different urban planting methods. The methods include: compacted soil; suspended pavement: Silva and strata cells; structural soil: CU structural soil[1], Stalite[2] alone, and Stalite/soil mix. All the trees are irrigated using a bubbler system.

A final report with the study findings was still in progress, at the time of this review [19]. However, preliminary results summarizing 14 months of growth were published in 2006. The paper concludes that the trees planted in non-compacted and suspended pavement (soil cells) grew larger, greener and faster than the other methods. Though, the study also draws attention to the tree species' reaction to the different soil mediums. For instance, the cherry tree's twig growth rate in non-compacted and soil cells double the rate of the structural soil (of the gravel/soil kind). Yet the twig growth rate of the Elm trees was virtually the same among the non-compacted, soil cells and structural soil (of the gravel/soil kind) [20]. The tree growth in 2005 and 2013 is shown in Figure 4.

A Virginia Tech study found successful tree growth in structural soil using: CU Structural Soil and the Stalite/soil mix [21]. Trees in these mediums exhibited better tree health and growth when compared to a typical street tree [22].

Project Costs

Regardless of the soil volume benefits that the soil cells provide, the capital costs associated to this technology has been a deterrent for many municipalities and private developers. Based on the total volume, structural soil is on average between 30 to 45% less costly than Silva Cell (soil cell) systems [23]. On the other hand, soil cells provide a higher volume of soil than structural soil per cubic meter. In order for the structural soil to deliver the same amount of soil volume as soil cells, up to five times the volume of structural soil is required [23]. This would consequently drive the structural soil cost up, making the soil cell the most cost effective option.

Space Constraints

In terms of design and constructability, soil cells are a challenge to install in retrofit conditions in comparison to structural soil. Soil cells are less versatile as they are manufactured in pre-determined dimensions that vary among manufacturers. Retrofit projects tend to have limited and irregular space due to existing utilities constraints. In many situations, the space does not allow enough room to fit a soil cell grid into the project. Structural soil on the other hand does not have this limitation and it can be easily poured to fit in any location.

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[1] Developed by Cornell University and licensed by Amereq Inc. The method components are ~80% crushed angular rock and ~20% loamy soil. The rock and soil is mixed with a proprietary tackifying agent [24].

[2] Stalite is heat expanded slate. This material is lightweight and offers high soil strength [17].

Soil Cell – Queen's Quay, Toronto
Image from DTAH

Figure 4: Urban Plaza Bartlett Tree Experiment. Trees after 14 month (top) vs trees after 9 years (bottom). Image Source: Bartlett Tree Lab [9]

Dr. Nina Bassuk, a leading structural soil researcher in the US, recommends that if a tree is to be installed in a right-of-way structural soil practice, the recommended practice minimum depth is 24 inches. Preferably the depth should be between 30 to 36 inches. In addition the tree selected has to be resistant to changes in soil pH and moisture [23] [24]. Consequently, if structural soil is not designed properly, structural soil cells can lead to tree mortality.

Tree Trenches in British Columbia

Structural soil and soil cells have been used for the purpose of tree root soil volume in the Lower Mainland for over ten years. Here are a couple notable examples:

City of Vancouver – The City of Vancouver is well-known for implementing novel approaches and technologies to meet the ambitious targets set by the Greenest City Action Plan and other strategic plans. The first installation of soil tree trench conducted by the City was at the Olympic Village in 2009. The project was divided in two phases and it set a target of planting 80 trees with expanded root volume areas. The goal was accomplished by using 7,000 Silva Cells in the project in a two layer system. The tree trenches along the Olympic Village Waterfront are not irrigated. They take runoff from the wide sidewalk promenade through the tree trench openings [25]. After four years, the project designer concluded that the trees planted in the soil cells are growing on average at twice the rate of other trees that were planted at the same time without the use of soil cells [26].

City of Maple Ridge – In 2010 the City of Maple Ridge installed 54 new trees in using soil cells [27]. Directing stormwater from the street into the soil cells was considered in the design for getting water to the tree roots, but it was ultimately decided to use an irrigation system. Maria Guerra from the City of Maple Ridge highlights that the cells were meant to provide root volume for the trees in the Downtown Maple Ridge area. She also confirmed that formal performance monitoring is not in place. However, she comments that the trees planted in this project have grown faster and healthier than the conventional street trees of similar age planted in other areas of the City [28]. Figure 5 shows the status of the trees after four years.

Figure 5: Maple Ridge Soil Cell. Image source: DeepRoot [27]

2.2 Stormwater Tree Trenches

Stormwater Tree Trenches are an evolution from the conventional tree trench. The main modification from a conventional soil cell and structural soil tree pit is its ability to take rainwater runoff from surrounding drainage areas, such as streets, parking lots, sidewalks, plazas, and rooftops, where it can be filtered and infiltrated or used by the tree. Both soil cells and structural soils are considered under the STT definition. An isometric view of both methods of STT is shown in Figure 6.

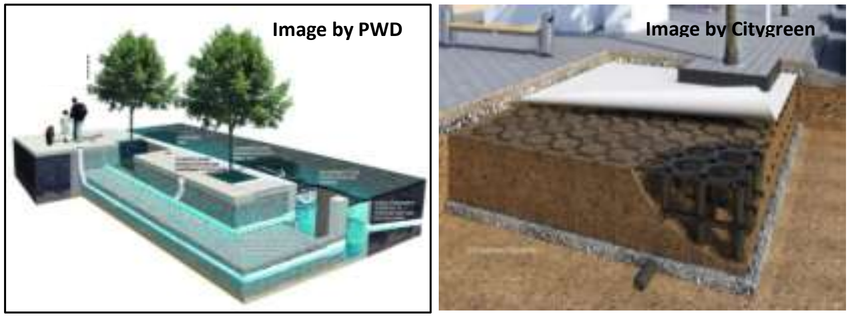


Figure 6: Stormwater Tree Trenches: Structural soil cell (left) and soil cell (right)

There are multiple ways for rainwater to enter the STT. For plazas, sidewalks, and parking lots, designers can use permeable pavement over the structural soil or soil cells to allow rainwater to percolate through from the surface [24]. Bringing street runoff into a boulevard STT is more challenging due to the curbs and elevation difference. The most common way is to use a conventional catch basin (CB). The CB preferentially drains stormwater into the STT. When the trench is saturated with rainwater, the rainwater will back up in the CB and drain to the sewer connection.

The following sections will focus on the application of STT in the Lower Mainland; Western Canada and the U.S. Pacific Northwest; Eastern Canada and U.S.; and Europe. When available, performance information will be discussed in each section.

Lower Mainland

City of Vancouver – Vancouver's first four STT projects were constructed in 2017 and 2018:

- Structural soil STT near Quebec St. & 1st Ave.;
- Soil cell STT in a traffic island at Smithe St. and Expo Blvd.;
- Structural soil STT on W 10th Ave. near Willow St.; and
- Structural soil STT in the Vancouver Art Gallery North Plaza.

These are described in more detail in Section 3.0, Case Studies. The first two on the list are included in the monitoring study that will be discussed in Section 5.0, with further details located in Appendix G. Performance monitoring on Vancouver's STT is not available as of August of 2018.

City of North Vancouver – As of 2018, the City of North Vancouver (CNV) has ten examples of STTs in their jurisdiction [30]. Figure 7 shows an example of a 2-year-old development that uses soil cells. As of 2014, developers are required to provide onsite stormwater controls and to manage the runoff from the frontage right-of-way. This includes the production of a 2-year monitoring program with yearly progress updates. Stormwater Tree Trenches are among the stormwater controls allowed [29]. To date, there are no publicly available reports on the performance of STT in CNV. Based on site visits and comments from the engineering department, the STT designs are functioning and the trees are healthy.

Soil Cell – Thomson Family Park, Calgary
Image by Citygreen

Figure 7: Soil cell STT in North Vancouver

City of Burnaby – There are various examples of STTs in Burnaby. Soil cells were installed in a private development called Station Square [27]. Structural soil was used along with various other GI designs on Burnaby Mountain in a sustainable community called UniverCity.

The STT have a fast draining structural soil medium and porous pavers on the surface that allow water to enter the practices. The combined discharge of the GI practices in UniverCity is monitored for water quality and quantity. Unfortunately, the individual practices are not monitored. Burnaby Mountain is exposed to severe winter conditions, thus de-icing methods such as road salting are heavily used. Based on visual observations, the fast drainage and road salts have negatively impacted the health of the trees in general according to PWL Partnership, the designers on the project [31].

City of Victoria and City of Saanich – On Vancouver Island, the Capital Regional District (CRD) reported that two STT were installed in right-of-way and one at a private property in the City of Victoria [32]. In Saanich, STTs have been used by private developers. None of the practices in Victoria or Saanich have been monitored to date according to the CRD [32] [33].

Western Canada and U.S. Pacific Northwest

Western Canada

City of Calgary – The City of Calgary has begun using STT to treat stormwater runoff. The STT design employed by Calgary includes a CB sump which serves as pre-treatment. The sump collects fine and coarse sediment in the runoff. Bert van Duin, City of Calgary Drainage Technical Lead, and Ken Clogg-Write, project manager at MPE Engineering, report that fine sediments over salts are the most detrimental factors to STT performance. Calgary's STT practices are designed for fast drainage. The salts are expected to be washed away after several storms [34] [35]. During the winter months, Calgary experiences Chinooks, which are unseasonably warm winds that cause an increase of temperature for a few hours [36]. The Chinooks cause snow to melt and the resulting runoff picks up salts and sand used for de-icing and traction, respectively. The fine sediment migrates into the practices, taking up pore space. Overtime, the fines clog the STT. For this reason, Calgary is considering shut off valves for closing off stormwater to STT during the winter. Bert stresses that research efforts should be directed to improving CB pre-treatment technologies as the current sump treatments are not effective enough [34].

Figure 8: Thomson Family Park Soil Cell. Image source: Citygreen [37]

Stormwater Tree Trenches in Calgary are installed in the right-of-way. Thomson Family Park in Downtown Calgary. The flagship project uses soil cell STT on the east side of the property, in the boulevard area. The park was renovated in 2016. The STT has a proprietary soil blend that filters contaminants from the street runoff and retains moisture [38]. Currently, the City of Calgary does not monitor their STT practices.

City of Edmonton – In 2015, the City used soil cell STT in a downtown revitalization project. The project aimed to integrate GI into the streetscape and reduce stormwater runoff. CBs are used to collect the street runoff and act as pre-treatment. The STT design uses an underdrain connected to sewers to capture the excess water that is not absorbed by the trees [39]. In total, 90 trees were planted in the soil cell system [40].

This site was designed for monitoring to assess the performance of the project [39]. To date, the monitoring reports are yet to be made publicly available.

U.S. Pacific Northwest

City of Seattle, WA – the City of Seattle has many GI examples implemented throughout the city's jurisdiction. The City of Seattle has nearly 20 years of experience with using bioretention and bioswales in the right-of-way, but they have not installed STTs. The City has a concern about the soils remaining saturated during the winter and harming tree health. This concern is based on the rainfall patterns in Seattle and the non-inclusion of underdrain systems to take away the excess rainwater if required. Nevertheless, the City has experimented with soil cell systems, not for street trees, but to increase storage in their right-of-way rain gardens. The soil cells are used to support sidewalks and are hydraulically connected to adjacent rain garden systems, acting as one storage volume. This design approach was used in the Ballard neighborhood rain gardens, but they have not been monitored [41] [42].

City of Spokane, WA – the City of Spokane is piloting a STT project in the West Central neighborhood. The total cost of the project is approximately $3.4 million USD. The project uses a Silva Cells underneath a boulevard [43]. According to the Spokane engineering department, they aim to take water out of combined sewer pipes in order to reduce CSOs [44]. Stormwater is collected and pre-treated in two sumps. The first sump is a CB that captures the street runoff. Water then flows into the secondary sump called "junction box" that also acts as a cleanout location. This sump is connected to two 6" in diameter pipes which distribute the rainwater into the soil cells. The soil cells are half filled with biofiltration soil compacted to between 70 to 80% proctor density. The void space left above the soil acts as an interim reservoir area where rainwater can pond and slowly soak into the soil cells [44] [45].

Figure 9: Soil cells used to support sidewalk and increase storage capacity in Ballard Neighborhood rain gardens in Seattle, WA.

City of Portland, OR – The City of Portland is a leader in North America when it comes to GI. The City has not installed STT, but as of 2018, the City has installed nearly 2,000 bioretention green infrastructure assets designed to reduce CSO [46]. The City of Portland estimates that about 1,000 trees have been planted in their bioretention practices with mixed health results. Some trees do fine in the GI practices while others struggle. The City is in the process of assessing the factors impacting trees, but the inclusion of a stone storage layer below the soil and use of liners correlate with more drought stress in bioretention trees and vegetation. Maintaining root access to subsoils and subsoil moisture should be considered with STT design. [47].


Soil Cell –Metropolitan Museum of Art New York
Image from Entro Media

Eastern Canada and U.S.

Eastern Canada

The province of Ontario is at the forefront of Canadian innovation in stormwater management. Various conservation agencies in the province spend time and resources monitoring GI projects, including STT.

City of Toronto, ON – The City of Toronto has used STT in various projects in the city. The revitalization of Queens Quay in Toronto's waterfront uses soil cell STT to manage ~47% of the stormwater runoff that falls in the catchment and is designed to handle a 1 in 100 year rain event. A CB acts as pre-treatment and a perforated pipe distributes the Stormwater into Silva Cells. In total, 134 trees were planted within the Silva Cells, which enabled the city to exceed their target soil volume of 30 cubic meters per tree [48]. This project is not monitored.


Figure 10: Silva Cells are used to support the Martin Goodman Bike Path while providing soil volume for the street trees along Queens Quay, which was reconstructed in 2014. Image source: Deep Root [48].

On the east side of Toronto, a pilot project called Queensway Sustainable Sidewalk Project uses STT to manage stormwater onsite. 260 soil cell frames were employed to manage a watershed area of 770m^2 [49]. This project has been monitored since 2009. A final report by the Toronto and Region Conservation Authority has yet to be released. However, Toronto Water presented preliminary results at the 2017 TRIECA conference. The soil cells were particularly effective in removing TSS (>77% removal) for the small and large events. The removal efficiencies for aluminum, zinc, nickel, iron and copper range from 47% to 94%. From the tree health perspective, the project evaluated two pairs of trees, one with soil cells connected to street runoff and one with soil cells disconnected from street runoff. The health of the trees was visually assessed. After four years, the STT accepting street stormwater runoff have shown significant growth (exceeding the height of a two-story building) when compared to the STT disconnected from street stormwater, as shown in Figure 11.


Figure 11: Queensway sustainable sidewalk tree comparison. Non-irrigated trees (left) vs irrigated trees (right). Image Source: DeepRoot [23]

City of Mississauga, ON – Credit Valley Conservation (CVC) is monitoring a retrofit project on the Central Parkway in Mississauga. This STT uses a soil cell with bioretention media as soil. The practice uses a CB as pre-treatment and it is not paved on the surface. The STT serves a catchment area of 854 m^2 with 93% imperviousness [50]. The CVC conducted a two year monitoring study that assessed the volume removal properties, peak attenuation, and water treatment benefits of the practice.

The CVC found that over the two year monitoring period, the practice provided a 95% volume reduction. Precipitation events less than 25mm had a 98% volume reduction. The peak flow reduction average was 96%, with a minimum reduction of 47% [3].

According to the CVC, the STT is particularly effective in removing suspended solids, with a calculated load reduction of ~98%. Moreover, the practice is also very effective in removing phosphorous, nitrogen, cadmium, iron, copper and zinc with load reduction averaging over 88%. Conversely, the practice was less effective in removing nickel and chloride. The load reduction for Nickel and Chloride were 71% and 55%, respectively.

Figure 13: Central Parkway Project STT. Image source: CVC [37].

Eastern U.S.

City of Philadelphia, PA – Philadelphia's structural soil design consists of tree pits with standard growing medium topsoil interconnected with a continuous crushed stone trench that stores and infiltrates rainwater [51] [52]. The Philadelphia Water Department (PWD) has a comprehensive GI monitoring program. In 2016, the PWD released the results of a four year pilot monitoring program that includes 49 GI practices, out of which 21 are STT [53]. The study found that their GI practices were outperforming their design goals. Most practices were managing in excess of the 3" (76.2mm) rainfall target, with storage capacity to spare. This has led PWD to consider increasing drainage areas to these practices by re-contouring surfaces and connecting additional CB [53].

City of Saint Paul, MN – The City of St. Paul includes STT in their design guidelines with the goal of increasing root volume in areas where space is restricted. Both soil cells and structural soils are allowed under the suspended pavement section of the Minnesota Stormwater Manual [54]. STT were used in the Green Line project, a light rail system that connects Minneapolis to St. Paul. In total, approximately eight kilometers of structural soil trenches were installed in 2012.

The trenches accommodate 1,250 trees and manage about 1" (25mm) of rainfall onsite [54] [55]. It was estimated that the installation costs ranges between $2,632-$4,800 USD per tree. The Green Line's STTs use permeable pavers on the surface, CBs as pre-treatment, and a feeder pipe for rainwater distribution. The design does not incorporate underdrains due to the fast draining properties of the soil. Figure 12 shows the practices after construction. A sandy soil mix is used in the STT. The practices are expected to drain within 48 hours. Sections of this project are being monitored for soil temperature and infiltration rates, using soil sensors and water level loggers in the monitoring wells [54]. A monitoring report is not yet publicly available.

Figure 12: St. Paul Green Line Integrated Street Trenches. Image Source: MPCA [54]

The City of St. Paul shared qualitative performance observations. After 5 years, the systems are draining and do not show signs of capacity issues. However, an unusually severe 2018 winter weather negatively impacted some of the trees in the corridor, but staff was unsure whether the STT design made the trees more vulnerable. A future goal for them is to perform forensic work on a trench to further understand the migration of fines to the bottom of the cell and investigate if water is exiting the perforated pipe at high speeds, creating preferential paths [56].

A notable lesson learned from Saint Paul has been with utility cuts. A lot of new development has occurred along the Green Line corridor resulting in new utility crossings through the STT. They recommend keeping the STT design simple for easier restoration work. Also, a tracer wire is recommended for distribution pipes and underdrains that will alert utility locaters as to the location of those pipes [56].

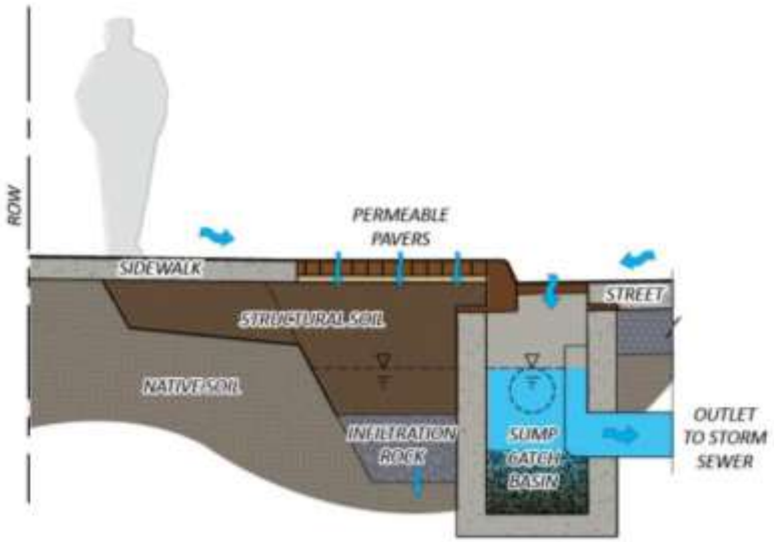


Figure 14: Cross-section of the St. Paul Green Line Stormwater Tree Trenches. Image Source: Minnesota Stormwater Manual

North Carolina (NC) – North Carolina State University conducted a STT study from July 2012 to September of 2013. This study monitored two soil cell practices. Both practices used a CB to collect street runoff and act as pre-treatment. The rainwater collected in the CB was then distributed to the STT through a feeder pipe system. The excess was collected in an underdrain [5].

