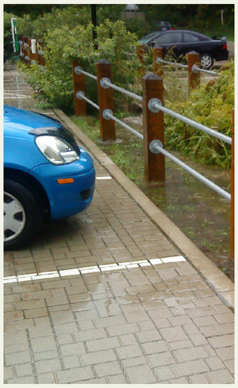
Performance Evaluation of a Bioretention System

TECHNICAL BRIEF

Low Impact Development Series

Bioretention or 'rain gardens' use the natural properties of soils, plants and associated microbial activity to infiltrate water and remove pollutants from stormwater runoff. It consists of a shallow, excavated depression with layers of stone, prepared soil mix, mulch and specially selected native vegetation that is tolerant to road salt and periodic inundation. They remove pollutants from runoff through filtration by soil media and uptake by plant roots. Runoff volumes are reduced through evapotranspiration and infiltration. The practice provides aesthetic benefits and can easily be modified to fit a wide variety of space and drainage contexts.

Bioretention is one of the most common low impact development practices used to clean and control stormwater runoff from urban developments. A review of 20 studies of bioretention facilities in the United States showed that, on average, 66% of runoff entering the bioretention facilities was retained, infiltrated or evapotranspired (Poresky et al., 2012).



This study evaluates the performance of a bioretention system that treats runoff from a commercial parking lot. Key parameters examined include runoff volumes, runoff reduction, surface ponding and infiltration, water quality, surface soil and effluent water temperatures, soil moisture and operation and maintenance requirements. Results show that bioretention systems can significantly improve the management of stormwater runoff from parking lots and other small drainage areas relative to conventional treatment practices. Runoff volumes were reduced by over 90% and the mass of pollutants discharged from the facility was between 65 and 92% less than that discharged from a nearby asphalt pavement. The concentrations of most pollutants in bioretention underdrainage were also significantly lower than in asphalt runoff. Runoff infiltrated well throughout the winter and vegetation remained healthy year round with little need for manual irrigation. A life cycle cost analysis showed that bioretention can provide a cost-effective alternative to conventional stormwater management, while offering substantial improvements in treatment and runoff control.

INTRODUCTION

Roads and parking lots alter the local hydrological cycle by increasing the volume and rate of stormwater runoff and decreasing infiltration and evaporation through the creation of impervious land surfaces and enhanced drainage systems. These higher runoff volumes pick up and transport contaminants to receiving waters where they degrade river ecosystems and pollute swimming areas. While conventional stormwater management facilities, such as ponds and constructed wetlands, help reduce peak flows and improve runoff quality, they have not been successful in achieving the level of management necessary to maintain baseflow characteristics in streams, prevent stream erosion and avoid degradation of aquatic systems.

Low Impact Development (LID) has emerged as an alternative to sole reliance on conventional urban stormwater management approaches. LID consists of a series of decentralized micro-controls at or near the source of drainage networks that supplements traditional detention facilities. This more distributed approach attempts to reproduce the pre-development hydrologic regime through site planning and engineering techniques aimed at infiltrating, filtering, evaporating and detaining runoff, as well as preventing pollution. Temporary storage and infiltration of stormwater is a central feature of most LID practices because the infiltration component of the water cycle is substantially reduced under most urban development scenarios.

Bioretention is an infiltration practice that utilizes the natural properties of soils and plants to reduce runoff volumes and remove pollutants from stormwater. It is an attractive and cost effective practice that can be configured to fit within public right-of-ways, commercial parking lots or residential developments. This study evaluates the performance of a bioretention system that treats runoff from a commercial parking lot at the Living City Campus in the City of Vaughan. Key parameters examined include runoff volumes, runoff reduction, surface ponding and infiltration, water quality, surface soil and effluent water temperatures and soil moisture. The study also documents life cycle cost and key operation and maintenance requirements.

STUDY SITE

This study was undertaken on a bioretention facility installed in April 2010 on a new parking lot owned and constructed by Earth Rangers at the TRCA's Living City Campus at Kortright in Vaughan. The bioretention area was configured as a 123 m^2 linear island in the centre of the parking lot, with 128 m^2 bump outs on either end (Figure 1). A second 84 m^2 swale section to the east was connected to the island via an underdrain, which joins the cells and conveys subsurface flows to a sampling vault along the eastern end of the cell. The sampling vault housed monitoring equipment used to measure flow rates, volumes, water quality and water temperature.