The researchers estimate a combined volume reduction of ~80% for the two practices. The study found the outflow rates to be higher during the first two months when compared to later months. The researchers attribute this to soil settling within the practice. [5].

Monitored pollutant concentrations in the stormwater flows decreased significantly after STT treatment. The removal of total phosphorus and total suspended solids was of at least 70% for both soil cell STT. Similarly, both sites decreased concentrations of copper, lead and zinc with removal rates between 86-94% [5].


Soil Cell with Structural Soil – Lincoln Center, New York
Image by DeepRoot

Eastern Europe

City of Stockholm, Sweden –In 2001, The City of Stockholm made a tree assessment and determined that ~20,000 streets that were dying for a variety of reasons that included lack of oxygen in soils, high road salt concentrations in the soil, compaction, among other factors [57]. To address the issues, the City developed its own tree planting method that is a form of structural soil. The City also recognized the opportunity of using structural soil to treat and infiltrate street runoff, potentially providing trees with nutrients and water.

The Stockholm method consists on using crushed rock (100-150mm in diameter) in layers of 250-300mm. A loam soil is placed on each lift and it is washed into the stone layer with a high pressure hose. The process continues until the void space in the rock is filled with soil. A fertilizer is added after each lift has been filled with soil. This process differs from other structural soil methods as structural soil tends to arrive premixed on site and a stabilizer is used to keep the soil in place. Perforated CBs are used to direct the water into the practices and allow the ingress of oxygen. In some cases, underdrains connected to the sewer are placed at the bottom of the practices to drain the excess water [58]. Figure 15 shows a picture taken in 2013 at the Swedenborgsgatan Street comparing a tree planted using the Stockholm method in 2003 against a tree planted in 1935 using methods current to the time.

City of Oslo, Norway – The Norwegian Public Roads Administration (NPRA) conducted an upgrade to the Carl Berner Plass (place) in 2010. The upgrades included adding trees to the sidewalks. The NPRA decided to utilize STT using the Stockholm method. The road was centerline crowned to drain towards the STT located on the edge of the sidewalk. The sidewalk itself was sloped to drain into the STT [59]. The STT are shown in Figure 16 and they are not monitored.

Figure 15: Tree comparison planting comparison. Image source:: B. Embren [39]

Figure 16: STTs in Oslo, Norway. Image source: Solfjeld, I. [39]

City of Salford, England – A multiagency partnership including the University of Manchester funded a STT project in Howard Street in the City of Salford [60]. The STT is a 20m long and 1.75m deep soil cell trench. The London Plane tree was the tree species selected by the designer due to the tree's innate survival resiliency. A total of three trees were installed in the trench. Figure 17 shows the soil cell STT.

Figure 17: STT in Salford, England. Image source: City of Trees [40]

Street runoff is taken directly into the soil cell system through a perforated curb, Figure 18. An underdrain was placed to collect the excess water not used by the trees and it is discharged into the sewer system. Both the inflow and outflow are being monitored for water quantity and water quality [6].

According to Dr. Rothwell, lead researcher, the STT retains on average 60% of the rainwater that enters the system. If water manages to reach the underdrain to the sewer system, Dr. Rothwell estimates that there is up to a 2 hour delay in some cases [4].

Figure 18: STT Curve Inlet System circled in yellow. Image source: Google Map data ©2018

3.0 Case Studies

1- **Structural Soil** – Quebec Avenue and 1st Street

2- **Soil Cell** – Expo Boulevard and Smithe Street

3- **Structural Soil** – West 10th Avenue and Laurel Street

4- **Structural Soil** – Vancouver Art Gallery North Plaza

Image: CoV – Property Viewer

Quebec Street and 1st Avenue Structural Soil Tree Trench

Image: CoV – Property Viewer

Location: STT is located under the off-street bicycle path

Type: Structural soil

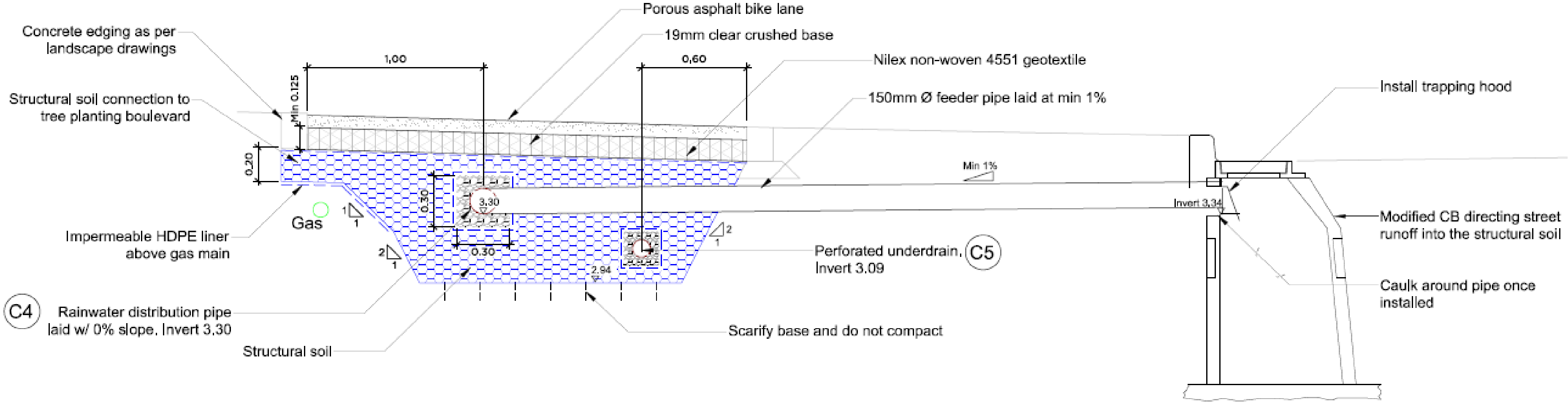
Medium: Custom Veratec SureBase (80% coarse aggregate and 20% Ecomedia Level 1)

Drainage area:

- Street catchment: 525 m^2
- Bike path and pad catchment: 55 m^2

Land use:

- Quebec Street is a busy arterial in Vancouver. The most recent daily traffic volume estimate for the southbound traffic was conducted in March of 2011 and estimated a volume approximately 12,000 vehicles per day [118]. Vehicle use on this road ranges from motorcycles to semi-truck trailers [101]. The road is centerline crowned.
- Behind the curb sits a concrete paved pad for Mobi bike share and an asphalt paved off-street bicycle lane. Both drain runoff to the structural soil trench via the street and pretreatment CB.



Structural soil cell design cross section (north into the page) for Quebec Street and 1st Avenue. Source: City of Vancouver - GI

Pre-development conditions looking south

Structural soil during construction looking north

GI features:

- This is the first site to use a biofiltration media as the soil in the structural soil mix as opposed to the standard growing medium soil blend. This is in an effort to capture pollutants and minimize nutrient leaching into the stormwater system.
- This site will be monitored from 2018 to 2019 for flow, water quality and soil moisture. The performance will be compared to a bioswale located across the street and a soil cell STT located in downtown Vancouver.

Lessons learned:

- Monitoring of construction by the site designer was essential to ensure that the structural soil was installed as intended and that solutions to any problems arising could be discussed and solved quickly within the tight timeframe of the project.
- The structural soil provides additional rooting volume for the boulevard trees on the east, but an existing gas line with a protective surround of existing subgrade limits the connection between the tree planting and structural soil area. See cross-section. There is a 20 cm depth of structural soil connecting the two areas. See cross-section. Improved strategies and standards for protecting utilities within and near GI are needed.

Post-construction looking north on Quebec St. The asphalt bicycle lane is covering

Expo Boulevard and Smithe Street Soil Cell Tree Trench

Image: CoV – Property Viewer

Location: Traffic Island at Expo Boulevard and Smithe Street

Type: Soil cell

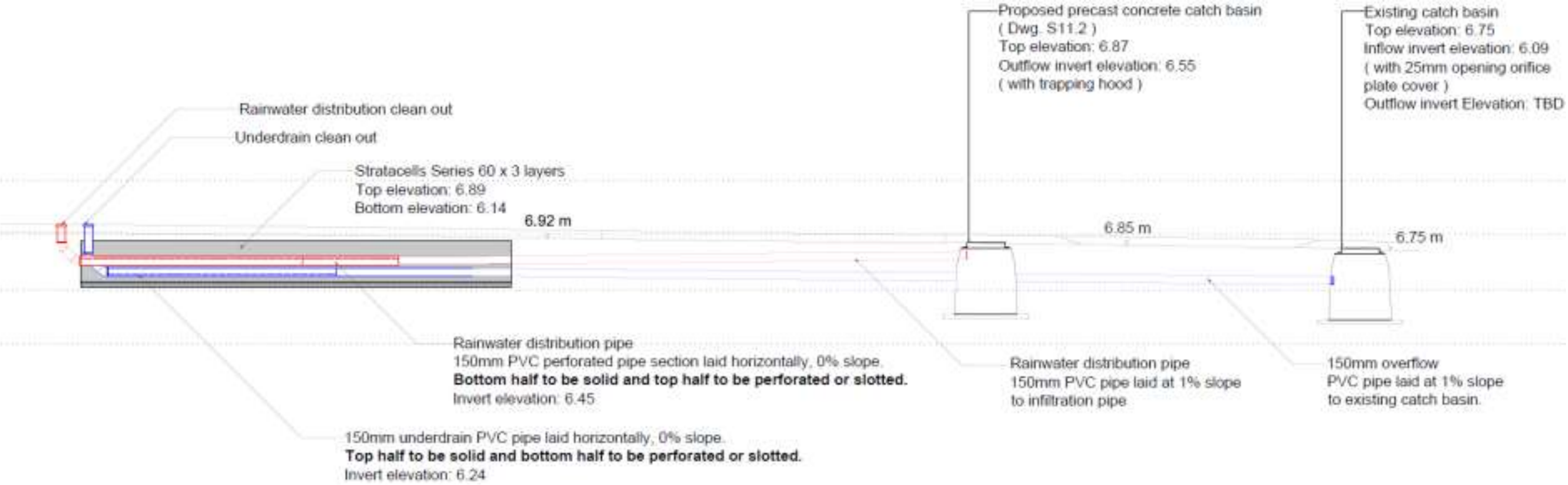
Medium: Three layers of Stratacells Series 60 filled with medium turf blend soil

Drainage area:

- Street catchment: ~421 m^2
- Traffic island catchment: ~222 m^2

Land use:

- Smithe Street and Expo Boulevard are heavily used arterials in Downtown Vancouver. Smithe St. receives the traffic from the Cambie Bridge driving into Downtown Vancouver. Daily traffic on Expo Blvd is estimated to be approximately 17,473 vehicles per day according to the latest count from March 25, 2007 [118]. No traffic information is available on Smithe St. Both streets allow the transit of all vehicle sizes [87]



Soil cell drainage concept design for Expo Blvd and Smithe St. Source: City of Vancouver – GI Branch

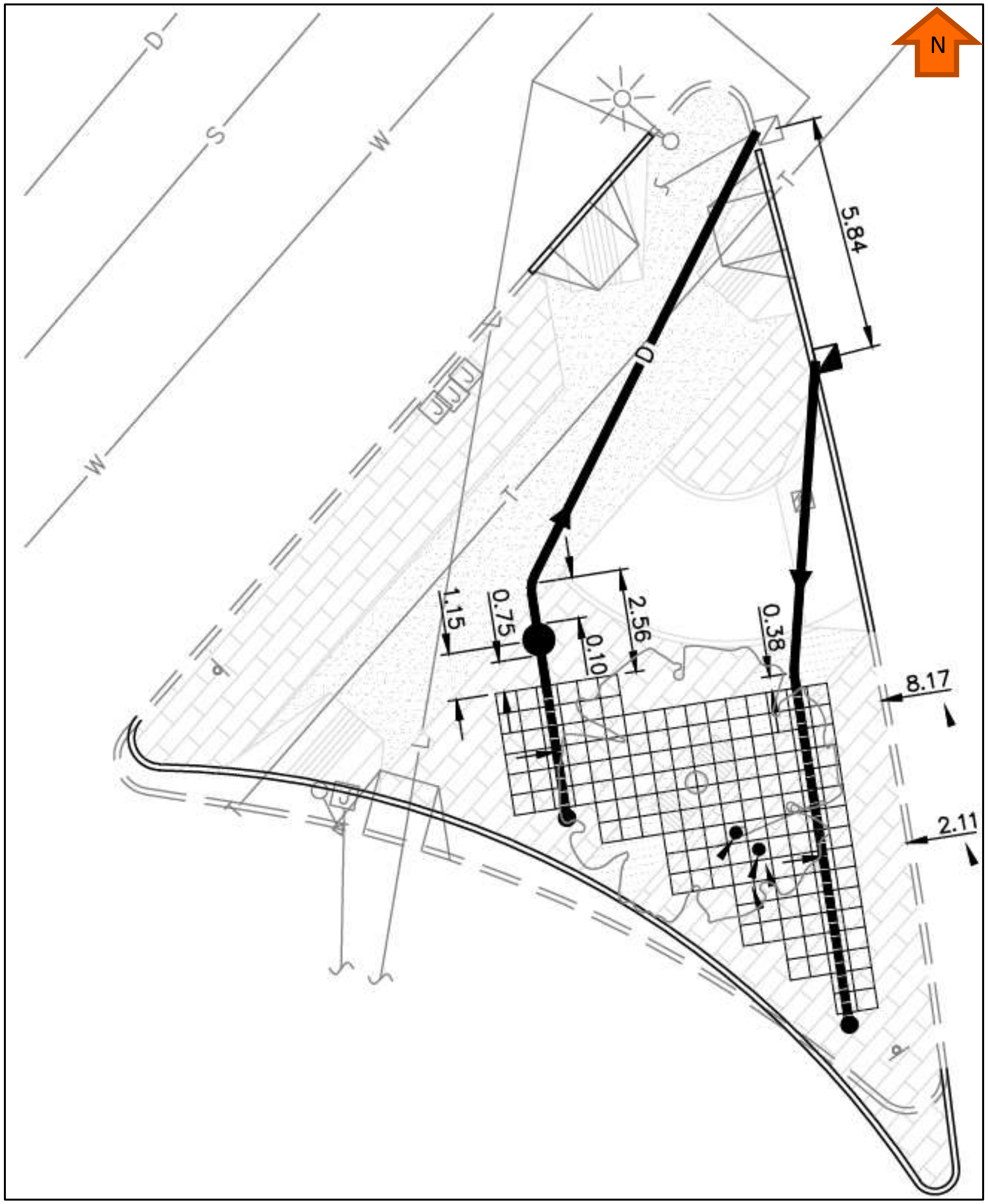
GI features:

- Permeable pavers will be used in the areas outside the bike path and main pedestrian pathways of the traffic island.
- A tree will be installed in the island, taking advantage of the accessible soil provided by the soil cells surrounding the tree pit
- This site will be monitored from 2018 to 2019 for flow, water quality and soil moisture. The performance of this STT will be compared to a structural soil STT and a bioswale located in the False Creek Neighborhood

Lessons learned:

- Prior to construction, the large triangular traffic island at the gateway to downtown was a disused, unsightly fully paved space with asphalt. The construction of the tower at 89 Nelson provided an opportunity to rebuild the traffic island. Working with the townerdeveloper and through inter-departmental cooperation, the space was made over with permeable paving and a tree planting in a soil cell STT.
- The site was identified an ideal location for performance monitoring. As the project was at an early stage, it was possible for the GI branch to request the developer to include space and adjust the drainage system to allow the installation of monitoring equipment.

Pre-development conditions looking north. Image source: Map data ©2018



Plan view of soil cell design with stormwater system for Expo Blvd and Smithe St. with Source: MPT Engineering

West 10th Avenue Structural Soil Tree Trench

Image: CoV – Property Viewer

Location: West 10th Avenue between Laurel Street and Willow Street

Type: Structural Soil

Medium: SureBASE from Veratec

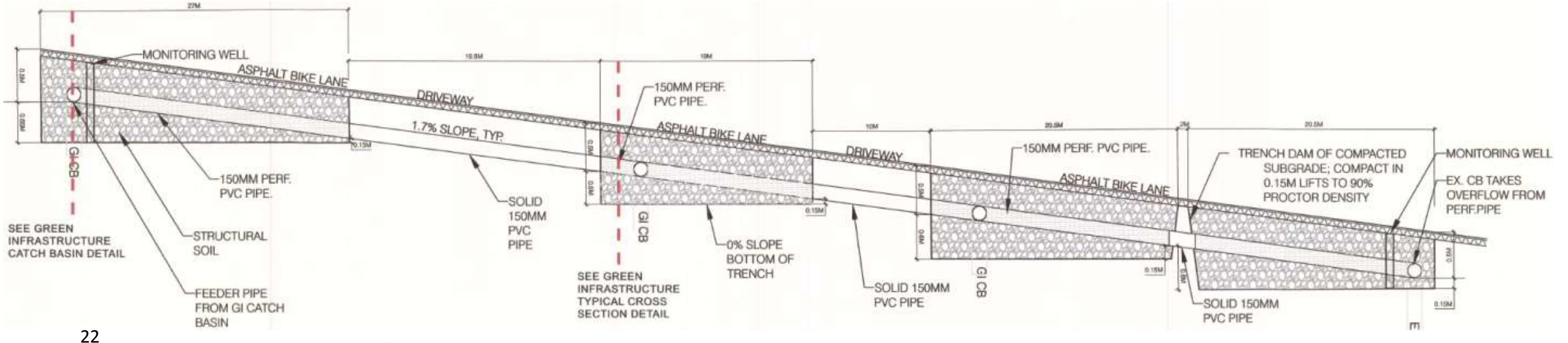
Location: STT is located under the off street bike path

Drainage area:

- Street catchment: ~500 m^2
- Bicycle lane catchment: ~203 m^2

Land use:

- West 10th Avenue is a small street in Vancouver that runs through the Vancouver General Hospital campus. Approximately 340m (between Oak Street and Willow Street) were reconstructed in 2018 to allow for the inclusion of a designated bicycle lane and general road improvements.
- Daily traffic on this road is estimated to be almost 5,000 vehicles per day according to the latest count from June 7, 2012 [118]. Vehicle use on this road ranges from motorcycles to large commercial and emergency vehicles [87]. Road is centerline crowned.