Facility Design

The bioretention surface contains a combination of plants and river rocks. Runoff drains into the bioretention cell and east swale as sheetflow from a 2,272 m^2 non-permeable interlocking concrete pavement, where it infiltrates into the silty clay native soils, is returned to the atmosphere as evapotranspiration, or is conveyed downstream through perforated underdrains approximately 1.3 m below the cell surface. During large rain events, excess ponded runoff is conveyed across the surface to a catchbasin that drains to a sewer pipe to prevent water from backing up onto the parking lot.

The filter media (0.6 m depth) was underlain by clear stone (0.2 to 0.75 m), in which the perforated underdrain was placed (Figure 2). Filter media was only placed in the center island portion of the cell. The east portion of the cell was back filled with finer textured native soils. A non-woven geotextile was used to separate the bioreten-

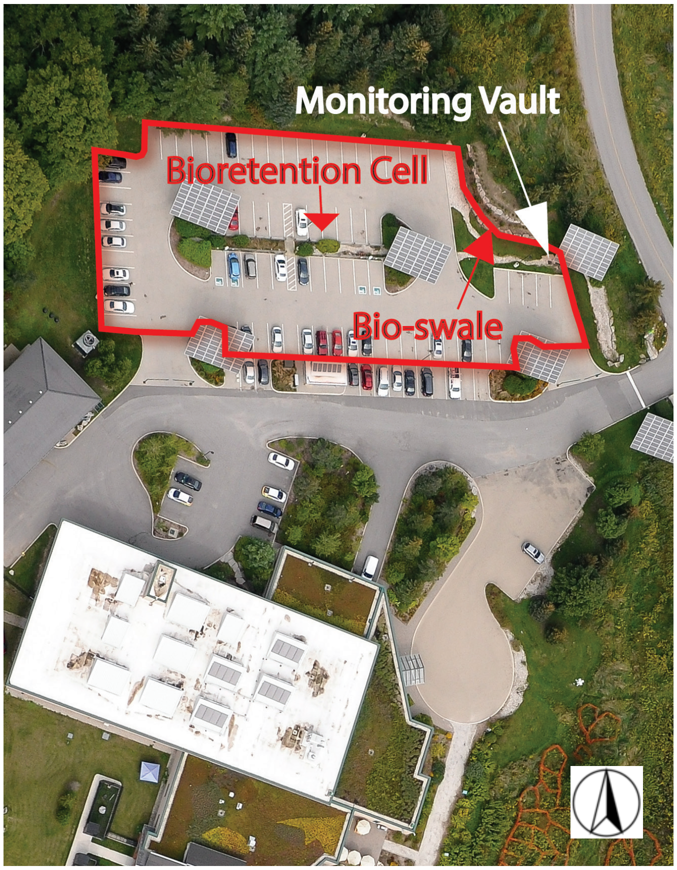


Figure 1. Bioretention and bio-swale facility location and drainage area (within red borders) as part of the Earth Rangers complex.

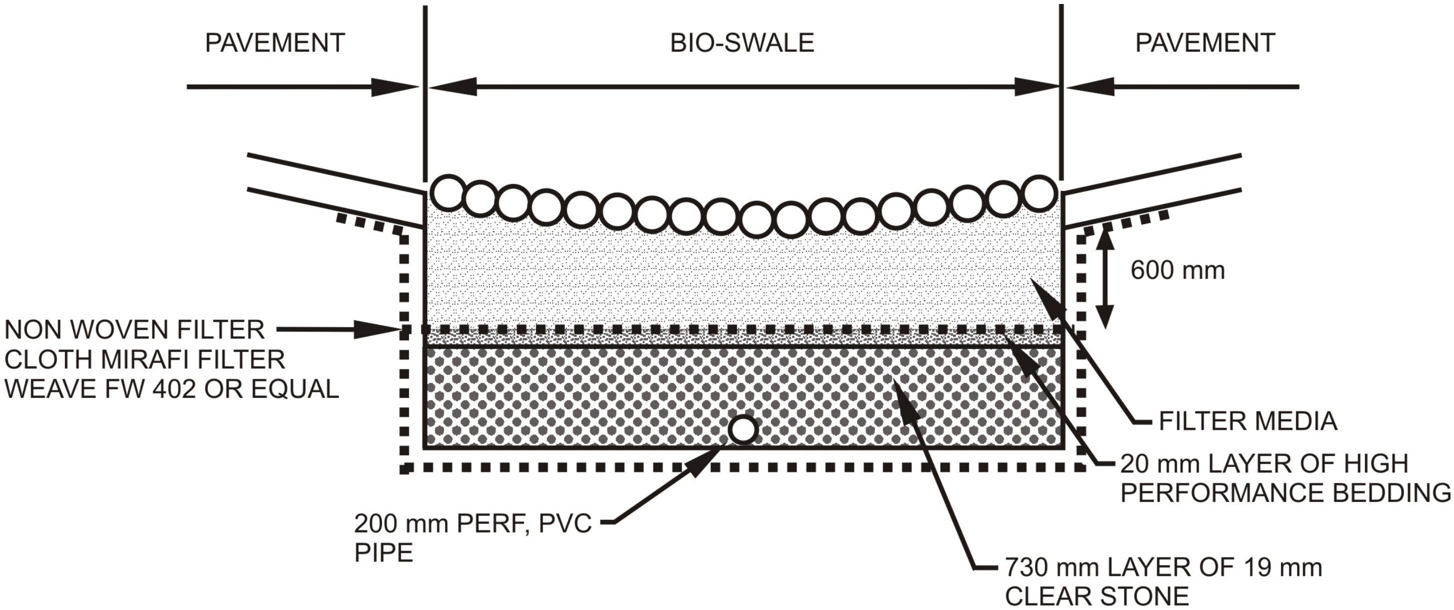


Figure 2. Cross section of the bioretention cell. The cell surface includes a combination of bioretention plants and river stone. Bump-outs are fully vegetated.

tion materials from the surrounding native soils. The entire paved drainage area is approximately 11 times larger than the combined bioretention cell and east swale. The bioretention cell is approximately 1.35 m deep, from the surface to the native soil.

APPROACH

The monitoring program consisted of co-ordinated measurements of precipitation, flow, water quality, water temperature and soil moisture. Evapotranspiration was estimated based on actual measurements over the same period in a well vegetated field less than 1 km from the study site. Flows entered the cell as sheetflow and therefore could not be measured directly. Instead, inflows to the system were estimated from precipitation, using an abstraction factor to account for direct losses from the parking surface. Outflows, water quality and water temperature were monitored in the sampling vault at the outlet. The difference between total inflows and total outflows was used as the basis for calculating the volume of runoff reduced through infiltration and evapotranspiration.

The capacity of the bioretention system to improve water quality was assessed through statistical analysis of the quality of outflows from the bioretention system outlet and the quality of untreated runoff from a nearby asphalt pavement with similar traffic density and sources of contamination. Samples at both locations were volume weighted to better represent the event mean concentration of the monitored events. Load reduction factors were estimated based on median concentrations and measured runoff and outflow volumes. Water quality variables included solids, chloride, general chemistry, nutrients and metals.

Soil moisture was measured over a two month period at 20 vegetated and non-vegetated locations throughout the cell to assess contributions of vegetation to runoff reduction and the need for irrigation during dry periods in the summer. Soil moisture was measured at 2 and 10 cm depths on a daily basis before and after rain events using a soil moisture meter. Measurements of vegetated and non-vegetated areas at the two depths were analyzed statistically to assess differences.

FINDINGS

Over 90% of the runoff directed into the facility from the paved drainage area either infiltrated or was returned to the atmosphere as evapotranspiration, indicating that this practice can provide effective stormwater treatment and runoff control, even on low permeability soils. Even during the largest storm observed over the study period (78 mm, of which 46 mm occurred over less than two hours), runoff volumes were reduced by approximately 81%. Peak flows were also significantly reduced, resulting in a less flashy discharge that closely mimicked overland flow patterns observed in natural landscapes. Cold weather did not dampen performance, despite lower winter evapotranspiration and infiltration rates. Similar runoff reduction rates were observed during the warm (April to November) and cold seasons (December to January) (Table 1). Effective cold season performance may be attributed largely to the slow process of snow melt, which allows bioretention systems the time needed to absorb and infiltrate the runoff, thereby minimizing overflows.

Table 1. Hydrologic summary of rain events for the summer and winter periods.

Parameter	Rainfall Depth (mm)	Parking Lot Runoff (m^3)	Surface Ponding Duration (hrs)	Underdrain Flow (m^3)	Overflow (m^3)	Runoff Reduction (%)
Summer - April to November 2011 and 2012 (n= 169)						
Minimum	1	0	0	0	0	65
Maximum	77.8	186.1	2.2	1.4	34.4	100
Average	8.5	15.7	0	0	1.2	97
Median	4.2	3.6	0	0	0	100
Total	1,438	2,662	---	10	231	91
Winter - January to March 2011, and December to March, 2012 (n= 63)						
Minimum	0.3	0	0	0	0	61
Maximum	49.4	115.6	38.4	0	10.3	100
Average	5.5	8.7	1.3	0	0	99
Median	2.5	0.5	0	0	0	100
Total	345.4	549.8	---	0.5	23	96

It was estimated that approximately 8.9 and 9.6% of total runoff inputs were evapotranspired by the bioretention cell between April and November in 2011 and 2012, respectively. Evapotranspiration estimates were derived from Bowen Ratio Energy Balance measurements over the same period in a well vegetated field less than 1 km from the study site (Delidjakova et al., 2014). Based on these estimates, it was determined that the volume of water returned to the atmosphere as evapotranspiration was similar to the proportion of runoff that drained out of the facility (Figure 3). Outflows occurred primarily when ponded water overflowed through the surface catchbasin during large events. Less than 5% of total outflows exited through the underdrain.