Structural soil cell IFC design for 10th Avenue. Image source: City of Vancouver – Transportation Division

Pre-development conditions looking west. Image source: Map data ©2018 Google

Structural Soil post-construction looking west. The asphalt bicycle lane is covering the structural soil

GI features:

- Dedicated GI catchbasins capture stormwater from half the street and direct it into the structural STT. The sidewalk and bike lane are sloped to drain towards the tree boulevard strip. A portion of the rain will be intercepted in the grass boulevard and the excess will drain into the street gutter and then into the STT.
- The structural soil system consists of four sections with flat bottoms that helps to distribute the infiltration area. Driveways on compacted subgrade are used as the check dams separating the sections.
- The STT sections are connected to each other and the GI catchbasins with a 150 mm continuous distribution pipe sloped at 1.7%. The distribution pipe has perforations located in the bottom half of the pipe. Typically, distribution pipes are flat and have perforations at the top of the pipe to allow for the even spreading of stormwater through the full length of the trench. This design allows the pipe to both distribute the water and to also act as an overflow once the trench is saturated.
- The soils are low infiltrating clayey silt. Each minimum 150 mm depth reservoir below the overflow that will force at least some infiltration to occur or possibly a saturated layer that trees roots can tap into during dry periods.

Lessons learned:

- Distribution and subdrain pipes require bends to bring water from catchbasins into the STT or excess water to the storm sewer. Often they are designed with 90 degree bends, but for ease of flushing, scoping, and removing clogs, a shallower bends are needed, preferably 135 degrees or wider.
- Pervious concrete was considered for the sidewalk and porous asphalt for the bike path. Pervious concrete was found to be too rough and would cause uncomfortable vibrations for wheelchair users. Porous asphalt was decided against due to the many shifts and turns in the bike path layout. Porous asphalt has a high viscosity and would have been difficult to push into the corners of the turns without sealing off the permeability.

Vancouver Art Gallery: North Plaza Structural Soil Cell Tree Trench

Image: CoV – Property Viewer

Location: Hornby Street and West Georgia Street

Type: Soil cell

Medium: 80% crushed aggregate and turf media

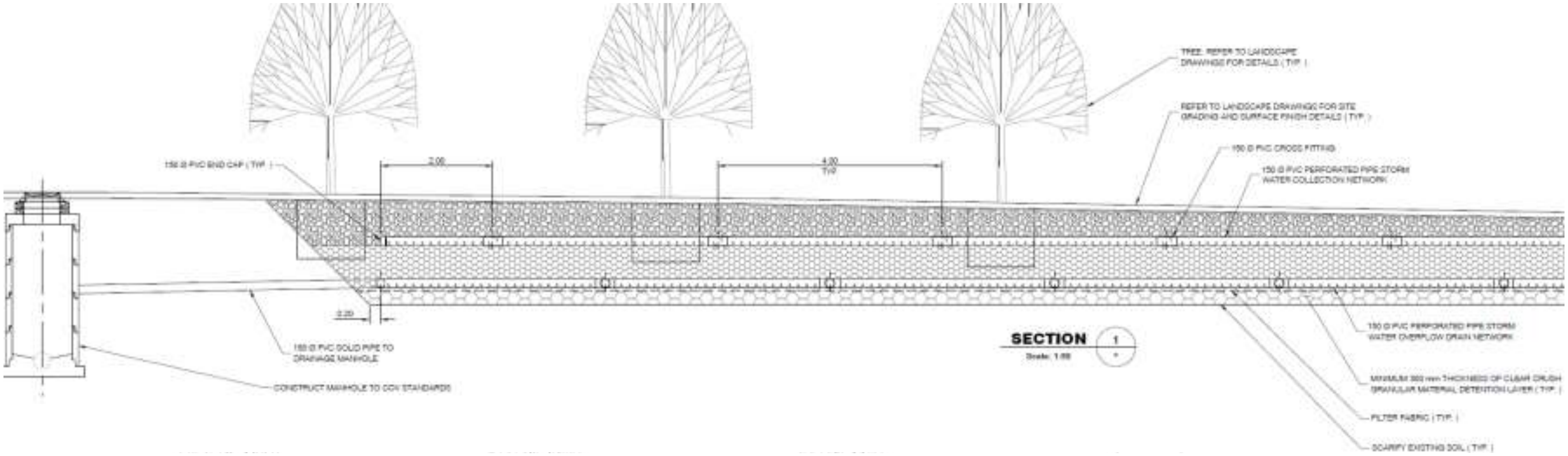
Location: STT is located under the Northwest side of the Plaza

Drainage area:

- Plaza catchment: 4,015 m^2

Land use:

- The Vancouver Art Gallery (VAG) was founded in 1931. The campus used to belong to the Province of British Columbia and it was used as the provincial court house. [89]. The soil has low infiltration rates
- The City of Vancouver invested $5.7 million CAD in 2016 to renovate the North Plaza of VAG [88]. The plaza was developed for daily pedestrian use. The plaza is also capable allowing the entry of food trucks and auxiliary vehicles to support festivals.



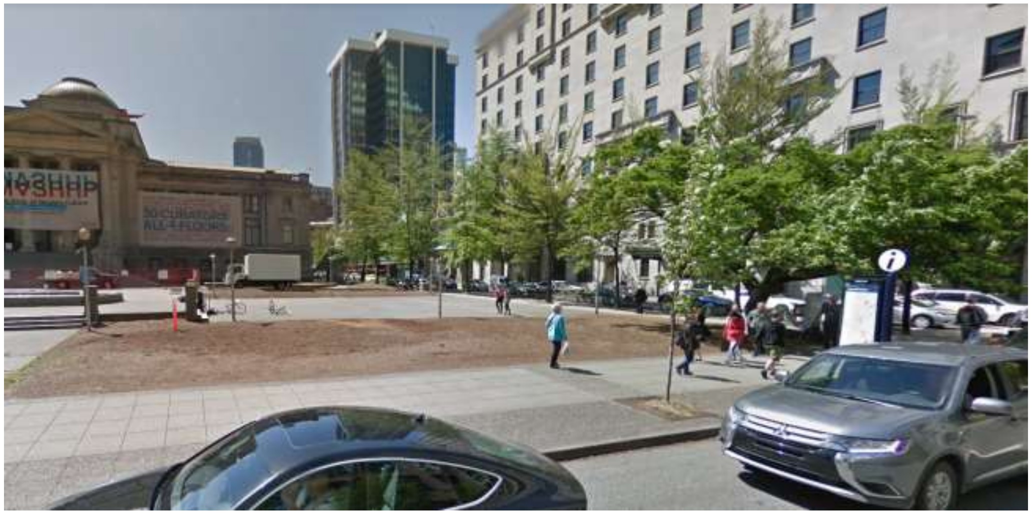
Structural soil cell IFC design for 10th Avenue. Image source: Kerr Wood Leidal

GI features:

- The plaza is predominantly paved. To accommodate the excess runoff, a soil cell system was designed to capture the stormwater. The plaza is sloped north down toward W Georgia St. where stormwater is intercepted before reaching the sidewalk by a grate covered trench drain. The water then drains towards the structural soil system and is distributed with a network of perforated pipes.
- The soil has 10 Red Maple Trees installed in the STT.

Lessons learned:

- The GI trench has a clear crush stone base. There is the suspicion that groundwater will not be absorbed by the structural soil through capillary action as the water will drain out freely by gravity.



Pre-renovation conditions consisted of a fountain and mix of paved and mulched areas. Source: Map data ©2018 Google

Artist rendering of the VAG North Plaza looking south. Image source: Nick Milkovich Architects Inc., Matthew Soules Architecture, and Hapa Collaborative

Soil cells post-construction looking west. Image Source: DailyHive


Soil Cell –Ribe Cathedral Square, Denmark
Image from Citygreen

4.0 Life Cycle Cost Analysis

Life Cycle Cost Analysis (LCCA) is a data driven tool widely used in the private and public sector to defend financial investments and decisions [61]. The LCCA in this report aims to evaluate a boulevard restoration project that includes a new sidewalk, off street bike lane, tree boulevard, and bike pad using four scenarios that include a conventional design approach versus three GI design approaches. The boulevard design for the northwest corner of Quebec St. and 1st Avenue in Vancouver, BC were used as a model for the analysis.

Table 1: LCCA Scenario Summary

Scenario	Design Approach
1	Standard method with growing medium in the boulevard
2	Identical to Scenario 1 with the addition of a generic water quality treatment unit downstream of the CB
3	Structural soil STT underneath the bike lane
4	Soil cell STT underneath the bike lane
5	Bioswale adjacent to street and tree pit. Bike lane and sidewalk under compacted soil

4.1 Life Cycle Cost Analysis Equations and Method

The LCCA accounts for the total costs of a project over the expected life of the asset [61]. The costs estimated in future years were brought to present day dollars. The present value (PV) formula was utilized for this purpose.

$$PV = \frac{FV}{(1+r)^n}$$

Where “FV” is future value, “r” is the interest rate, and “n” is the year of the future value. Currently, the CoV does not have an organizationally sanctioned discount rate. An interest rate of 3% was used.

The general equation that will be used to calculate the Net Present Value (NPV) for each project is shown below:

$$NPV = CAPEX + OPEX - TB$$

Where “CAPEX” is the capital expense of the scenario, “OPEX” is the operational expense (annual and long term maintenance), and “TB” are the tree benefits.

The capital costs were estimated by using a sizing tool developed by the City of Vancouver GI Branch. This tool takes into account the dimensions of the project and unit cost rates as of 2018. The tree benefits were calculated with iTree^{TM} which is a peer reviewed tool from the USDA Forest Service. This tool takes into account parameters such as tree species, tree diameter, nearby buildings, and the tree’s sun exposure to estimate stormwater intercepted by the tree, carbon dioxide sequestered by the tree and energy savings by the adjacent building. However, this tool does not take into account stormwater removed from the sewer network when it is used as part of a stormwater green infrastructure practice [62]. The model inputs are discussed further in Section 4.2.1.

4.2 Life Cycle Cost Analysis Inputs and Results

This section contains the model inputs and results of LCCA analysis for the boulevard restoration project.

4.2.1 Model Inputs

The LCCA model used the following design parameters for all scenarios:

- A design life of 50 years
- Roughly 96 m^2 of boulevard will be reconstructed
- The practice will manage street runoff from an impervious area of 325m^2 in addition to the 96 m^2 of boulevard to be reconstructed
- The boulevard reconstruction consist of:
    - 2.4 m wide concrete sidewalk
    - 1.4m wide tree boulevard strip
    - 2.5m wide asphalt bike lane
    - 2.4m wide concrete bicycle pad for a Mobi bike share station (which is replaced by the bioswale in the Scenario 5)

The CAPEX was calculated using the sizing tool developed by the City's GI Branch. The following were considered in the CAPEX:

- Excavation and soil removal costs
    - 0.45 m depth replacement of soil with growing medium in the tree boulevard
    - 0.75 m depth replacement of material under the bike lane with structural soil or soil cells in the STT scenarios
    - 0.45 m depth replacement of material in the bike pad area with bioswale soil.
- Curbing, pavement, and base costs
- CB and other drainage pipes and cleanouts needed for the GI practices
- Sediment and erosion control
- Street tree purchasing costs. A red maple tree will be planted in the street boulevard
- The staff hours required to design and approve the construction drawings for execution

The OPEX calculations include the annual and long-term maintenance estimations based on the GI branch's approved maintenance schedule for GI practices.

A further breakdown of the assumptions can be found in Appendix C.

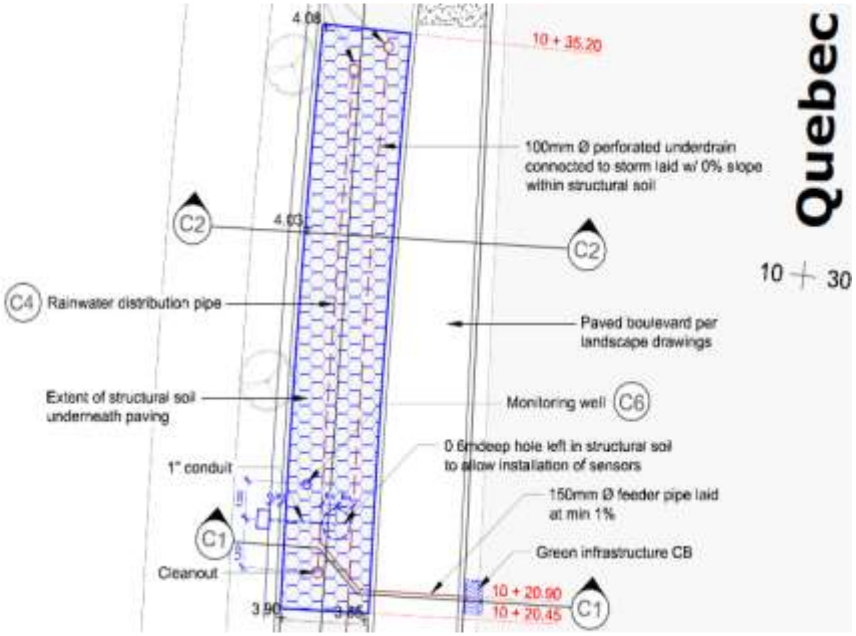


Figure 19: Design plan for the northwest corner of Quebec St. and 1st Ave. boulevard reconstruction with structural soil under the bike path.

4.2.2 Life Cycle Cost Analysis Results

This section will present the results of the LCCA along with the respective project plan views and cross-sections.

Structural Soil –Kensico Dam Plaza, North Carolina
Image from gibneyCE.com

Scenario 1: Conventional Street Restoration

This method does not include any stormwater treatment measures. Unlike the GI scenarios, this scenario assumes that the tree in the planting boulevard will die and be replaced every 16 years. A typical urban tree life cycle urban tree lifecycle ranges between 13 to 20 years [64]. The tree benefits were modeled to reflect the tree mortality. The summary of the LCCA results can be found in the table below.

Table 2: Scenario 1 Summary

CAPEX	Maintenance PV & Tree Benefits	NPV
$ 30,864	$ 13,607	$44,471

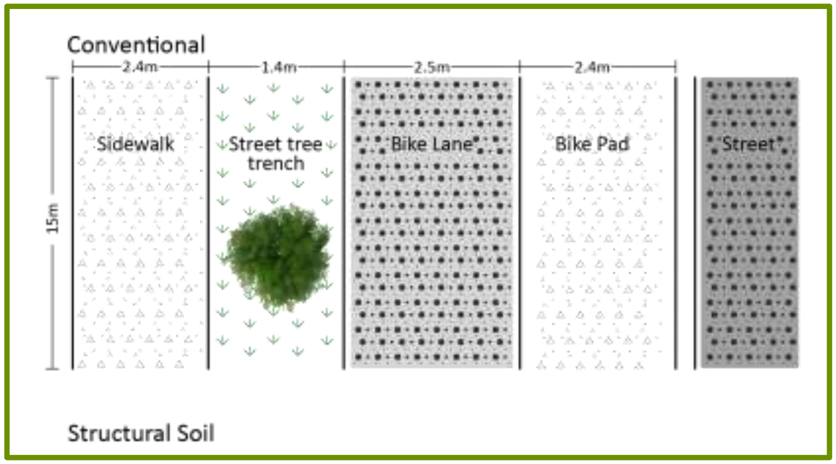


Figure 20: Scenario 1 LCCA Project Plan View

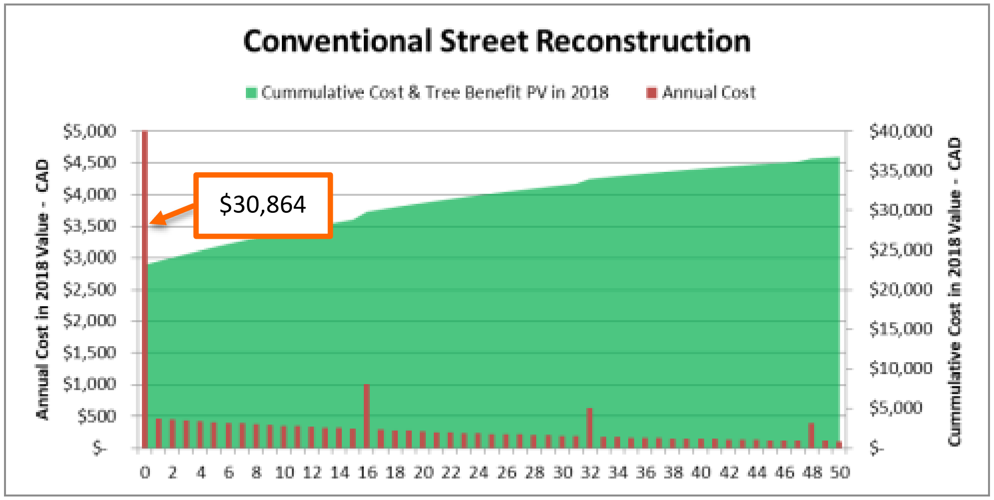


Figure 21: Scenario 1 LCCA Summary

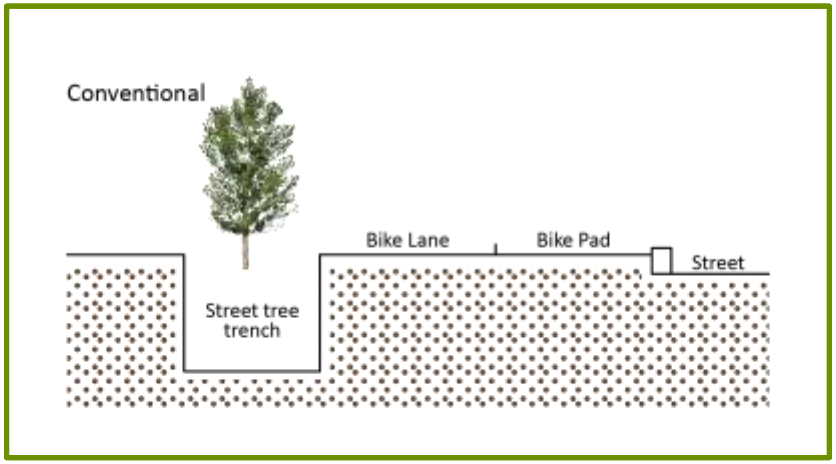


Figure 22: Scenario 1 LCCA Project Plan Cross-Section

Scenario 2: Conventional Street Restoration with Water Quality Treatment Unit

This method has the same assumptions as Scenario 1 with the addition of a manufactured proprietary stormwater treatment unit in the CAPEX. A common method to meet water quality goals is to add a treatment device like a hydrodynamic separator or filter to a drainage system. They are typically the size of a manhole and are located underground. This option meets the water quality goal but fails to meet other stormwater management goals like water balance and peak flow reduction [16]. The summary of the LCCA results can be found in the table below.