Throughout the summer, water ponded on the surface only during large or high intensity rain storms, and rarely for more than 20 minutes. The short ponding durations (Figure 4) were an indication of the rapid rate of infiltration through the filter media. These high rates of infiltration occurred despite the presence of a high proportion of silt and clay in the filter media, suggesting that estimates of soil infiltration capacity based on soil texture alone can be misleading. During the winter, ponding was less frequent but lasted longer (<38 hours), particularly when snow melt events were combined with rain. Surface temperature measurements and direct observations revealed that winter ponding was caused by the formation of a thin layer of ice at the surface. Infiltration resumed when temperature increased, causing the ice layer to melt. Throughout the year, the parking lot remained free of standing water because the overflow elevation was below that of the pavement surface.

The concentrations of most pollutants in bioretention underdrainage were significantly lower (α=0.05) than in asphalt runoff. These included total suspended solids, total phosphorus, ammonia nitrogen, total kjeldahl nitrogen, lead, iron, manganese and aluminum (Figure 5). Other variables, such as oil and grease (solvent extractable) and vanadium, had lower detection frequencies in bioretention samples. Nitrate nitrogen ($NO_2 + NO_3$) was higher in bioretention underdrain flows, but consistently below the Canadian Environmental Sustainability Indicator of 2.93 mg/L. Phosphorus concentrations from the bioretention system were similar to levels observed in area streams (TRCA, 2013a), despite exceeding the provincial guideline 69% of the time. Hardness and pH were both higher in bioretention outflows, which is considered beneficial, as higher values of these variables helps to reduce the toxicity of some heavy metals to aquatic life (e.g. lead).

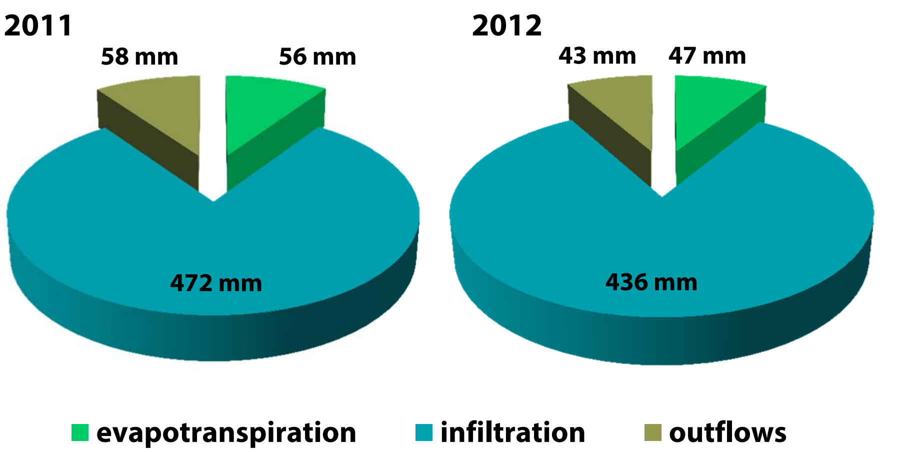


Figure 3. The proportion of runoff entering the bioretention system that infiltrated, evapotranspired, or was discharged to receiving waters from April to November in 2011 and 2012.

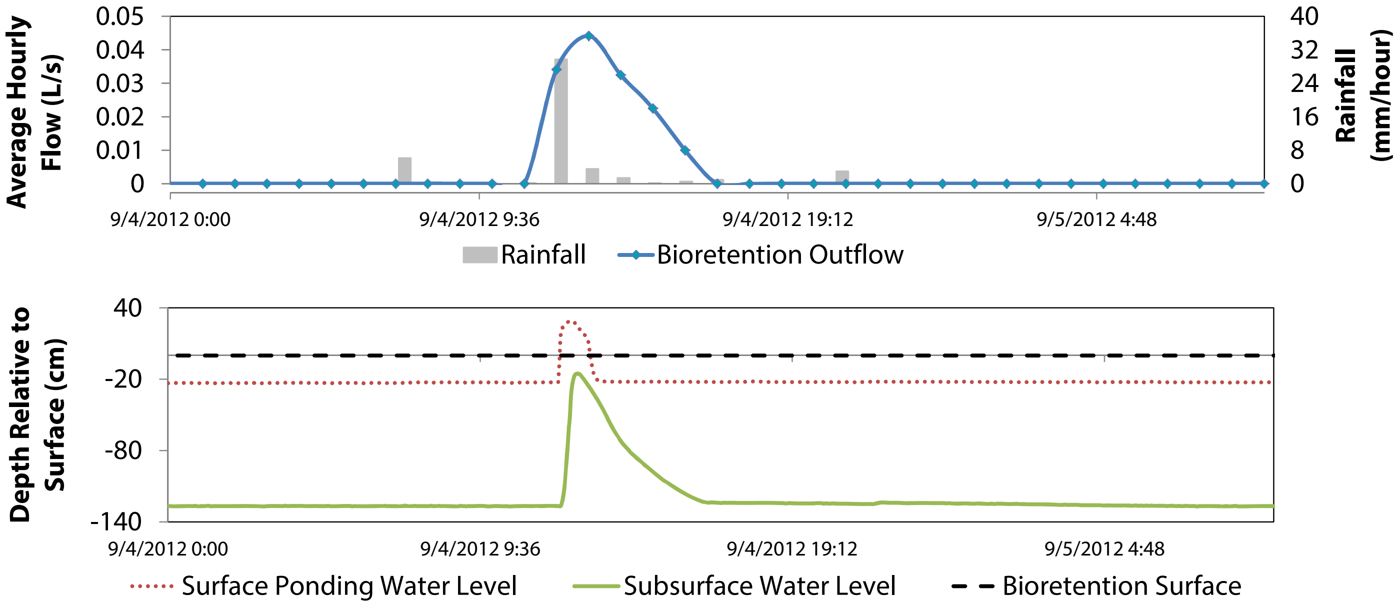


Figure 4. Hydrologic response to a 43 mm rain event on September 4, 2012. Note that ponding depths below the surface (dashed line) represent water level changes in the monitoring well embedded approximately 22 cm into the surface soils.

On a unit area basis, the mass of contaminants discharged from the bioretention facility was over 90% less than that discharged from the conventional asphalt control for most water quality variables. Exceptions included E.coli (86%), and variables such as strontium (66%), manganese (71%) and boron (88%), the latter of which are not considered to pose a threat to receiving waters at observed concentrations. The high contaminant load reductions were largely a result of runoff volume reductions associated with infiltration and evapotranspiration. Improvements in the quality of stormwater passing through the filter media played a relatively small role in overall treatment because less than one percent of total runoff inputs to the facility were discharged through the underdrain. A larger proportion of water was conveyed as overflows through the surface catchbasin, but this stormwater did not receive