Table 3: Scenario 2 Summary

CAPEX	Maintenance PV & Tree Benefits	NPV
$ 55,864	$ 17,875	$73,739

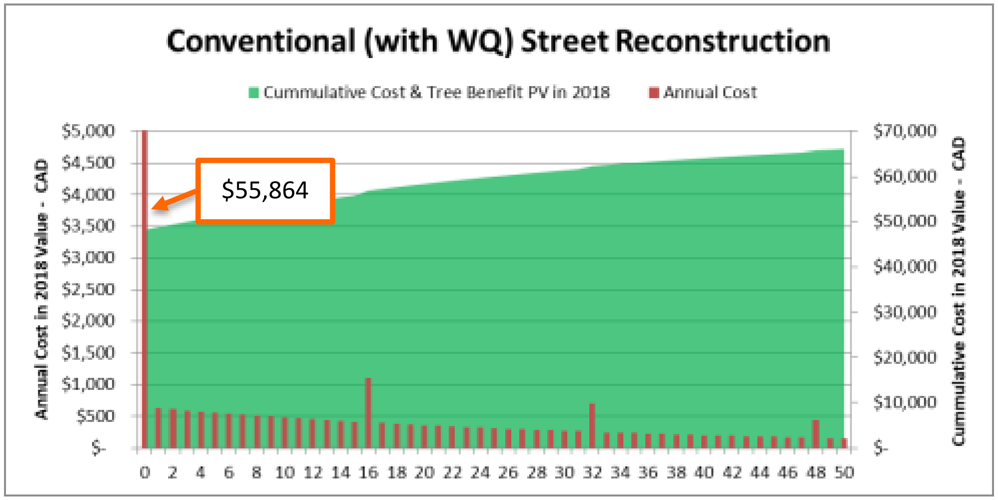


Figure 25: Scenario 2 LCCA Summary

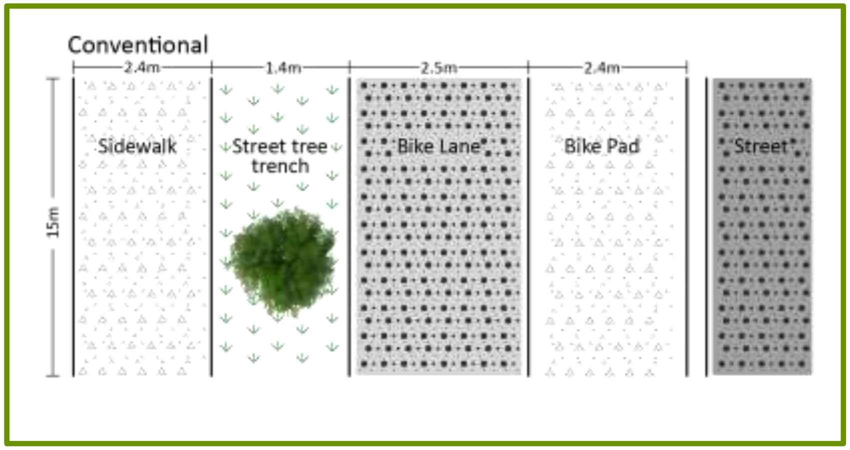


Figure 23: Scenario 2 LCCA Project Plan View

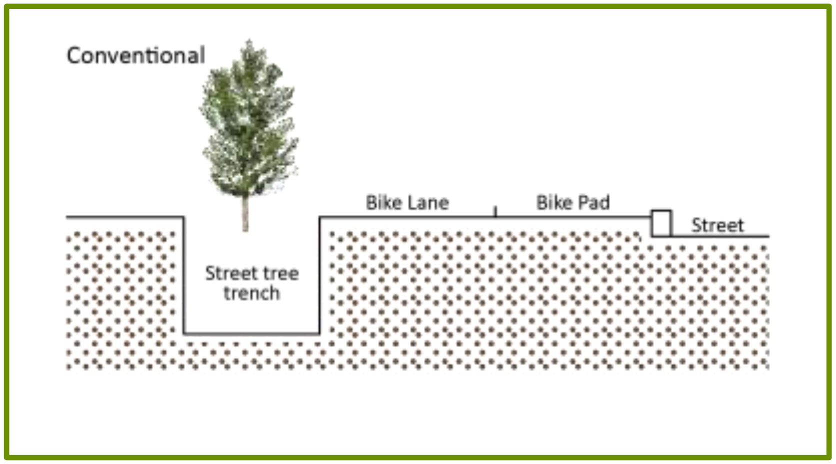


Figure 24: Scenario 2 LCCA Project Plan View Cross-Section View

Soil Cell –Navy Pier, Chicago
Image from GreenBlue Urban

Scenario 3: Structural Soil STT

The CAPEX for Scenario 3 includes the use of a proprietary structural soil mixed with a biofiltration soil. This option meets all of the stormwater management goals as well as soil volume goal for the street tree. The summary of the LCCA results can be found in the table below.

Table 4: Scenario 3 Summary

CAPEX	Maintenance PV & Tree Benefits	NPV
$ 43,692	$ 13,176	$56,868

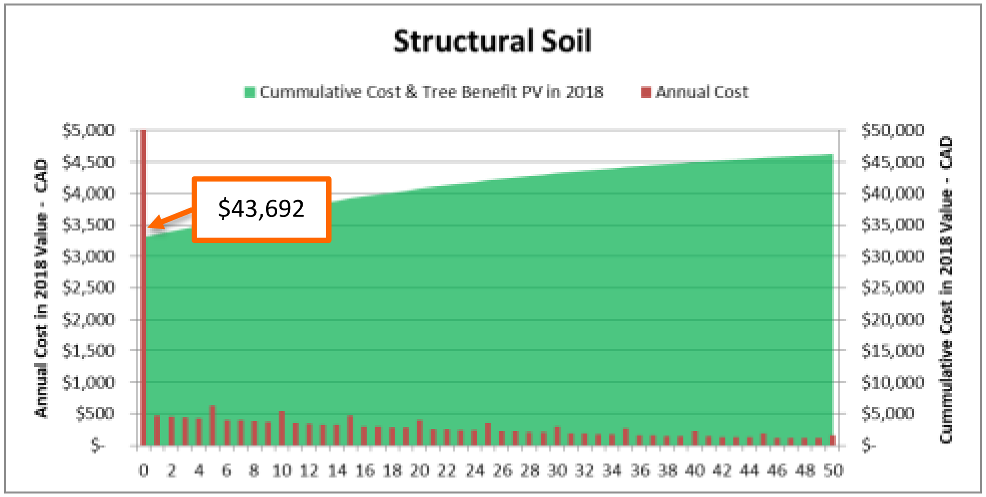


Figure 27: Scenario 3 LCCA Summary

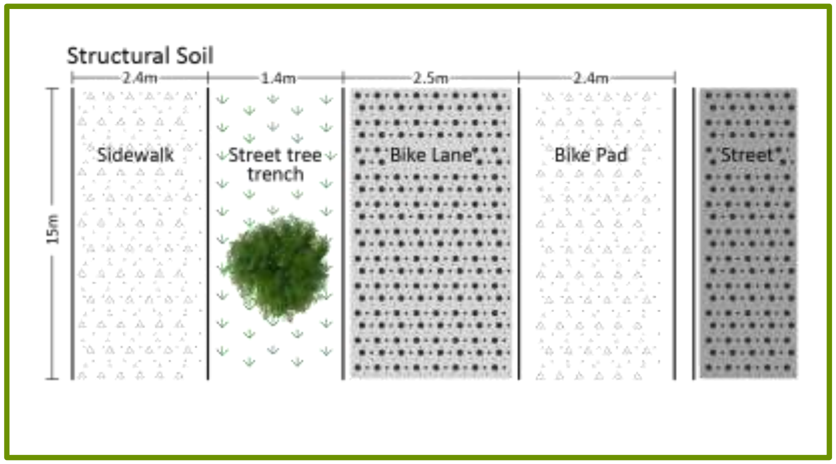


Figure 26: Scenario 3 LCCA Project Plan View

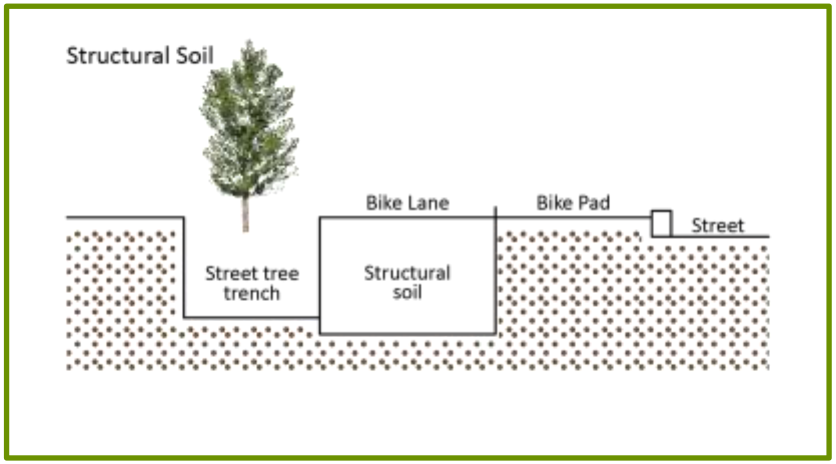


Figure 28: Scenario 3 LCCA Project Plan View Cross-Section View

Scenario 4: Soil Cell STT

The CAPEX for Scenario 4 includes the use of Silva Cells filled with a bioretention soil mix. This option meets all of the stormwater management goals as well as soil volume goal for the street tree. The summary of the LCCA results can be found in the table below.

Table 5: Scenario 4 Summary

CAPEX	Maintenance PV & Tree Benefits	NPV
$ 50,321	$ 13,176	$63,497

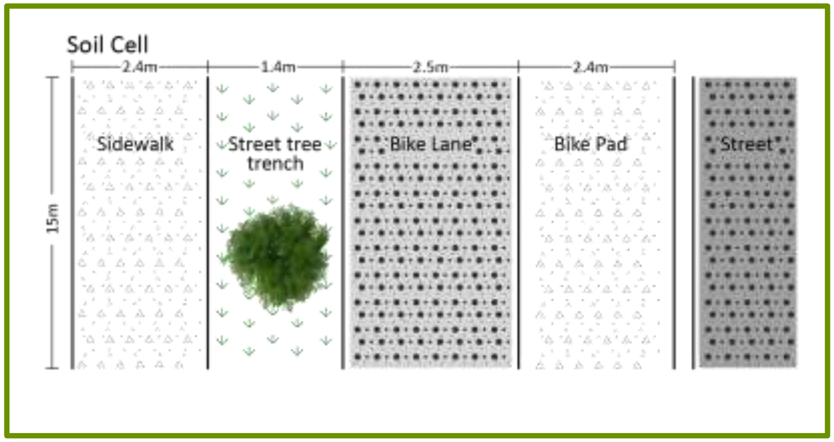


Figure 29: Scenario 4 LCCA Project Plan View

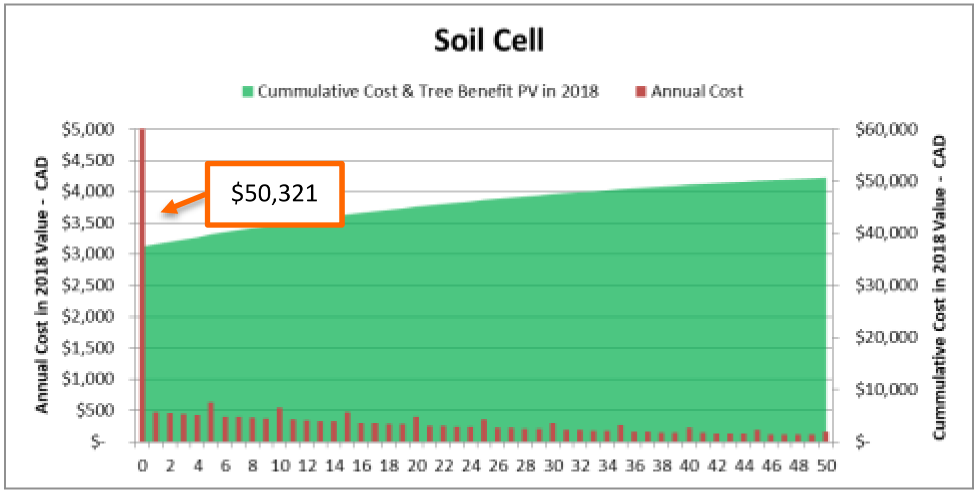


Figure 30: Scenario 4 LCCA Summary

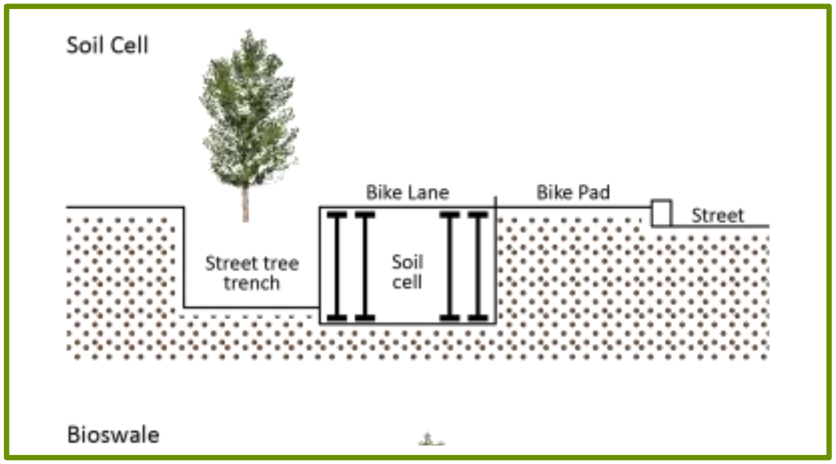


Figure 31: Scenario 4 LCCA Project Plan View Cross-Section View

Soil Cell –King's Cross Square, London, UK
Image from GreenBlue Urban

Scenario 5: Bioswale Cell

The CAPEX for this project include the use of a proprietary bioretention. This option meets all of the stormwater management goals as well as soil volume goal for the street tree, but it requires the removal of the bicycle pad for the bike share station. The summary of the LCCA results can be found in the table below.

Table 6: Scenario 5 Summary

CAPEX	Maintenance PV & Tree Benefits	NPV
$ 49,473	$ 21,358	$70,831

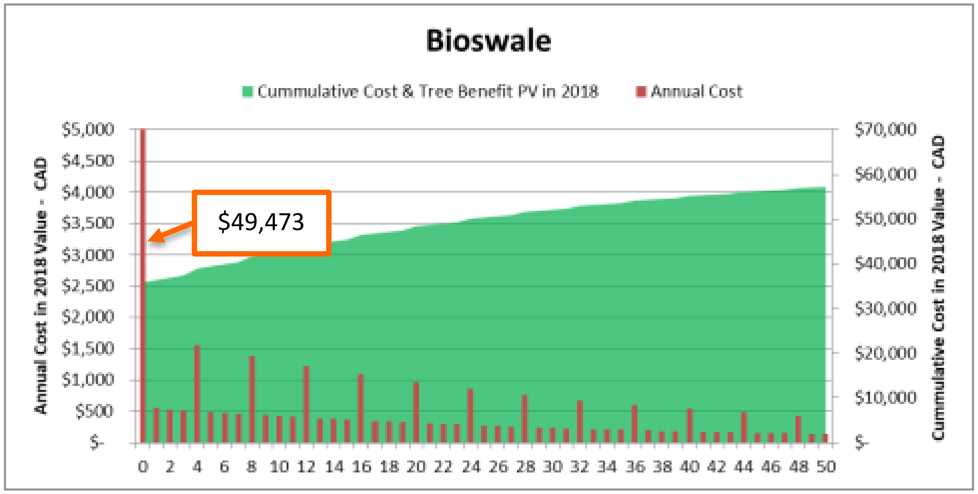


Figure 33: Scenario 5 LCCA Summary

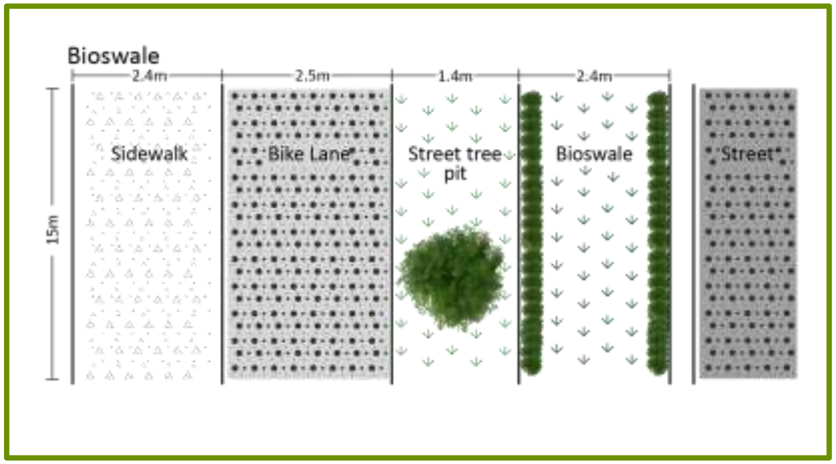


Figure 32: Scenario 5 LCCA Project Plan View

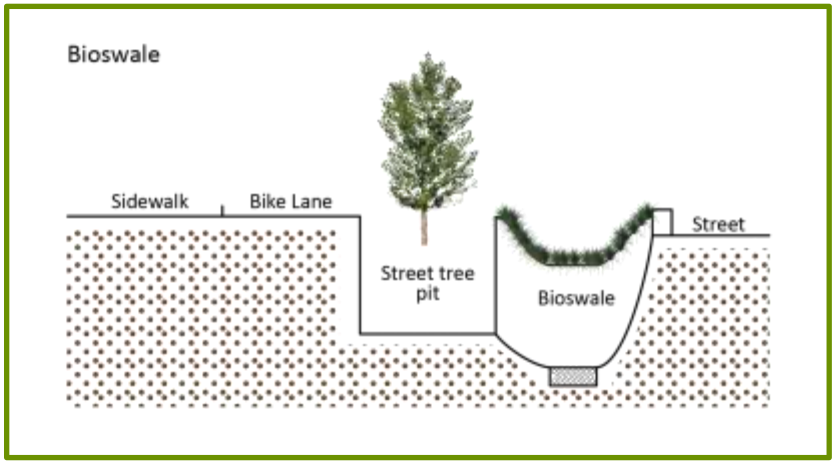


Figure 34: Scenario 5 LCCA Project Plan View Cross-Section View

4.3 Sensitivity Analysis

A sensitivity analysis with respect to soil volume and maintenance costs was performed to evaluate their effect on the NPV of the five scenarios.

4.3.1 Soil Volume

This sensitivity analysis focuses on the soil volume achieved by each retrofit method assessed in the LCCA. Trees require a minimum soil volume to thrive in urban environments and the volumes varies between species. As per the City of Vancouver's Engineering Design Criteria Manual for street trees placement, it was determined that a minimum of 15m^3 are required to sustain a medium size tree placed in a shared trench [63]. The sensitivity analysis followed the sequence order shown below:

1. Determine the amount of soil provided by the tree pits and calculate the amount of soil provided by each GI practice.
2. Total the amount of soil by method and the amount of soil still required to achieve soil volume target.
3. Adjust the practice's dimensions to accommodate the required soil volume to achieve the target by modifying depths or widths of the practices
4. Calculate the new CAPEX and compared against original CAPEX.

The results of the sensitivity analysis are shown in Table 7. The CAPEX savings by practice are shown in Figure 35.