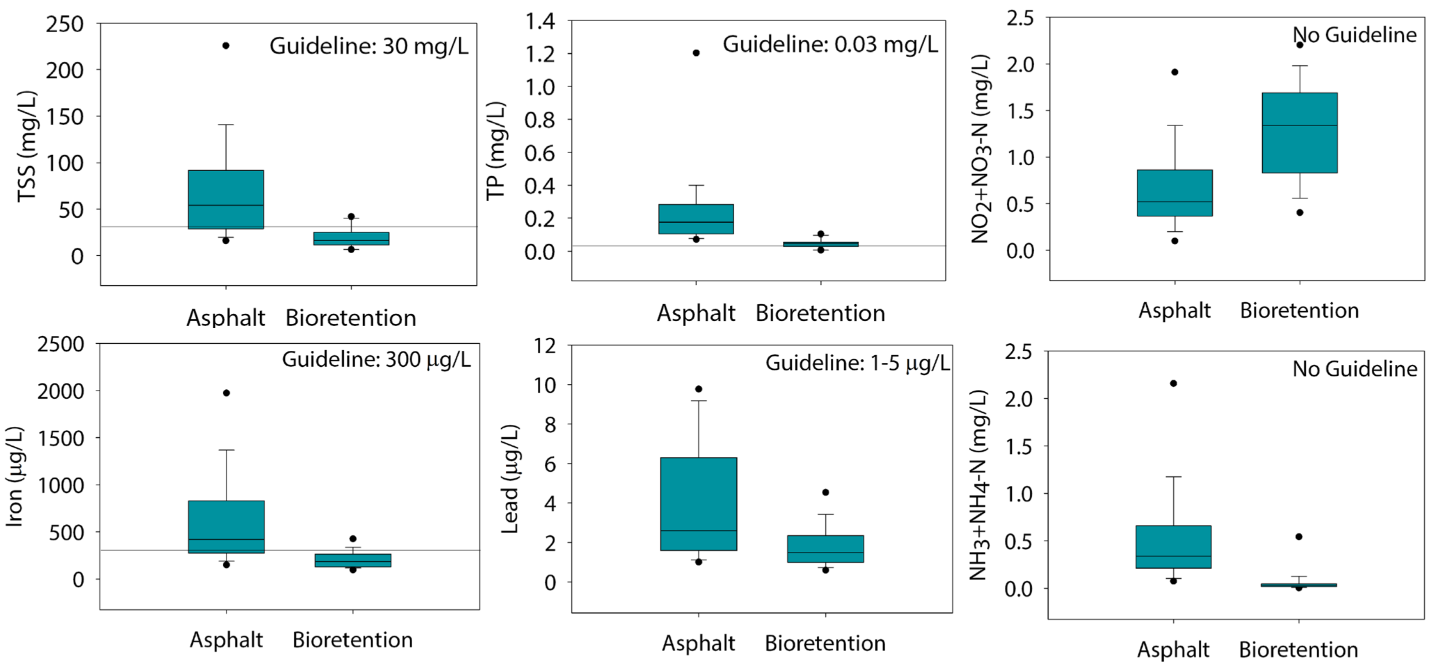


Figure 5. Box plots and receiving water guidelines for selected water quality variables with statistically significant difference between asphalt and bioretention. The whiskers represent the 10th and 90th percentiles, and the individual points are the 5th and 95th percentiles.

treatment. This underscores the central role that infiltration and evapotranspiration play in the treatment functions of bioretention systems.

Soil moisture content was significantly greater in the non-vegetated than vegetated areas of the bioretention cell, indicating that cells without vegetation have less capacity to reduce runoff through temporary soil moisture storage and evapotranspiration. Figure 6 shows the soil moisture content difference between the two areas of the cell over a two month period during the summer. Soil measurements were taken manually before and after rain events at 2 and 10 cm depths below vegetated and non-vegetated areas of the bioretention cell. The non-vegetated areas consisted of river stone, while the vegetated areas consisted of a combination of herbaceous plants and shrubs. While soil moisture was lower in vegetated areas, it was not so low as to inhibit plant growth. Ample supplies of water from pavement runoff, combined with good retention through mulches, helped maintain soil moisture within the root zone at levels sufficient for plant survival and growth during most of the summer.

Relative to the asphalt pavement, average temperatures of the bioretention media was warmer during the winter and considerably cooler during the summer. Temperatures were measured in the bioretention cell and nearby asphalt pavement at 4 depths extending from 6 to 58 cm below the surface (Figure 7). In

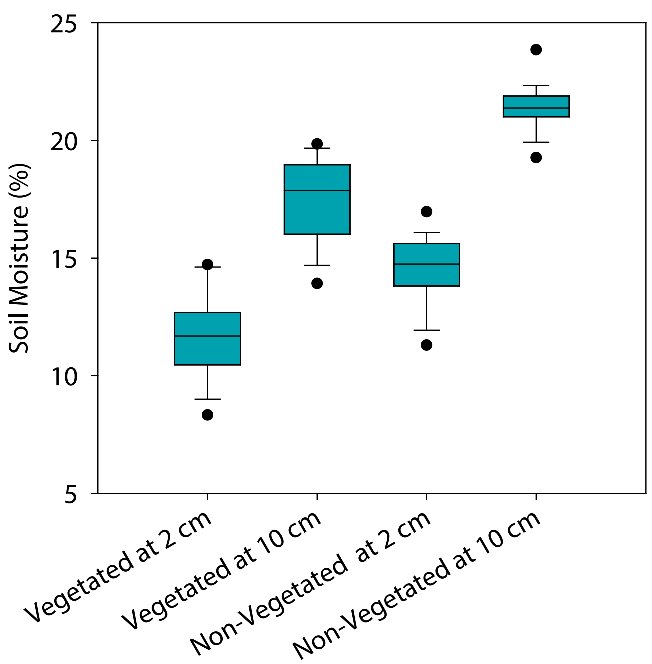


Figure 6. Box plots of soil moisture content at the 2 and 10 cm below the surface of vegetated and non-vegetated areas within the bioretention cell.

the summer, peak bioretention soil temperatures at 6 cm below the surface were just over 25°C, compared to above 40°C on the asphalt. During the winter, an ice layer formed on the bioretention cell; hence surface measurements reflected the temperature of the ice (zero degrees) rather than the materials and air surrounding the sensor (as was the case below the asphalt). Below the snow and ice layer, cell soil temperatures were approximately 5°C warmer than at the same depth below the asphalt. This finding highlights the benefit of bioretention in reducing urban heat island effects, and limiting frost penetration, allowing for more rapid melting.