Table 7: Soil Volume Sensitivity Analysis Summary

Practice	Conventional	Conventional with Water Quality Treatment	Structural Soil	Soil Cell	Bioswale
Soil from Tree Pit (m^3)	6.8	6.8	6.8	6.8	6.8
Soil from GI Practice (m^3)	-	-	9.4	25.5	20.5
Total Soil (m^3)	6.8	6.8	16.1	32.3	27.3
Soil Required for Target (m^3)	8.3	8.3	-1.1	-17.3	-12.3
Volume Change from Original Design to meet Soil Target (%)	222%	222%	88%	50%	60%
Original CAPEX	$ 23,168	$ 48,168	$ 33,081	$ 37,500	$ 35,840
New CAPEX Post Soil Vol. Target	$ 25,032	$ 50,032	$ 32,472	$ 32,832	$ 34,403

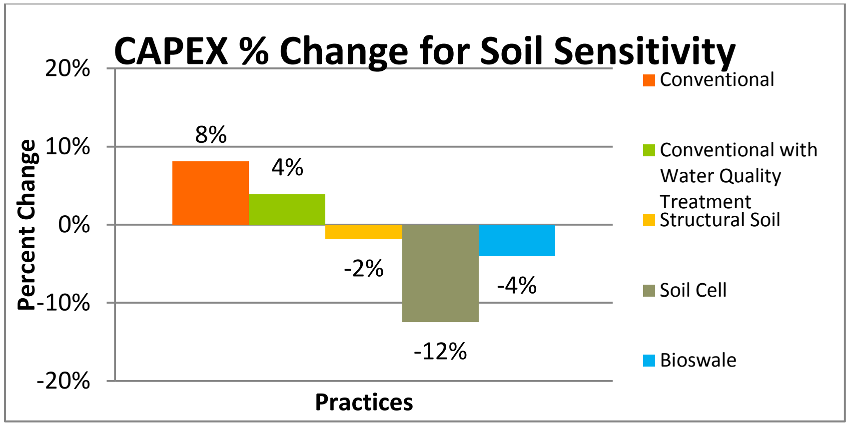


Figure 35: CAPEX % Difference Results from Soil Sensitivity Analysis

The soil sensitivity analysis focuses on achieving the minimum soil target set by the City of Vancouver for a tree planted in a shared tree pit. The tree pit alone does not achieve the soil volume target due to space constraints. Hence, the conventional method practices did not meet the soil volume requirements as there is no other additional source of loose soil. Conversely, the soil cell, structural soil and bioswale complement the missing soil volume not achieved by the tree pit.

The analysis demonstrates that the conventional methods have an increase in CAPEX associated to the modifications to the tree pits. The analysis determined that the tree boulevard would need to have a 1.0 m depth of growing medium to achieve the soil volume goal. However, it should be noted that having the roots confined to a narrow trench can result in poor tree stability and it is best to allow the tree roots to spread in a third direction. Also, the majority of tree roots prefer to stay in the top 0.5 m of soil; so providing deeper soil volume is of less benefit to the tree.

Opposite to the conventional methods, all of the GI practices experienced savings. When considering only the tree volume target, all of the GI methods could be reduced in size and cost. The soil cells are the GI method that sees the largest savings as it accommodates the largest amount of soil per cubic


Structural Soil – Zuccotti Park, New York
Image from Orange Daily Photo Blog

meter of available space. The savings almost equalize the costs between soil cell STT and structural soil STT. It is important to mention that by reducing the GI practice dimensions, the rainwater volume reduction to the stormwater system is also decreased.

4.3.2 Maintenance Requirements

The base case analyzed in the LCCA utilized the maintenance schedule established by the GI branch. The schedule differentiates between low and high-profile zones only. A low-profile zone corresponds to a low traffic/low pollution concentration area. Conversely, the high-profile zone is a high traffic/high pollution concentration area. The LCCA assumed a mid-point between the two profile zones by averaging the requirements of the low and high-profile zones. This analysis focused on the sensitivity of the averaging assumption in the LCCA. The results are shown in Figure 36.

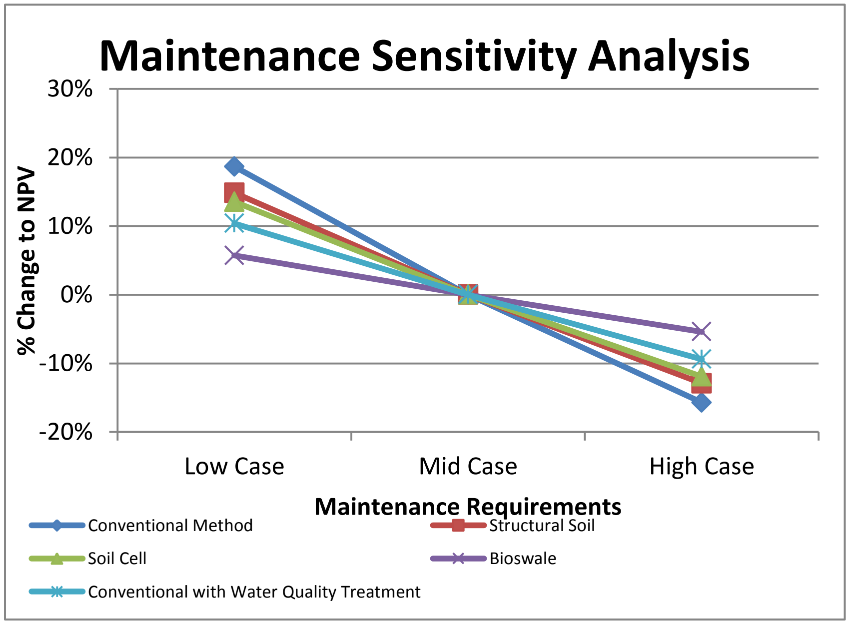


Figure 36: Maintenance Requirement Sensitivity Analysis

The analysis shows that the conventional method without water quality treatment is the most sensitive to changes on the maintenance cost, experiencing changes in the NPV of up to 19%. Conversely, the bioswale method is the least sensitive of all the methods evaluated. The NPV changed up to a max of 6% from the base case. Bioswales have the highest maintenance costs among the GI methods evaluated. Hence, this analysis determined that the sensitivity to the maintenance costs is associated with how much the maintenance costs represent to the overall NPV.

4.4 Life Cycle Cost Analysis Conclusion

The LCCA and subsequent sensitivity analysis included the quantifiable costs and benefits associated to each practice. Figure 37 summarizes the results of all the scenarios.

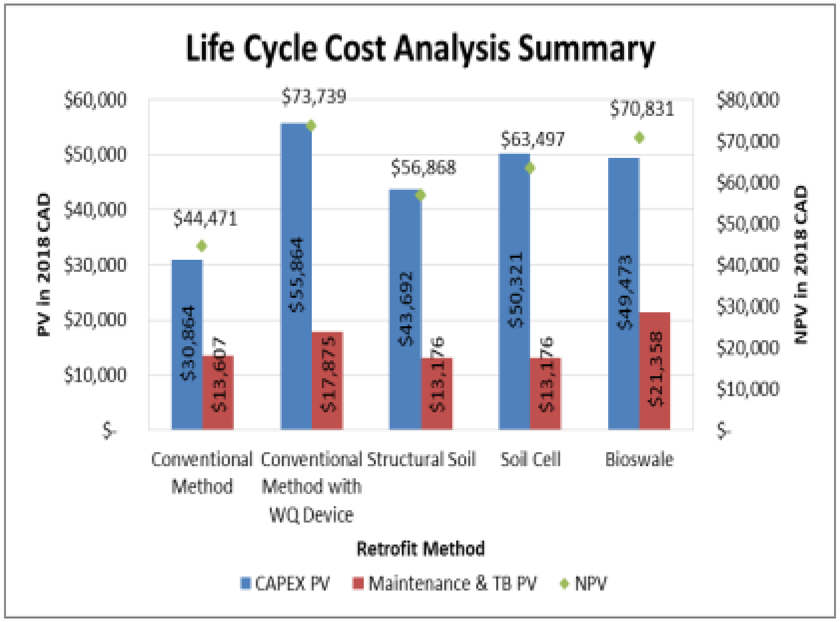


Figure 37: LCCA Summary

The conventional method with no stormwater treatment capability is the most cost-effective option, but it ignores external costs of water pollution and the many other difficult to quantify benefits from a GI design approach. Table 8 summarizes a few benefits that are associated with each scenario. It is evident from the summary table that the conventional method, even with the inclusion of a stormwater treatment unit, does not achieve the same benefits that GI can for a fraction of the cost. From a rainwater management perspective, the STTs are the most cost effective method.

Table 8: LCCA Stormwater Benefits Summary

Practice	Stormwater Direct Benefits		Stormwater Indirect Benefits					
	Stormwater Water Quality Treatment	Stormwater Water Volume Reduction	Heat Island Effect Reduction	Groundwater Recharge	Downstream Waterbody Protection	Tree Soil Volume (15m^3)	Supports Greenest City Action Plan	Supports Healthy City Strategy
Conventional - No Treatment	No	No	No	No	No	No	No	No
Conventional - With Treatment	Yes	No	No	No	Yes	No	Partially	No
Structural Soil	Yes	Yes	Yes	Yes	Yes	Partially[3]	Yes	Yes
Soil Cell	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bioswale	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

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[3] The structural soil scenario in the LCCA met the soil volume requirement because of the additional space under the bike path which allowed the use of enough structural soil to meet the soil volume requirements. However, in other situations where there is only a sidewalk, the structural soil might not meet the soil volume requirements.


Bioswale at 63rd and Yukon Street
Vancouver, BC

5.0 Monitoring Plan Summary

The Vancouver STT Monitoring Plan was created to evaluate the performance of STT in the Vancouver context. The monitoring study aims to answer the following questions:

1. Are design infiltration assumptions for the STT and bioswale valid?
2. What is the pollutant removal capacity of the STT in Vancouver's context and how does it compare to bioswales?
3. What is the rainwater volume retention performance of the STT in Vancouver's context and how does it compare to bioswales?
4. Can the STT retain moisture during the summer months to support street trees through dry periods?
5. Can the STT drain sufficiently during the winter months to absorb frequent rain events and not harm the tree with oversaturated soil?
6. How well do CBs perform in pre-treating stormwater runoff and what should the maintenance frequency be?

To answer the above questions, the following performance objectives will be monitored for each STT and bioswale in the monitoring study for a period of one year (2018-2019):

- Pollutant removal effectiveness
- Peak flow attenuation and volume reduction
- Soil infiltration rates
- Soil moisture content
- Sediment accumulation in pre-treatment CBs

A more detailed version of this draft monitoring plan can be found in Appendix G: Monitoring Plan Draft – August 2018.

5.1 Flow Monitoring

Inflow and outflow will be monitored continuously during the study. The equipment selected has continuous data logging capabilities. Table 10 summarizes the flow monitoring process and considerations.

Table 10: Flow Monitoring Considerations

Flow	Practice	Flow System	Consideration	Equipment/Method
Inflow	**STT**	**Catch Basin**	Catch Basin inner dimensions and backwater in rainwater distribution system in the STT	Pressure transducer and formula
	Bioswale	**Curve Inlet**	Runoff ingress to swale generated by storm based on drainage are and rainfall	Formula
Outflow	**STT/Bioswale**	**Underdrain**	Outflow estimation based on water levels measured in a 6" through pipe	Ultrasonic non-contact water level sensor and rating curve

5.2 Precipitation, Soil and Water Quality Monitoring

Precipitation and soil conditions will be monitored continuously. Water quality will be monitored during rain events only. Table 9 summarizes the monitoring plan.

Table 9: Precipitation, Soil and Water Quality Monitoring Summary

Monitoring	Practice	Sampling Location and/or Intervals	Consideration	Equipment/Method
Precipitation	All Practices	Creekside Community Centre located at <1 km from all the practices. Set at 5 minute recording interval	Data is owened by the Sewer and Drainage Design Branch of the City of Vancouver.	Non-heated tipping Bucket Rain Gauge and Telog data logger
Soil Monitoring	Structural Soil, Soil Cell and East Bioswale	Placed below grade to record Volumetric Water Content (VWC), Bulk Electrical Conductivity (ECb) and temperature. Set at 5 minute recording interval	Soil sensors spaced by 20cm to avoid electric interference	TEROS soil sensor and Data logger
Water Quality	All Practices	Inflow from structural soil CB. Outflow from all practices	24 samples avaialble for water quality and one for sample for QA/QC	ISCO water quality sampler. Composite samples

6.0 Recommendations

The City of Vancouver has the opportunity to meet many strategic goals with the implementation of STT. The following recommendations will help the City of Vancouver to implement the STT in the most successful and cost effective way. The recommendations are based on the lessons learned from the interviews, literature research, and LCCA analysis.

6.1 Performance

There are no monitoring studies on STT performance in BC's Lower Mainland or the Cascadia region of the USA. However, STT studies in other regions have shown the following performance results:

- Studies of STT have found similar rates of stormwater peak flow attenuation and volume reduction as with other infiltration type GI practices:
    - Volume reduction results varied from 70-98%
    - Reported peak flow rate reductions varied from 47 to 98%
- There were no structural soil STT reports on water quality performance. However, the literature review determined that pollutant capture by soil cell STT is similar to those found with bioretention:
    - TSS and Phosphorus removal rate of at least 70%
    - Metals such as Aluminum, Copper, Zinc, and Iron can be removed with efficiencies of at least 86%
- Trees can be successfully supported using either STT method.

The Vancouver STT Monitoring Study will evaluate whether similar stormwater and tree benefits are found in Vancouver's urban conditions and climate. In addition, Vancouver's monitoring study will contribute to the body of knowledge on STT by monitoring the water quality treatment performance of structural soil STT.

6.2 Application and Design

Vancouver is densifying to accommodate population growth. This situation puts pressure on space availability, including the right-of-way where GI is installed along with other public amenities and utilities. Finding space for GI becomes increasingly more challenging.

STTs offer a solution that allows for more active transportation space on the surface, supports healthier and more mature trees, while still meeting all of the rainwater management goals that aim to protect Vancouver's waterbodies. Here are some recommendations for the application and design of STT in Vancouver:

- **Life Cycle Costs –** When comparing boulevard reconstruction scenarios that meet stormwater management requirements and urban forestry soil volume targets, the STT options were between 20-30% cheaper than the bioswale or conventional with treatment device options.
- **Water quality treatment units –** Adding a water quality treatment unit to the conventional method partially addresses the stormwater management requirements. However, this increases the initial capital cost by 66%, making it more expensive than any of the GI practices
- **STT configuration –** Liners and gravel storage areas bellow the STT should be avoided in order to support tree health. This will allow the tree roots to access subsoils and allow groundwater moisture to percolate up through the soil during dry periods.
- **STT Type** - When choosing between structural soil and soil cells, designers must:
    - **Weigh soil volume goals –** Easier to achieve with soil cells STT.
    - **Consider space constraints** – Available subsurface areas that are non-uniform and constrained by other utilities and foundations may favor the use of structural soil which can easily fill unusually shaped spaces.

- Several design components remain to be optimized and tested, including:
    - **Pre-treatment** - CB sumps are the most common form of pre-treatment, but they fail to effectively remove fine sediment which may reduce the STT performance over time.
    - **Soil mixes in STT** – Soils used in the soils cells and structural soils must balance drainage needs, filter requirements, and tree needs such as moisture retention and nutrients. The soils used for non-stormwater soil cell and structural soil applications may not be ideal for STT applications.
    - **Distribution and sub-drain pipes** – The location of the distribution pipe and the orientation of the perforations impacts how well stormwater is distributed throughout the trench and maximizes the storage volume. To enhance volume control performance, the sub-drain pipes can be raised from the bottom, include elbow bends or have slow release orifice controls.
- **Tree Health –** Research has shown that both soil cell STT and structural soils STT can successfully support trees. However, not all tree species can be installed in STT. Tree species selection must consider:
    - **Soil moisture conditions –** Tree species that are resistant to dry and saturated soil conditions are recommended.
    - **Soil pH –** The tree selected needs to be able to withstand changes in soil pH. The soil pH may vary due to the pH of the stormwater, the STT soil medium, and the use of road salts in the winter, among other factors.
    - **Tree growth –** The final growth of the trees species is another important factor to be considered. The STT, as well as the street tree pits, have a determined amount of available soil volume and space. The designer must ensure that in the future, the tree will not outgrow the allotted space and soil volumes.

6.3 Maintenance and Asset Management

- **Onsite utility mapping –** Utility cuts must be considered in the design of these linear right-of-way facilities. The design must be kept simple for easy restoration. Consider the use of tracing wire through distribution pipes and sub drains so that they can be identified with M-scope utility line detectors.
- **Short term maintenance –** While STT may have less maintenance than a bioswale or bioretention rain garden, they still require regular maintenance. The frequency of vacuum truck cleanouts of pre-treatment CBs will depend on the street’s uses, traffic volumes, and leaf drop. At a minimum, CB sumps should be vacuumed at least once a year. A monitoring program should be implemented to evaluate the accumulation rate of sediment in CBs critical to GI and stormwater management functions.
- **Inspection and maintenance access points –** Access for inspections and maintenance must also be considered. Sub drains and distribution pipes need cleanout access points, and pipe bends need to be limited to 135 deg to allow pipe cleaning equipment to access the full length of pipe. Monitoring wells should be installed to monitor water levels in the STTs.

7.0 Conclusion

The purpose of this report was to compile the performance of STT and support their use at the City of Vancouver. The research backs the application of both soil cell STT and structural soil STT to tackle water quantity and water quality issues in urban watersheds.

In urban watersheds, the high incidence of impervious surfaces increases the amount of runoff that is generated by each storm. Climate change is expected to make this situation worse. Climate models forecast more intense storms by the end of the century. On the water quality end, pollutants accumulate on the streets. These pollutants are washed away during rainfall events and end up in our receiving waterbodies. Research has shown the negative implications of exposing aquatic life and associated ecosystems to untreated stormwater runoff.

Both soil cell and structural soil methods can be used under the STT umbrella. The added benefits of STT include:

- The removal of rainwater from the sewer/stormwater system;
- The effective removal of heavy metals and other contaminants from the stormwater; and
- The addition of rooting space for trees to grow.

The literature review compiled examples of many STT applications across the Lower Mainland, Canada, U.S., and Europe. STTs were effectively used to address:

- **Peak Flows –** Research on STT in eastern Canada, U.S. and Europe concluded that peak flows are reduced and delayed by STTs.
- **Stormwater Volume Reduction –** All of the performance monitoring studies reported that stormwater was successfully diverted from entering the sewer system by allowing the stormwater to slowly infiltrate into the native soils. The main benefit to the infiltration process is that the STT mimics of the natural water cycle that would happen in a non-urban environment.
- **Water Quality –** The research shows that soil cell STT can effectively remove particulate bound pollutants and heavy metals accumulated on the streets. Unfortunately, there was no publicly available information on water quality studies for structural soil STT. The Vancouver STT Monitoring Plan aims to address the water quality knowledge gap on structural soil STT.
- **Tree Health –** Both of the STT methods researched were capable of providing trees with the necessary rooting soil volume and nutrients to grow healthy. It is important to highlight that adaptable, resilient tree species should be selected for all STT practices.