The reduction in runoff and cooler bioretention outflow temperatures helped to mitigate the thermal impact of the parking lot on downstream aquatic communities. This represents an important benefit of bioretention over other treatment systems, such as ponds or concrete sedimentation devices, because aquatic organisms are very sensitive to even small changes in thermal conditions. Much of this thermal benefit can be attributed to the low outflow volumes from the system. Unlike stormwater ponds, which often discharge warm water even during dry weather, the bioretention system virtually eliminated dry weather flows. The temperature of bioretention underdrain flows was also substantially lower than asphalt runoff. The maximum temperature of underdrainage during hot summer periods was just over 20°C, which was over 10°C lower than peak asphalt runoff temperatures during the same events, and also below the 21°C threshold required for protection of cool water fisheries.

After more than four years of operation, the system continues to infiltrate and drain very well. Maintenance has been limited to routine weeding, pruning and spring planting, which is conducted as part of the larger landscape maintenance activities on the site. Regular maintenance of the parking lot bioretention and bump-outs accounted for approximately $1500 of the annual landscape maintenance budget for the site. Manual irrigation was almost never required to supplement parking lot sources of water. Pipes and outlets remained clear of debris and there was no evident damage to vegetation from snow plowing or winter parking lot maintenance activities..

The initial construction and 50 year life cycle costs of the bioretention cell were estimated to be $39,378 and $83,321, respectively. These estimates represent respective capital and life cycle costs of $190 and $402 per square meter, and do not include paving of the asphalt. Costs for the design, construction and materials of the bioretention cell were estimated based on a life cycle costing tool developed by STEP for the Greater Toronto Area (TRCA, 2013b). The life cycle cost includes routine maintenance activities and periodic rehabilitation costs incurred over a 50 year evaluation period. Life cycle costs are expressed as 'net present values', which represents the value of the future stream of costs (i.e. cell maintenance, rehabilitation) discounted to the present value via a 'discount rate', which reflects the investor's time value of money. The discount rate for this example was assumed to be 5%.

Comparisons of the cost of bioretention with that of conventional treatment through an oil grit separator showed comparable construction and life cycle costs, but bioretention was found to be much less expensive when the treatment benefits of the two practices were considered. These cost comparisons were developed as part of a separate STEP project on the life cycle cost of LID practices (Uda et al., 2013). Bioretention and OGS practice costs were determined for the same land use and drainage area, without considering land costs. The initial construction and life cycle costs of bioretention were found to be slightly more expensive. However, when the costs were denominated in terms of the water quality benefits of the practices, the bioretention system construction and life cycle costs were 34 and 39% lower, respectively.

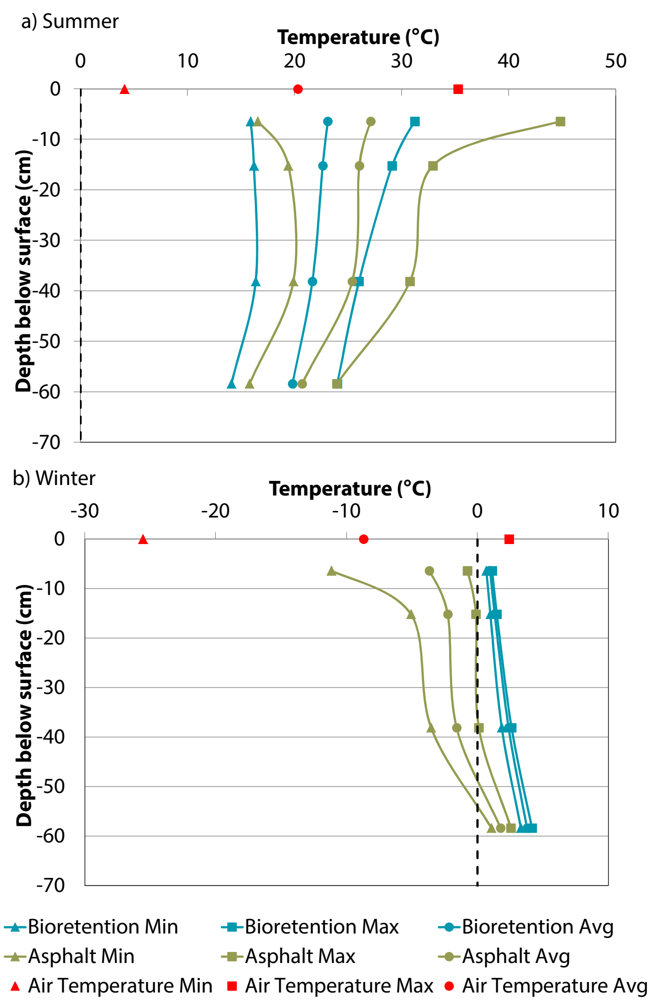


Figure 7. Soil temperature profile summary statistics for a) summer and b) winter periods, as measured at depths of 6.4, 15.2, 38.1 and 58.4 cm below the ground.

RECOMMENDATIONS

This study demonstrated the viability of bioretention as a stormwater practice within the climatic context of the Greater Toronto Area. The following recommendations on bioretention design and further research needs are offered based on the findings from this study.

- The soil filter media is a critical component of bioretention design that controls infiltration rates, surface ponding, water quality performance and long term maintenance needs. In this facility, the correct bioretention media was specified and purchased, but in situ tests revealed the media to have a finer texture than specified, suggesting that it was mixed or supplemented with other native materials and/or contaminated during the construction process. Soil media in bioretention facilities should be tested for grain size and permeability as part of the facility commissioning to ensure that the appropriate soil media has been used and that its properties have not been compromised by construction site runoff. Contracts with soil mixing companies should include clauses that guarantee that the material delivered meets required specifications.

- Despite the presence of a high percentage of silt and clay in the soil media, runoff infiltrated extremely well through the surface, with ponding occurring for less than 20 minutes during most large events. While further investigation is needed, this finding may lend support to reducing the high sand content in the current specification (from 88% to approximately 75 - 80%). The sand was specified to ensure good drainage, but it can also inhibit the establishment of some plant species and necessitate more manual irrigation than may otherwise be required.

- Underdrain outlets should always be raised at least 30 cm above the native soil, even on low permeability soils, to provide the storage and hydraulic head needed to maximize infiltration. Further reductions in discharge volumes and peak flows can be achieved by restricting flow through the underdrain outlet, allowing treated water to discharge slowly over a 72 to 96 hour period.

- The bioretention cell evaluated in this study was surfaced primarily with river stone and some plants and shrubs. Vegetated area soils were shown to have lower soil moisture contents and higher capacities to retain runoff than neighbouring non-vegetated areas. Wherever possible, vegetation should be used in bioretention systems both to improve runoff retention and create the living soil conditions that help trap contaminants and maintain the long term infiltration capacity of the soil media.

- Current TRCA/CVC guidelines on bioretention systems recommend that the drainage area to bioretention facilities should be no more than 15 times the size of the facility footprint to ensure optimal performance over the life of the facility. In this study, the bioretention cell functioned well with a drainage-to-facility area ratio of 13:1 (11:1 for the combined cell and swale), confirming that an area at least this size can be effectively treated without surface soil erosion or pre-mature sediment clogging.

- Gravel diaphragms or sediment forebays are often recommended in bioretention facilities to dissipate energy and provide pre-treatment of runoff. In this facility, runoff was directed across the full length of the cell with vegetation providing a pre-treatment filtering function prior to entering the filter media. The absence of soil erosion and strong growth of vegetation along the cell edges suggest that this method can be a viable alternative to other techniques that may require more space and offer less aesthetic appeal.

FURTHER RESEARCH NEEDS

- Further research on the long-term performance of bioretention facilities is needed to provide better data on the required frequency of maintenance, the interval at which full scale rehabilitation may be needed, and changes in functional performance over time.

- The role of vegetation and associated microbial processes in maintaining infiltration in bioretention facilities is not well understood. Further research is needed to identify the types of vegetation best suited to meeting the stormwater treatment and runoff control functions of bioretention, and how the selected cover types influence long term maintenance.

- The sandy filter media used in bioretention systems is designed to remove contaminants, support healthy plant growth, and allow rapid infiltration of runoff. In areas where plant growth is not a key consideration, however, clear stone filtration systems can be designed to infiltrate water at much higher rates while consuming less land area and providing similar runoff volume reductions. The performance of high flow rate systems from a water quality and overall operation and maintenance point of view requires further assessment in cold climate urban settings.

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For more information on STEP's other LID projects, or to access the full report for this study, entitled Performance Evaluation of a Bioretention System, visit us online at www.sustainabletechnologies.ca

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