This report explored the life cycle costs of a retrofit project in Vancouver, BC. The LCCA evaluated two conventional street reconstruction approaches (with and without a water quality treatment unit) and three GI approaches, the two STT methods and a bioswale. The analysis concluded that:

- **Conventional Approach Cost –** The conventional street reconstruction method is the most cost effective option. However, this method fails to meet rainwater management goals and urban forestry goals that the GI options can provide. Adding a water quality treatment unit to the conventional reconstruction, which will only meet water quality goal, significantly increases CAPEX, making it more expensive than any of the GI methods.
- **Green Infrastructure Approach Costs** – The STT options were both cheaper in terms of capital and maintenance costs when compared to the bioswale option. Among the STT, the soil cell option was more expensive that structural soil practice. However, matching the soil volume of each method almost equalizes the costs between the practices.

STT are a cost effective green infrastructure approach well suited to the denser urban redevelopment happening in the City of Vancouver. They are a compliment to active transportation improvements and achieve tree soil volume goals in addition to meeting rainwater management objectives. Fitting with the City's reputation as a leader in sustainable design, there are also many opportunities to innovate on the STT design.

8.0 Bibliography

[1] City of Vancouver, "Report - Rainwater Management Plan: 2016 Apr 19," 2016.

[2] MoE British Columbia, "Indicators of Climate Change for British Columbia: 2016 Update," MoE British Columbia, Victoria, 2016.

[3] CVC, "Central Parkway: Case Study," 2016c.

[4] The Mersey Forest Offices, "Meeting Salford's remarkable anti-storm trees," 7 February 2017. [Online]. Available: https://www.merseyforest.org.uk/news/meeting-salfords-remarkable-anti-storm-trees/. [Accessed 28 July 2018].

[5] J. Page, R. Winston and W. Huntt III, "Soils beneath suspended pavements: An opportunity for stormwater control and treatment," *Ecological Engineering,* vol. 82, pp. 40-48, 2015.

[6] C. o. Trees, Director, *Howard Street, Salford.* [Film]. Salford.2016.

[7] US EPA, "What is Green Infrastructure?," 2018a. [Online]. Available: https://www.epa.gov/green-infrastructure/what-green-infrastructure. [Accessed 16 May 2018].

[8] CVC, "Central Parkway Road Right-of-Way Retrofit Technical Report," 2016a.

[9] Environmenta Canada, "Municipal wastewater status," 25 July 2013. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/wastewater/resource-documents/municipal-status.html. [Accessed 26 July 2018].

[10] W. Li and A. Cruickshank, "The Star," 13 April 2018. [Online]. Available: https://www.thestar.com/vancouver/2018/04/11/we-really-should-be-a-model-for-the-entire-world-but-were-just-not-there-yet-advocate-on-vancouvers-sewage-overflow-problem.html. [Accessed 26 July 2018].

[11] Phillips et al., "Are stormwater pollution impacts significant in life cycle assessment? A new methodology for quantifying embedded urban stormwater impacts," *Science of The Total Environment,* pp. Pages 115-123, 2018.

[12] Scholz et al., "Recurrent Die-Offs of Adult Coho Salmon Returning to Spawn in Puget Sound Lowland Urban Streams," *Plos One,* vol. 6, no. 12, pp. 1-12, 2011.

[13] Spromberg et al., "Coho salmon spawner mortality in western US urban watersheds: bioinfiltration prevents lethal storm water impacts," *Journal of Applied Ecology,* vol. Coho salmon spawner mortality in western US urban watersheds: bioinfiltration prevents lethal storm water impacts, no. Journal of Applied Ecology, pp. 398-407, 2015.

[14] Yong et al., "Urban stormwater runoff negatively impacts lateral line development in larval zebrafish and salmon embryos," *Scientific Reports,* pp. 1-14, 2018.

[15] City of Vancouver, "2017-2021 Budget Outlook," 2017a.

[16] City of Vancouver, "Greenest City 2020 Action Plan: 2016-2017 Implementation Update," 2017b.

[17] City of Vancouver, "Healthy City Strategy - Four Year Action Plan Phase 2 (2015-2018)," 2015.

[18] J. Urban, "Comparing Silva Cells and Strucural Soil," n.a..

[19] D. T. Smiley, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[20] Smiley et al., "Comparison of Structural and Noncompacted Soils for Trees Surrounded by Pavement," *International Society of Arboriculture,* pp. 164-169, 2006.

[21] J. Bartens, Trees and Structural Soil as a Stormwater Management System in Urban Settings, Virginia Tech, 2006.

[22] Bassuk et al., Using CU-Structural Soil™ in the Urban Environment, Ithica: Cornell University, 2005.

[23] Urban, James and Bassuk, Nina, "Two Different Approaches to Improve Growing Conditions for Trees," *American Society of Consulting Arborists,* vol. 46, no. 2, pp. 5-14, 2013.

[24] Bassuk et al., "CU-Structural Soil®: A Comprehensive Guide," Cornell University, Ithaca, 2015.

[25] DeepRoot, "A Forward-Looking Athletes Village," 2015a. [Online]. Available: http://www.deeproot.com/products/silva-cell/case-studies/sefc.html. [Accessed 22 May 2018].

[26] S. (. a. P. A. (. Farmand, Director, *Surroundings: Episode 3.* [Film]. Canada: Rain City Productions, 2013.

[27] DeepRoot, *DeepRoot Green Infrastructure,* 2018.

[28] M. Guerra, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[29] C. o. N. V. CNV, "STORMWATER MANAGEMENT: Three or More Units," City of North Vancouver, 2014.

[30] D. Matsubara, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[31] J. Wegman, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[32] N. Bandringa, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[33] B. Czypyha, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[34] B. V. Duin, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[35] K. Clogg-Write, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[36] Accuweather, "Snow Eaters: What are Chinook Winds?," 2018. [Online]. Available: https://www.accuweather.com/en/weather-glossary/what-are-chinook-winds/3885079.

[37] Citygreen, "CALGARY ALBERTA USES STRATAFLOW TREEPITS FOR COUPLING GREEN WITH BLUE," 2016.

[38] C. o. C. CoC, "Thomson Family Park," 2018. [Online]. Available: http://www.calgary.ca/CSPS/Parks/Pages/Locations/Downtown-parks/Thomson-Family-Park.aspx.

[39] CoE, "CASE STUDY: THE QUARTERS DOWNTOWN SOIL CELLS," 2016.

[40] SWS, "REVEALING THE INVISIBLE," 2016. [Online]. Available: https://www.estormwater.com/revealing-invisible. [Accessed 24 June 2018].

[41] S. Colwell, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[42] T. Tackett, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[43] M. James, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[44] K. Hill, "The Spokesman Review," 21 July 2018. [Online]. Available: http://www.spokesman.com/stories/2018/jul/21/lego-cells-buried-beneath-new-west-central-sidewal/. [Accessed 27 July 2018].

[45] City of Spokane, "CSO 14 & 15 Basin Improvements," City of Spokane, Spokane, N/A.

[46] WERF, "Building a Nationally Recognized Program Through Innovation and Research," 2009. [Online]. Available: http://www.werf.org/liveablecommunities/studies_port_or.htm. [Accessed 25 June 2018].

[47] I. Dunlap, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[48] DeepRoot, "REVITALIZING TORONTO’S WATERFRONT ALONG QUEENS QUAY," 2015b. [Online]. Available: https://www.deeproot.com/products/silva-cell/case-studies/queens-quay.html.

[49] DeepRoot, "Toronto’s Proof-of-Concept Sidewalk Silva Cell case study," 2016a. [Online]. Available: http://www.deeproot.com/blog/blog-entries/torontos-proof-of-concept-sidewalk-silva-cell-case-study.

[50] CVC, "July 2018 Performance Monitoring Summary: Central Parkway LID (2015-2017)," CVC, Mississauga, 2018.

[51] PWD, "Stormwater Tree Trench," 2018. [Online]. Available: http://www.phillywatersheds.org/what_were_doing/green_infrastructure/tools/stormwater_tree_trench. [Accessed 16 May 2018].

[52] J. Brennan and M. Dalrymple, Interviewees, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[53] PWD, "Pilot Program Final Report," 2016.

[54] MPCA, "Case studies for tree trenches and tree boxes," 2017. [Online]. Available: https://stormwater.pca.state.mn.us/index.php?title=Case_studies_for_tree_trenches_and_tree_boxes. [Accessed 27 June 2018].

[55] CRWD, "Green Line Green Infrastructure Practices – Water Quality," n.d.. [Online]. Available: http://www.capitolregionwd.org/our-work/watershed-planning/cclrt_wq/.

[56] W. Saunders-Pearce, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[57] L. Phillips, "The Stockholm Solution for Planting Trees," Linkedin, Stockholm , 2017.

[58] B. Embrén, "PLANTING BEDS IN THE CITY OF STOCKHOLM: A HANDBOOK 2009.02.23 GH100322," City of Stockholm, Stockholm, 2009.

[59] I. Solfjeld, *Structural soil Research and examples from Norway,* 2014.

[60] City of Trees, "Pioneering street tree research project could hold answer to urban flooding," City of Trees, 2016. [Online]. Available: http://www.cityoftrees.org.uk/news/pioneering-street-tree-research-project-could-hold-answer-urban-flooding. [Accessed 30 July 2018].

[61] ASCE, *Maximizing the Value of Investments Using Life Cycle Cost Analysis,* Washington: American Society of Civil Engineers, 2014.

[62] USDA Forest Service, *About i-Tree,* 2018.

[63] City of Vancouver, "ENG - PMO - Design and Construction Standards Update - Design Criteria Manual - Section 9.0 Landscape and Public Realm Comments on Draft 4 - 2018-01-30," Cov, Vancouver, 2017.

[64] L. Roman, "How Many Trees Are Enough? Tree Death And," *Scenario Journal,* no. Scenario 04: Building the Urban Forest, 2014.

[65] State of Minnesota Department of Natural Resources, "Growth Factor Worksheet," 2014.

[66] Schifman et al., "Situating Green Infrastructure in Context: A Framework for Adaptive Socio-Hydrology in Cities," *Water Resources Research,* 2017.

[67] O. Vega, "Green Infrastructure in the City of Vancouver: Application and Performance Monitoring of Stormwater Tree Trenches and Bioswales (Unpublished Master's Thesis)," The University of British Columbia, Vancouver, 2018.

[68] T. Schueler, "Controlling Urban Runoff: a practical manual for planning and designing BMPs," Department of Environmental Program, Metropolitan Washington Council of Governments, Washington, D.C., 1987.

[69] NH DES , "NH DES Stormwater Manual Volume 1: Stormwater and Antidegradation," New Hampshire Department of Environmental Services, New Hampshire , 2008.

[70] T. Schueler, "Controlling Urban Runoff: a practical manual for planning and designing BMPs," Department of Environmental Program, Metropolitan Washington Council of Governments, Washington, D.C., 1987.

[71] CVC, "Elm Drive Road Right-of-Way Retrofit Technical Report," 2016b.

[72] H. Bengtson, *Spreadsheet Use for Partially Full Pipe Flow Calculations,* CED engineering.com, 2012, p. 26.

[73] Potter et al., Mechanics of Fluids, Stamford: Cengage, 2012.

[74] T. Camp, "Design of sewers to facilitate flow," *Sewage works journal,* pp. 3-16, 1946.

[75] Isenmann et al., "Stage– discharge relationship for a pipe overflow structure in both free and submerged flow," Engineering Applications of Computational Fluid Mechanics, 2016.

[76] D. Thompson, The Rational Method, Civil Engineering Deptartment Texas Tech University, 2006.

[77] Senix Corp., "ToughSonic® Series: Installation and Operating Instructions," 2016.

[78] METER, "Teros 12 User Manual," Meter Group, 2018.

[79] LeBoutillier et al., "Prediction of Pollutant Load in Stormwater Runoff from an Urban Residential Area," *Canadian Water Resources Journal,* 2000.

[80] US EPA, *Green Infrastructure,* 2018b.

[81] B. M. o. E. a. C. C. S. BCMoE, "British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture - Summary Report," 2018.

[82] Metro Vancouver, "Monitoring and Adaptive Management Framework for Stormwater," 2014.

[83] Metro Vancouver, "Integrated Liquid Waste and Resource Management Plan," Metro Vancouver, 2010.

[84] US EPA, "Green Infrastructure and Climate Change: Collaborating to Improve Community Resiliency," 2016.

[85] J. Jin, "Green Stormwater Infrastructure on City Streets," The University of British Columbia, Vancouver, 2016.

[86] E. Luker, "Lessons Learned from Rainwater Management Strategies Used in the Olympic Village Development," The University of British Columbia, Vancouver, 2017.

[87] M. Bos, "Long-throated flumes and broad-crested weirs," Wageningen University and Research, 1985.

[88] Van Den Bosch et al., "Flow Measurement," in *Structures for water control and distribution*, 1993, pp. 29-37.

[89] E. Kuichling, "The Relation Between the Rainfall and the Discharge of Sewers in Populous Districts," *Transactions of the American Society of Civil Engineers,* pp. 1-56, 1889.

[90] W. P. &. S. B. WPSB, "British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture," BC Ministry of Environment & Climate Change Strategy, Victoria, 2018.

[91] Geotech, "Geopump Peristaltic Pump: Installation and Operation Manual," 2017.

[92] ABL, *Thomson Family Park,* 2016.

[93] P. Cheung and R. Anderton, "The Queensway Sustainable Sidewalk Pilot Project," in *TRIECA Conference*, 2017.

[94] Saint Paul, "Rooting out Pollution," 2013.

[95] Deeproot, "Suspended Pavement Study at the Bartlett Tree Lab, Year 9," 2013. [Online]. Available: http://www.deeproot.com/blog/blog-entries/suspended-pavement-study-at-the-bartlett-tree-lab-year-9. [Accessed 27 June 2018].

[96] SMART CITIES DIVE, "A Brief History of Trees in Suspended Pavement," 2013. [Online]. Available: https://www.smartcitiesdive.com/ex/sustainablecitiescollective/brief-history-trees-suspended-pavement/248906/. [Accessed 27 June 2018].

[97] DeepRoot, "Which Planting Solution is Best for Trees? Bartlett Lab Field Trials," 2016. [Online]. Available: http://www.deeproot.com/blog/blog-entries/which-planting-solution-is-best-bartlett-lab-field-trials. [Accessed 27 June 2018].

[98] DeepRoot, "A Brief History of Trees in Suspended Pavement," 2014. [Online]. Available: http://www.deeproot.com/blog/blog-entries/a-brief-history-of-trees-in-suspended-pavement. [Accessed 27 June 2018].

[99] T. Smiley, *Growing Trees in an Urban Plaza Environment,* n.d..

[100] B. Embren, *Trees and Stormwater Management: The Stockholm solution,* Stockholm, 2016.

[101] City of Vancouver, "Truck route maps and regulations," City of Vancouver, Vancouver, 2018.

[102] Vancouver Sun, "City issues contract to transform Vancouver Art Gallery's north plaza," Vancouver Sun, 2016. [Online]. Available: https://vancouversun.com/news/local-news/city-issues-contract-to-transform-vancouver-art-gallerys-north-plaza. [Accessed 20 July 2018].

[103] Vancouver Art Gallery, "WHO WE ARE," Vancouver Art Gallery, 2018. [Online]. Available: http://www.vanartgallery.bc.ca/about-us/about-us.html. [Accessed 23 July 2018].

[104] DeepRoot, "Silva Cell Article in the BC Globe and Mail," DeepRoot, 2012. [Online]. Available: http://www.deeproot.com/blog/blog-entries/silva-cell-article-in-the-bc-globe-and-mail. [Accessed 27 July 2018].

[105] T. d. Crom, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[106] P. Cheung, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[107] T. V. Seters, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[108] S. Wilson, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[109] J. Brooks, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[110] B.-M. Alvem, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[111] D. Mikkelsen, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[112] S. Lovering and B. Gooden, Interviewees, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[113] L. Agnew, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[114] C. Girling, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[115] D. Roehr, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[116] H. Schreier, Interviewee, *Green Infrastructure - Structural Soil/Soil Cell Study - City of Vancouver.* [Interview]. 2018.

[117] State of Minnesota - Department of Natural Resources, "Growth Factor Worksheet," n.a..

[118] City of Vancouver, "VanMaps," City of Vancouver, Vancouver, n.a..

Appendix A: Stormwater Tree Trench Summary Table

Country	City	Location	STT Method	Monitoring Information		Inlet/Pre-treatment Method
				Water Quality	Water Quantity	
Canada	Vancouver	W 10th Ave.	Structural Soil	No	No	Catch Basin
		VAG North Plaza	Structural Soil	No	No	Perforated grate/sump
		Quebec St. and 1st Ave.	Structural Soil	TBD	TBD	Catch Basin
		Smithe St. and Expo Blvd.	Soil Cell	TBD	TBD	Catch Basin and Permeable Pavers
	North Vancouver	New residential developments since 2014	Soil Cell	N/A	N/A	Catch Basin
	Burnaby	UniverCity	Structural Soil	No	No	Permeable Pavers
	Calgary	16 Ave. SW and 11 St. SW	Soil Cell	No	No	Catch Basin
	Toronto	Queen's Quay	Soil Cell	No	No	Catch Basin
		Queensway and Moynes Ave.	Soil Cell	Yes	Yes	Catch Basin
	Mississaugua	Central Pkwy East and Burnhamthorp St.	Soil Cell	Yes	Yes	Catch Basin
United States	Seattle	Ballard Street	Soil Cell	No	No	Bioswale
	Spokane	West Central Neighborhood	Soil Cell	No	No	Catch Basin and Sump
	Philadelphia	Various locations throughout the city	Structural Soil	Yes	Yes	Catch Basin
	Saint Paul	Along Green Line Rapid Transit corridor	Structural Soil	N/A	N/A	Catch Basin
	Charlotte	Orange St. and S 10 St.	Soil Cell	Yes	Yes	Catch Basin
		Ann St. and S 10 St.	Soil Cell	Yes	Yes	Catch Basin
England	Salford	Howard St. and Steeple Dr.	Soil Cell	Yes	Yes	Perforated Street Curve
Sweden	Stockholm	Swedenborgsgatan St.	Structural Soil	No	No	Perforated Catch Basin
Norway	Oslo	Carl Berner Plass	Structural Soil	No	No	Perforated Catch Basin

Appendix B: Interviews for Literature Review

Name	Organization	Meeting/Contact Date	Country
Ted de Crom	City of Richmond	07-May-2018	Canada
Dr. Thomas Smiley	Bartlett Tree Experts Lab	28-Jun-2018	USA
David Matsubara	City of North Vancouver	25-May-2018	Canada
Jason Wegman	PWL Partnership	14-Jun-2018	Canada
Maria Guerra	City of Maple Ridge	22-Jun-2018	Canada
Natalie Bandringa	Capital Regional District	05-Jun-2018	Canada
Brianne Czypyha	City of Victoria	20-Jun-2018	Canada
Bert Van Duin	City of Calgary	08-Jun-2018	Canada
Ken Clogg-Write	MPE Engineering	13-Jun-2018	Canada
Tracy Tackett	City of Seattle	10-May-2018	USA
Shanti Colwell	City of Seattle	14-May-2018	USA
Ivy Dunlap	City of Portland	10-May-2018	USA
Patrick Cheung	City of Toronto	04-Jun-2018	Canada
Tim Van Seters	Toronto and Region Conservation Authority	05-Jun-2018	Canada
Stephanie Wilson	Credit Valley Conservation	13-Jun-2018	Canada
Jessica Brooks	Philadelphia Water Department	14-Jun-2018	USA
John Brennan	Philadelphia Water Department	18-Jun-2018	USA
Matthew Dalrymple	Philadelphia Water Department	18-Jun-2018	USA
Wes Saunders-Pearce	Saint Paul, Minnesota	24-May-2018	USA
Britt-Marie Alvem	Stockholm	08-Jun-2018	Sweden
Dale Mikkelsen	UniverCity	30-May-2018	Canada
Mike James	DeepRoot	08-May-2018	Canada
Stephen Lovering	Citygreen	02-May-2018	Canada
Ben Gooden	Citygreen	02-May-2018	Australia
Larry Agnew	Veratec	11-Apr-2018	Canada
Cynthia Girling	The University of British Columbia	28-May-2018	Canada
Daniel Roehr	The University of British Columbia	05-Jun-2018	Canada
Hans Schreier	The University of British Columbia	11-Jun-2018	Canada

Appendix C: LCCA Assumptions

The LCCA analysis conducted the analysis of a right-of-way boulevard reconstruction. The LCCA analysis was conducted under the following assumptions:

- Costs are current as of 2018. A constant dollar approach will be used in this analysis: inflation will not be factored
- Design per GI is 3 week/practice with 7 hour days and 5 work days @ $40/hour to get GI from design stage to IFC
- Expected life for a street tree is between 13-20 years according to research. A midpoint between the age range will be used for the LCCA analysis:
    - Conventional boulevard reconstruction method: Trees will die every 16 years.
    - Green Infrastructure boulevard reconstruction methods: Trees will outlive the projects design life.
- Cost calculations were compared including the modelled tree benefits. The benefits of stormwater captured by the practices are not factored in.
- A red maple tree will be used in the STT life cycle analysis [65]:
    - Tree growth assumed to be similar to forest conditions
    - A growth factor of 4.5 was used for the red maple tree.
- Monitoring costs will not be included in the cost estimations
- Maintenance scheduled derived based on the Typical GI Maintenance Schedule developed by the GI Branch

Appendix D: LCCA Tree Benefit Modeling

The tree benefits used in the LCCA calculation were derived from an online tool called iTree™. The tool was developed by the USDA Forest Service. The tool is peer reviewed and is the result of interagency cooperation [62].

The tree benefits were calculated for a red maple (*Acer Rubrum*) at different years from installation: 0, 1, 10, 20, 30, 40 and 50 years. To project the red maple growth over the years, the technique developed by the International Society of Arboriculture was used [65]. The formula is shown below, and it was modified to the metric system.

$$Tree\ Age = \frac{Growth\ Factor * DBH}{2.54}$$

The formula requires DBH of the tree to determine the tree age and the Growth Factor for the specific tree in question. The growth factor was determined to be 4.5 for a red maple [65]. The formula above was modified to return the tree diameter, which is the input for iTree™. A local nursery (Trees Wholesale Nurseries Ltd.) was contacted to determine the current price of a red maple with 15ft in height. It was determined that the DBH for the tree is 6 cm and the price is $215 CAD (price used in LCCA). The tree DBH was projected with the formula shown above. The inputs to iTree™ are summarized in Table 11. The sample output from iTree™ is shown in Appendix C.

Table 11: iTree ™ Input Conditions

Input Conditions for itree
DBH according to tree projection
Building to the East of Tree
Tree in good conditions
Red Maple
Sun exposure - Full sun
Building built after 1980
Building between 0-6m from tree

The results of the tree benefit calculation are shown in the Table 12.

Table 12: iTree™ Benefits Summary

Age	Benefits of Tree	DBH (cm)	iTree™ Yearly Benefits
0	Year 0	6	$1.6
1	Year 1	6.56	$1.7
10	Year 10	11.64	$3.1
20	Year 20	17.29	$11.5
30	Year 30	22.93	$15.7
40	Year 40	28.58	$31.3
50	Year 50	34.22	$38.6

It was determined that the tree benefits increase over time as the tree growths in size overall. To account for the increase in benefits, a curve was fitted to the data points calculated in Table 12. A second order polynomial was chosen as it better represented all the data points. The results of the curve fitting exercise are shown in Figure 38.

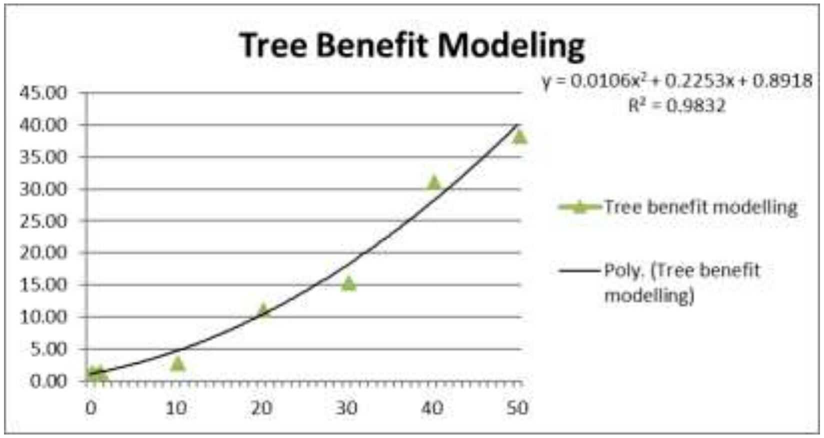
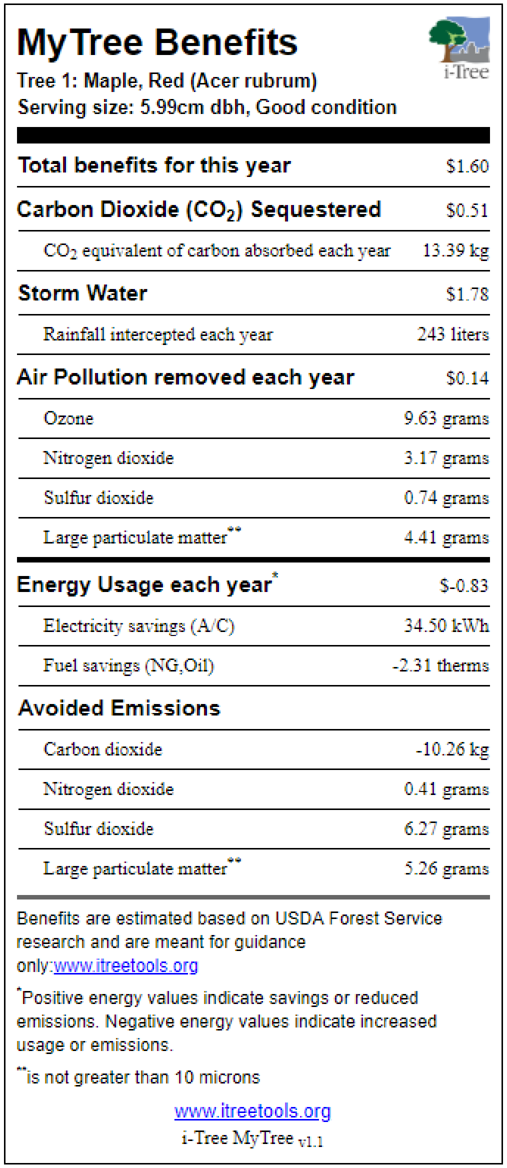


Figure 38: Tree Benefit Modeling

The PV for the tree benefits were calculated using the equation derived from the curve fitting analysis. The PV calculation was divided in two categories: PV for the conventional practices and the PV for the GI practices. The driver behind this is due to the assumption for the conventional practices that an urban tree will die every 16 years. This condition does not apply to the GI practices where it will be assumed that the trees will outlive the 50-year design life of the practice. The results are shown in Appendix D.

Appendix E: Example iTree^{TM} Output



MyTree Benefits

Tree 1: Maple, Red (Acer rubrum)
Serving size: 5.99cm dbh, Good condition

Total benefits for this year	$1.60
Carbon Dioxide (CO_2) Sequestered	$0.51
CO_2 equivalent of carbon absorbed each year	13.39 kg
Storm Water	$1.78
Rainfall intercepted each year	243 liters
Air Pollution removed each year	$0.14
Ozone	9.63 grams
Nitrogen dioxide	3.17 grams
Sulfur dioxide	0.74 grams
Large particulate matter**	4.41 grams
Energy Usage each year*	$-0.83
Electricity savings (A/C)	34.50 kWh
Fuel savings (NG,Oil)	-2.31 therms
Avoided Emissions	
Carbon dioxide	-10.26 kg
Nitrogen dioxide	0.41 grams
Sulfur dioxide	6.27 grams
Large particulate matter**	5.26 grams

Benefits are estimated based on USDA Forest Service research and are meant for guidance only:www.itreetools.org

*Positive energy values indicate savings or reduced emissions. Negative energy values indicate increased usage or emissions.

**is not greater than 10 microns

www.itreetools.org
i-Tree MyTree v1.1

Appendix F: Tree Benefit Modelling Summary Table

Year	Tree Benefits Inputs from iTree^{TM}	Modeled Benefits	PV for GI Practices	PV for Conventional Methods
0	1.60	$ 0.9	$0.89	$0.89
1	1.73	$ 1.1	$1.09	$1.09
2		$ 1.4	$1.31	$1.31
3		$ 1.7	$1.52	$1.52
4		$ 2.0	$1.74	$1.74
5		$ 2.3	$1.97	$1.97
6		$ 2.6	$2.20	$2.20
7		$ 3.0	$2.43	$2.43
8		$ 3.4	$2.66	$2.66
9		$ 3.8	$2.90	$2.90
10	3.14	$ 4.2	$3.13	$3.13
11		$ 4.7	$3.36	$3.36
12		$ 5.1	$3.59	$3.59
13		$ 5.6	$3.82	$3.82
14		$ 6.1	$4.05	$4.05
15		$ 6.7	$4.27	$4.27
16		$ 7.2	$4.49	$4.49
17		$ 7.8	$4.71	$0.54
18		$ 8.4	$4.92	$0.66
19		$ 9.0	$5.13	$0.79
20	11.45	$ 9.6	$5.34	$0.92
21		$ 10.3	$5.54	$1.05
22		$ 11.0	$5.73	$1.19
23		$ 11.7	$5.92	$1.33
24		$ 12.4	$6.10	$1.47
25		$ 13.1	$6.28	$1.61
26		$ 13.9	$6.45	$1.75
27		$ 14.7	$6.62	$1.89
28		$ 15.5	$6.78	$2.03
29		$ 16.3	$6.93	$2.17
30	15.72	$ 17.2	$7.08	$2.31
31		$ 18.1	$7.22	$2.45
32		$ 19.0	$7.36	$2.58
33		$ 19.9	$7.49	$2.72
34		$ 20.8	$7.62	$0.33
35		$ 21.8	$7.73	$0.40
36		$ 22.7	$7.85	$0.48
37		$ 23.7	$7.95	$0.56
38		$ 24.8	$8.05	$0.64
39		$ 25.8	$8.15	$0.72
40	31.28	$ 26.9	$8.24	$0.80
41		$ 27.9	$8.32	$0.89
42		$ 29.1	$8.40	$0.97
43		$ 30.2	$8.47	$1.06
44		$ 31.3	$8.53	$1.15
45		$ 32.5	$8.59	$1.23
46		$ 33.7	$8.65	$1.31
47		$ 34.9	$8.70	$1.40
48		$ 36.1	$8.74	$1.48
49		$ 37.4	$8.78	$1.56
50	38.62	$ 38.7	$8.82	$1.64

Appendix G: Monitoring Plan Draft – August 2018

Monitoring Objectives

The STT monitoring program will involve the study of two STT designs (soil cell and structural soil), and two bioswale designs (with different soil medium). The monitoring program aims to assess the performance of the SSTs and bioswales in the CoV. This study is aimed to provide planners, architects and designers with applicable performance results on GI practices in the Lower Mainland.

The monitoring involves the analysis of the following facets:

- Pollutant removal effectiveness
- Peak flow attenuation and volume reduction
- Soil infiltration rates
- Qualitative observations of ancillary benefits such as vegetation growth and plant drought resistance

Monitoring Plan

The monitoring plan consists of the following sections: Precipitation monitoring, flow monitoring, monitoring wells, soil monitoring and water quality monitoring. This is the first draft of the monitoring plan. Further modification will be made to incorporate improvements in the method and to accommodate designs changes after the publishing date of this report.

Precipitation Monitoring

Precipitation is a key component to be monitored in every hydrological study. Figure 39 shows the location of the rain gauge relative to the monitoring location. This rain gauge is owned and operated by the Sewer and Drainage Design Branch of the CoV. The rain gauge is a non-heated 260-2501-A Tipping Bucket Rain Gauge made by Nova Lynx. The data will be uploaded and accessible through FlowWorks^{TM}. The GI Branch will have unlimited access to the data provided by this rain gauge.

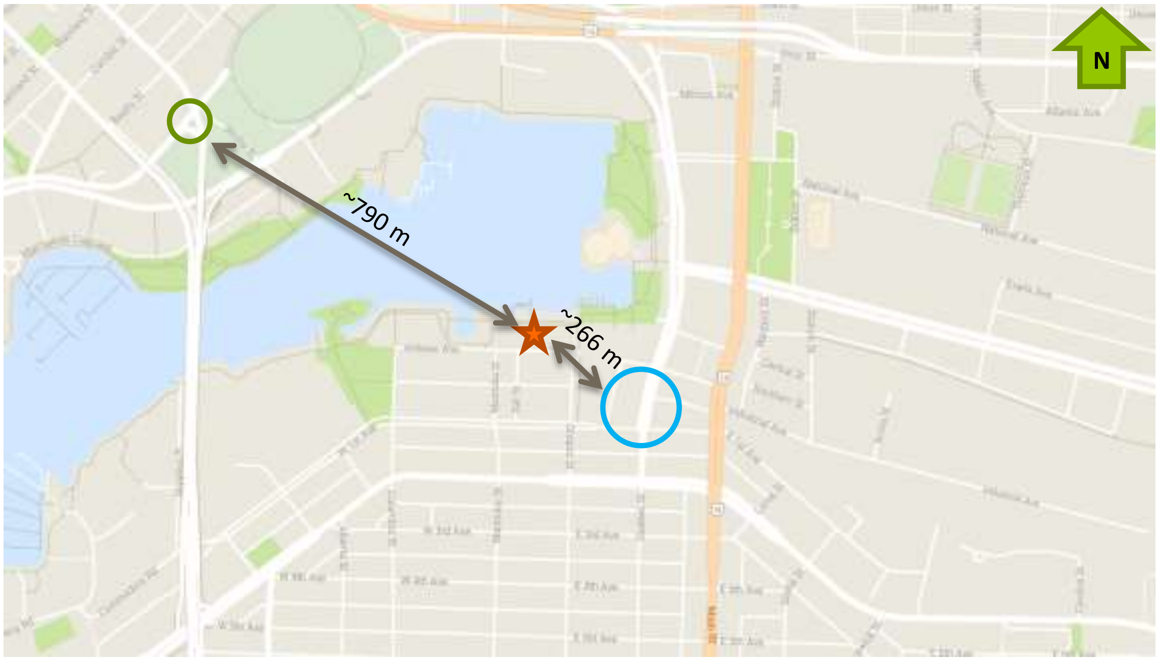


Figure 39: Rain gauge site location relative to monitoring locations

The rain gauge is located at the Creekside Community Recreation Center (orange star) in the False Creek Neighborhood. The Quebec St and 1st Avenue monitoring location is circled in blue and it is located ~266 SW from the gauge location. The Expo and Smithe monitoring location is circled in green and it is at ~790m NE from the rain gauge location.

Flow Monitoring

Green infrastructure is very versatile and effective in managing a diversity of landscape changes that occur in the urban environment [66]. The versatility of GI is what makes monitoring challenging [67]. GI are typically constructed on ROWs. This adds difficulty in monitoring studies as space tends to be a constraint. Adding weirs and flumes to monitor a system might not be a possibility to accurately measure inflows and outflow.

The equipment chosen for this monitoring study were selected to monitor inflow and outflows from the GI practices. The following constraints were identified in the study:

- Accuracy to measure low flows
- Continuous data logging with minimal maintenance including battery replacement
- ROW constraints: minimize GI catch basin work due to proximity to road
- Manhole cover weight minimization – a single staff member should be able to comfortably open and close the lid
- Budget

Inflow Monitoring

As mentioned previously, GI have various methods to allow ingress of stormwater into the practices. The study will monitor two STTs and two bioswales.

Bioswales

Bioswales allow water ingress through curb openings. The curb opening used for the bioswales in this study is shown in Figure 40. This inlet is flushed with the street gutter. There is a small drop onto a concrete slab to allow the radial distribution of water and trapping of sediment. The concrete slab is surrounded by round river stone which dissipate the energy of the inflow, preventing scouring.

Figure 40: Bioswale inlet design

The Simple Method was chosen to estimate the inflow into the bioswales. This method was developed by Schueler in 1987. It provides flow estimation by accounting for factors such as annual precipitation, runoff coefficients and drainage area [68]. Because the Simple Method is based on annual precipitation, modifications to the formula are necessary. This report will follow the same procedure developed by the Credit Valley Conservation (CVC). The changes are:

- The bioswale (GI area) will be incorporated to the calculations. This will be an added term without accounting for a runoff coefficient as it will be assumed that 100% of the rainfall is captured in the practice.
- Event precipitation information will be used instead of the annual precipitation information used by the original formula developed by Schueler.

The discharge formula, including the modifications mentioned above, is the following:

$$Q = [(GI\ Area) + (Drainage\ area\ to\ GI * R_v)] * i$$

In this equation, areas are provided in m^2. “i” is the rainfall intensity in mm/h, Rv is the runoff coefficient that is defined by the following equation:

$$R_v = 0.05 + (0.9 * I_a)$$

The runoff coefficient specifies a value of 0.9 which refers to the fraction of rainfall events that produce runoff (CVC 2016a, 2016 b). The term I_a is a dimensionless number called: impervious fraction. The impervious fraction equals the impervious area over the total drainage area to the GI practice.

The limitations of the modified Simple Method are:

- The Simple Method is sensitive to the impervious cover coefficient. The coefficients are derived from a linear relationship with R^2 values of 0.71 and a sample number of 47 data points [69] [70]
- The Simple Method does not account for bacground loadings. It was developed to estimate the loadings per storm event [3] [69] [8] [71]
- The simple method should not be used in complex watershed. Modelling should be used as a more robust tool [8] [71]
- The Simple Method will over estimate the inflow discharges [69]. When the time of concentration is smaller than the storm duration, the Simple Method will not be used. It will be assumed that the stormwater was captured by the GI (no underdrain flow).

Stormwater Tree Trenches

The STT were designed to capture street runoff using a conventional street CB. The street CB is called GI Catch Basin (GICB). A single distribution pipe is connected to the GICB. This feeder pipe distributes the water evenly within the practices. The inflow monitoring will make use of a pressure transducer to measure the water level relative to the mouth of the pipe as shown in Figure 41. Another pressure transducer will be installed in the feeder pipe section to measure the water level within the pipe.

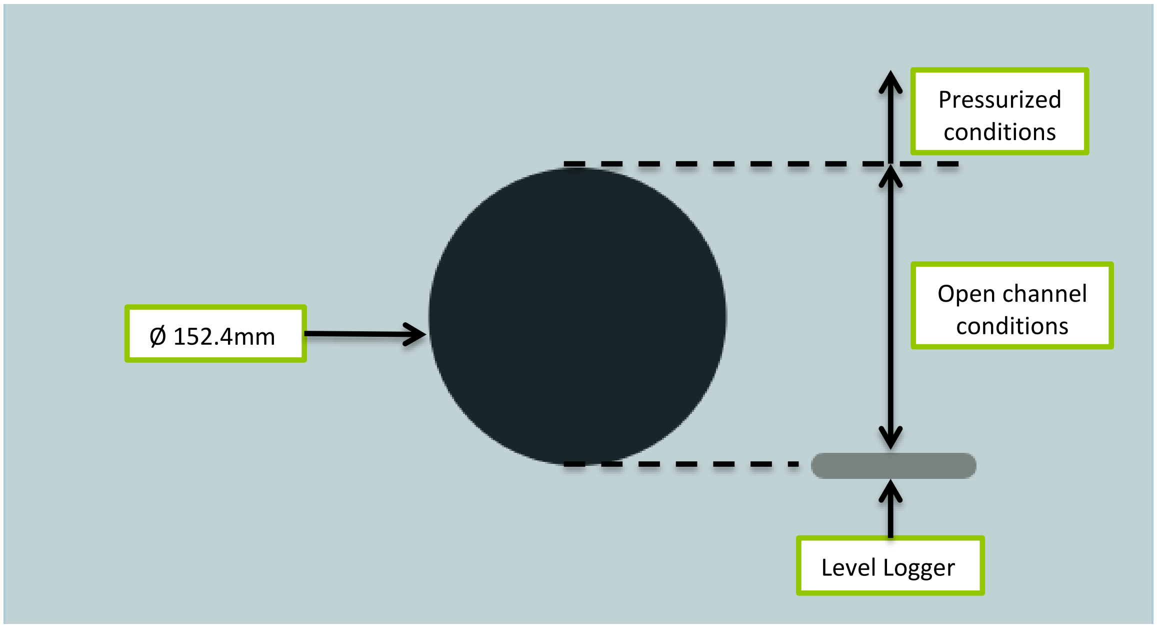


Figure 41 : GICB inflow monitoring flow conditions

The mouth of the pipe can be treated as an open channel flow when the water depth relative to the bottom of the orifice does not exceed the diameter (ø 152.4mm). Manning's equation will be used to estimate the discharge [72] [73]:

$$Q = \frac{1}{n} * A * (R_h)^{2/3} * (S)^{1/2}$$

In the previous equation, the discharge Q is in m^3/s, "A" is in m^2, R_h is the hydraulic radius, "n" is Manning's roughness coefficient and "S" is the slope of the pipe. Considerations will be taken to account for the dynamic conditions manning's roughness coefficient. Camp first discussed that the roughness coefficients for full vs partially full conditions are different. In Camp's paper, he argued that the roughness coefficient is higher for partially filled pipes. The variable roughness coefficient can be expressed as a function of y/D, where y is the water height with respect to the bottom of the pipe as shown in Figure 41 and D is the diameter of the pipe. The full pipe and variable pipe roughness coefficients will be extracted from literature [72] [73] [74].

Field tests will have to be conducted to determine the downstream influences exerted by the horizontal distribution pipe. Backwater issues from the distribution pipe will affect the flow profile as shown by Isenmann et al. [75]. The system will be considered under pressurized conditions when the water level exceeds the diameter of orifice relative to the bottom of the pipe. The Bernoulli equation will be used to estimate velocity of the flow. Friction losses will be accounted at the inlet using literature values [73].

Figure 42: HOBO U20-001-04 pressure transducer

A HOBO U20 level logger, Figure 42, will be used to measure the water level at the inlet and inside the pipe. This sensor is capable of measuring the absolute pressure (absolute pressure = static pressure + barometric pressure). The barometric pressure is measured with another HOBO U20 logger. This compensation logger is located at the GI branch offices.

Out flow monitoring

Outflow monitoring will be conducted with the use of a flume like-system. The system is located in a monitoring manhole. The manhole is a 30 inch in PVC stand pipe. The manhole is enclosed by a lockable, hinged fiberglass cover. The weight of the cover and the hinge system facilitate the open and closure on the monitoring manhole. A single person should be able to comfortably lift cover. Proper lifting techniques should be followed when lifting the cover. Figure 43 shows the cross section of the monitoring manholes.

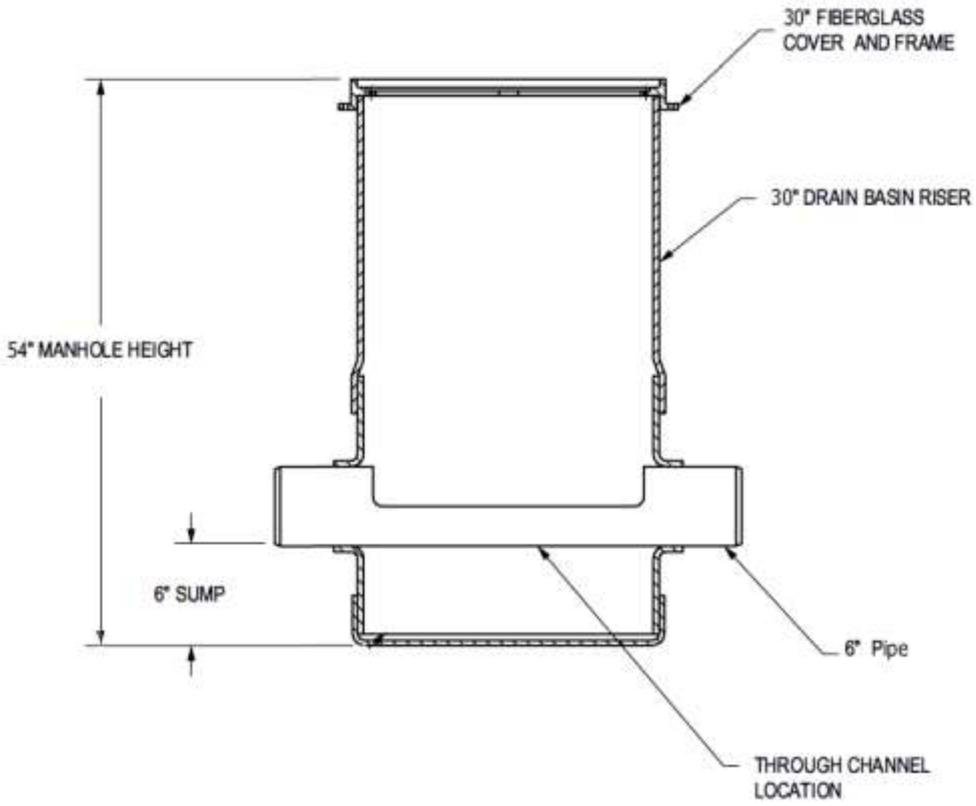


Figure 43: Monitoring manhole cross section. Source: ADS-pipe shop drawings

The through channel will be used as a flume device. A rating curve will be developed to related discharge to stage. This rating curve test will focus on +/- 50% of the maximum expected flow.

The Rational Method was used to estimate the discharges expected in practices. The Rational Method was developed by Kuichling in 1989. The formula is limited to drainage basins under tens of acres (Kuichling, 1889, Thompson, 2006). The rational method formula is:

$$Q = C_{u*}C * i * A$$

Where C_u is the unit conversion factor (1/3.6 for SI units), “i” is the rainfall in mm/h, A is the catchment area in km^2, and C is the runoff coefficient factor. The runoff coefficient for impervious surface (asphalt in this case) is 0.95 [76].

The summary of the Rational Method results are shown in Table 13. The through channel should be able to have a flow capacity of 1.46 L/s.

Table 13: Rational method flume sizing

Site	Design Storm (L/s)			
	20 Minutes		25 Minutes	
	2 Year	10 Year	2 Year	10 Year
Structural Soil	0.82	1.38	0.69	1.11
Soil Cell	0.10	0.16	0.08	0.13
Bioswale	0.74	1.24	0.62	1.00
Hybrid Cell	0.87	1.46	0.73	1.18

To record the water level in the through channel, an ultrasonic water level sensor will be employed. The sensor will be connected to a data logger to continuously record the sensor's readings. The Toughsonic (TS) 14 will be used for its low power consumption and its IP68 certification. The sensor has a resolution of 0.086mm [77].

Figure 44: Toughsonic 14 Sensor. Image source: Senix Corporation

Figure 44 shows the TS14 sensor that will be used in the study. A custom bracket will be used to attach the sensor to the through channel. The bracket will ensure that the sensor is stabilized and secure. The sensor will be calibrated with the use of the staff gauge.

The data logger will be installed at the top of the monitoring manhole. The logger will be secured to the PVC wall for easy access. The information collected from the loggers will be downloaded by the use of a shuttle. The information will be transferred to a PC via USB cable.

Monitoring Wells

Monitoring wells are an inexpensive method to monitor the water levels in the GI practices. All of practices for this study have a monitoring well that consists of a 150mm perforated PVC pipe. The well heights are variable as their extent depends on the depth of each practice. The well sits at the subgrade and extends to the top of the GI practice. Figure 45 shows a typical cross section for a GI monitoring well. Water level loggers are installed at these wells to continuously monitor the water levels in the well. A barometric compensator logger is installed at the GI branch offices. The procedure to interpret the information is similar as the process described earlier.

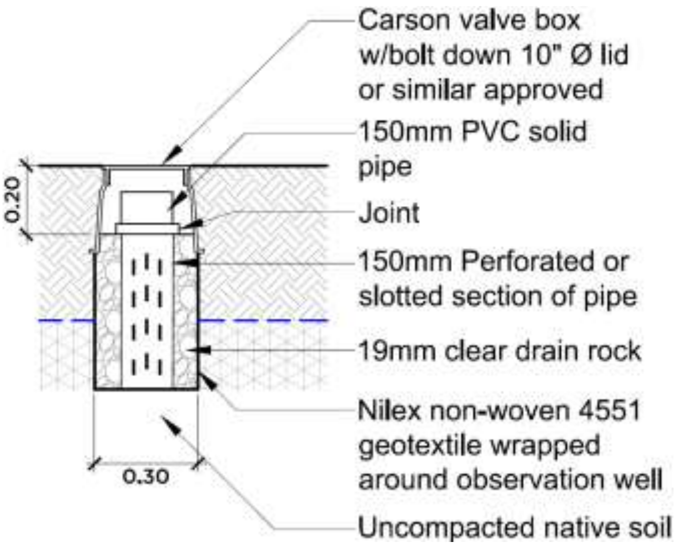


Figure 45: Monitoring Well. Image source: GI Branch

Soil Monitoring

Soil monitoring is included in the scope of the monitoring plan. Soil sensors will be used to assess the drainage behaviours of the GI practices, to track contaminants such as salts, and to correlate the responsiveness of the monitoring wells. The TEROS 12 sensor will be used for this study (shown in Figure 46). This device is capable of tracking the Volumetric Water Content (VWC), Bulk Electrical Conductivity (EC_b) and the soil temperature.

Figure 46: TEROS 12 Sensor. Image source: METER Group

This sensor makes use of the dielectric properties of soil. The sensor runs at a high frequency (70MHz) which minimizes the need for custom calibration. The default error on the sensor is 3%. The sensor has large volume of influence (1,010 mL). Nevertheless, the soil closest to the needles has a larger influence on the overall readings [78]. The sensors were installed on a vertical mode similar to the picture shown above. The sensors will be used to create a moisture, EC and temperature profile at different depths. The sensors will be spaced by 20cm to avoid causing interference between the electrical signals of the sensors. Table 14 summarizes the number of sensors per GI practice.

Table 14: Soil sensor per GI practice

Soil Sensors	**Sensor #**
Structural Soil	3
Soil Cell	3
Bioswale	2

A data logger will continuously record the information provided by the sensors. The Em50 data logger by METER Group will be used. The data loggers will be installed in a custom Pelican box to protect the data loggers from moisture. A #3 composite valve box was installed in or next to all the practices to guard the data loggers and maintain them off the public sight. Figure 47 shows a composite valve box installed in the field.

Figure 47: CoV standard valve box. Source: GI Branch

The soil sensor cables should be routed upwards and towards the valve box. A 1" hole should be drilled or pushed into the valve box to allow the sensor cables to go through. The soil sensors in structural soil will need to be protected by a PVC pipe. The aggregate in the structural soil is coarse and sharp. The sensors and cables in the structural soil have the risk of being destroyed during construction or the cable pierced by the compaction process. The information stored in the data loggers will be retrieved manually to a field computer.

Water Quality

Water quality is an important component of the monitoring study. Pollutant loads in urban watershed have become a major concern due to the negative effects on receiving water bodies [79]. One of the reported benefits of GI is the decrease in pollutant loads even for stormwater that is not retained within the GI. The treatment to the more transient water is less when compared to the water that is retained within the GI practices [80]. Ultimately, GI practices should be able to discharge directly into receiving water bodies if required.

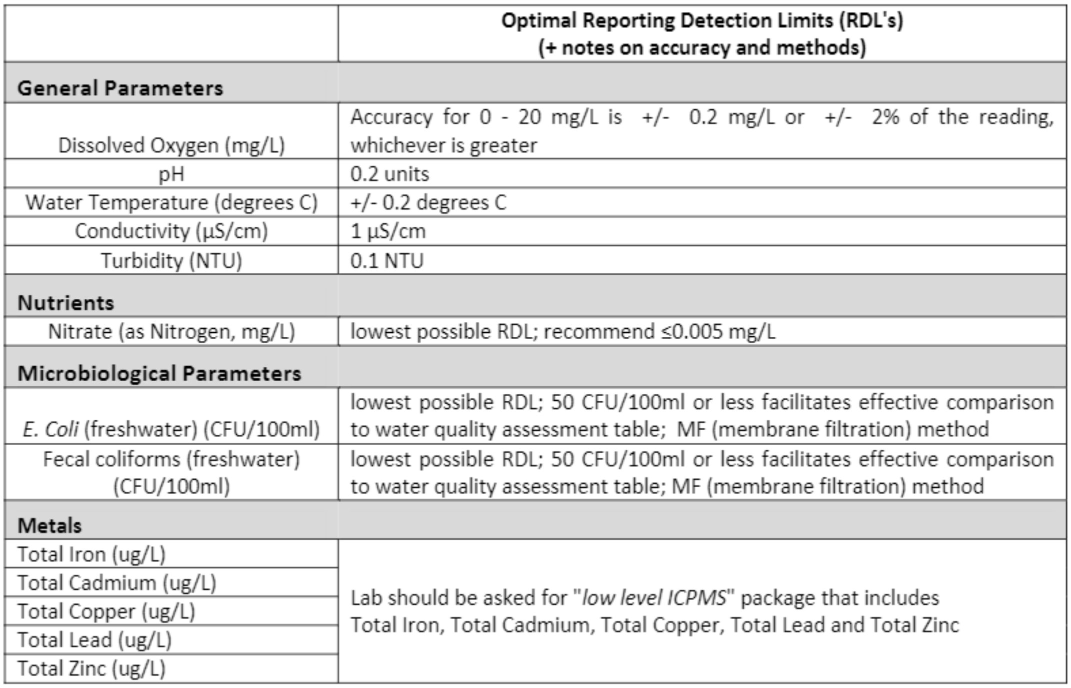
This monitoring program will conduct a water quality study of the four GI practices. The water quality samples will be taken from the GICB at the structural soil practice and possibly at the soil cell GICB in Downtown Vancouver. Water quality samples will be also obtained from the underdrains of the practices at the monitoring manhole locations.

The sampling method to be used is time based grab samples. Two ISCO 3700 Portable Samplers will be used to collect the grab samples. The grab samples will be composited into a larger container within the sampler. The samples will be collected at 15 minute intervals. The time of extraction will also be recorded. A paired watershed approach will be used to estimate the loadings to the bioswales inlets based on the estimated discharge.

Water Quality Parameters

The water quality samples will be processed at Metro Vancouver's laboratory. A total of 25 samples will be processed at this lab (as of August 2018). 24 samples will be distributed equally among the practices. One of the samples will be used for QA/QC which is discussed below. The water quality parameters tested by Metro Vancouver are summarized in Table 15. The lab will provide the Reporting Detection Limit (RDL), which will be used to compare against BC's water quality guidelines for aquatic life, wildlife and agriculture [81]. If a parameter is not found in BC guidelines, the CCME (Canadian Council of Ministers of the Environment) guidelines for the protection of aquatic life will be used.

Table 15: Water quality parameters tested by Metro Vancouver [82]



	Optimal Reporting Detection Limits (RDL's) (+ notes on accuracy and methods)
General Parameters	
Dissolved Oxygen (mg/L)	Accuracy for 0 - 20 mg/L is +/- 0.2 mg/L or +/- 2% of the reading, whichever is greater
pH	0.2 units
Water Temperature (degrees C)	+/- 0.2 degrees C
Conductivity (µS/cm)	1 µS/cm
Turbidity (NTU)	0.1 NTU
Nutrients	
Nitrate (as Nitrogen, mg/L)	lowest possible RDL; recommend ≤0.005 mg/L
Microbiological Parameters	
E. Coli (freshwater) (CFU/100ml)	lowest possible RDL; 50 CFU/100ml or less facilitates effective comparison to water quality assessment table; MF (membrane filtration) method
Fecal coliforms (freshwater) (CFU/100ml)	lowest possible RDL; 50 CFU/100ml or less facilitates effective comparison to water quality assessment table; MF (membrane filtration) method
Metals	
Total Iron (ug/L)	Lab should be asked for "*low level ICPMS*" package that includes Total Iron, Total Cadmium, Total Copper, Total Lead and Total Zinc
Total Cadmium (ug/L)	
Total Copper (ug/L)	
Total Lead (ug/L)	
Total Zinc (ug/L)	

QA/QC

Precautions will be taken to ensure the quality of all the samples. The tubbing used in the peristaltic pump is disposable. The disposable tubbing will only be used once per practice to avoid cross contamination between practices. Metro Vancouver [82] monitoring framework suggests that at least 10% of the sampling budged is dedicated for QA/QC to test for contamination. Due to the limited number of samples, only one of the samples will be used for QA/QC (~5% of the sampling budget).

Ancillary Benefits

The ancillary benefits of interest are vegetative growth and drought resistance. The vegetative growth will be assessed by a temporal analysis of the vegetation in the practices. Photographs will be taken at the start of each month showing the status of the vegetation in the practices (where applicable). The photographic comparison will be used to assess the health of the vegetation throughout the year. The photographic information will be paired with the climatic conditions of the previous months to aid in the assessment of the plant conditions. The drought resistance conditions will be assessed by analyzing the water content variations of the practices throughout the spring and summer months.