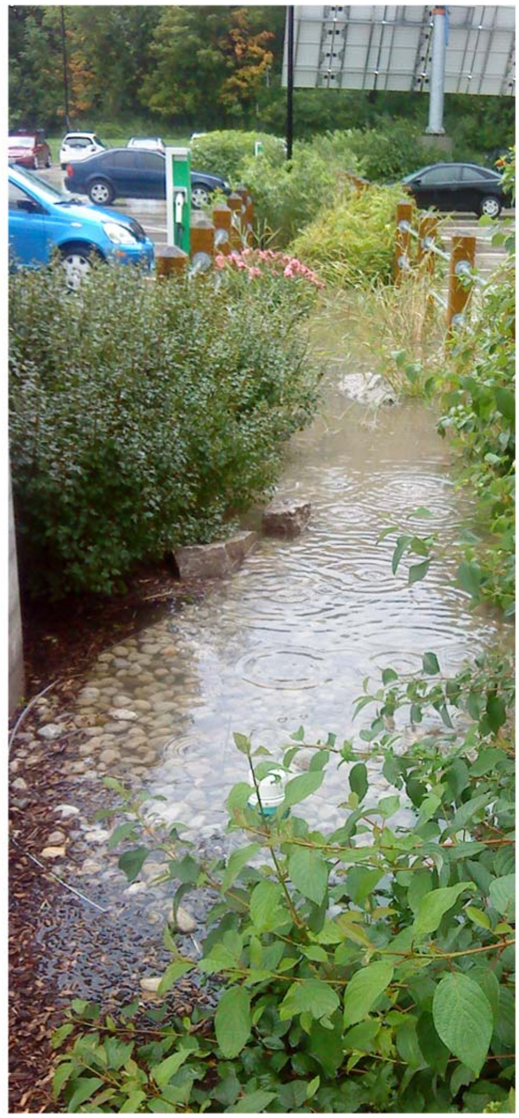
Performance Evaluation of a Bioretention System

Earth Rangers, Vaughan



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PERFORMANCE EVALUATION OF A BIORETENTION SYSTEM
Earth Rangers, Vaughan

Final Report

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Tim Van Seters, MES, B.Sc.
Manager, Sustainable Technologies
Toronto and Region Conservation
Authority 5 Shoreham Drive,
Downsview, Ontario
M3N 1S4

Tel: 289-268-3902

Fax: 416-661-6898

E-mail: TVanSeters@trca.on.ca

THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program, led by the Toronto and Region Conservation Authority (TRCA). The program helps to provide the data and analytical tools necessary to support broader implementation of sustainable technologies and practices within a Canadian context. The main program objectives are to:

- monitor and evaluate clean water, air and energy technologies;
- assess barriers and opportunities to implementing technologies;
- develop tools, guidelines and policies, and
- promote broader use of effective technologies through research, education and advocacy.

Technologies evaluated under STEP are not limited to physical products or devices; they may also include preventative measures, alternative urban site designs, and other innovative practices that help create more sustainable and liveable communities.

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EXECUTIVE SUMMARY

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.

Bioretention is a common LID practice that uses 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. Bioretention systems installed on less permeable native soils may include an underdrain to facilitate drainage. They remove pollutants from runoff through filtration by soil media and uptake by plant roots. Runoff volumes are reduced through evapotranspiration and full or partial infiltration depending on the underlying soil permeability. The practice provides aesthetic benefits and can easily be modified to fit a wide variety of space and drainage contexts, making it one of the more common LID practices for reducing runoff volumes and achieving groundwater recharge targets on development sites.

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 and soil moisture. The study also documents key operation and maintenance requirements.

Study Site

The site for this study is a bioretention facility installed in April 2010 on a new parking lot owned by Earth Rangers at the TRCA's Living City Campus at Kortright in the City of 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. 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 houses various instruments used to measure flow rates, volumes, water quality and water temperature.

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 impermeable interlocking concrete pavement, where it infiltrates into the 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 an outlet to prevent water from backing up onto the parking lot. Native soils in the area consist of silty clay glacial till.

Study 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. Therefore, 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 account for changes in water quality over the course 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.

Study Results

Site observations and monitoring data collected over the two year study period showed that the bioretention system is capable of substantially reducing runoff volumes and improving the quality of stormwater drainage from the parking lot. The main study findings were as follows:

1. *Hydrology:* 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. Runoff reduction levels were similar in cold (December to March) and warm seasons (April to November) despite slower infiltration during the winter.
2. *Surface Ponding and Infiltration:* Throughout the summer, surface ponding occurred only during large or high intensity rain storms, and rarely for more than 20 minutes, indicating rapid infiltration. During winter, ponding was less frequent but lasted longer, 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. In all cases, the parking lot remained free of standing water because the overflow elevation was below that of the pavement surface.

3. *Evapotranspiration:* Evapotranspiration estimates derived from actual measurements over the same period in a well vegetated field less than 1 km from the study site indicated that approximately 8.9 and 9.6% of total runoff inputs were evapotranspired between April and November in 2011 and 2012, respectively.
4. *Water Quality Loads*: On a per unit area basis, the mass of contaminants discharged from the bioretention facility was estimated to be between 65 and 92 percent less than that discharged from the conventional asphalt control.
5. *Water Quality Concentrations*. The concentrations of most constituents in bioretention underdrainage were significantly lower than in asphalt runoff (α=0.05), including total suspended solids, total phosphorus, ammonia nitrogen, total kjeldahl nitrogen, lead, iron, and aluminum. Exceptions included nitrate nitrogen, which was higher in bioretention effluent, as well as copper and zinc, which were not significantly different (α=0.05). The concentration of some constituents in bioretention effluent, such as zinc, copper and phosphorus, exceeded receiving water objectives more than 60% of the time.
6. *Nutrient Concentrations*. Previous studies have often found elevated nutrient concentrations in bioretention effluents. These elevated levels have been attributed to high phosphorus concentration in soils or leaching from organic soil amendments. In this study, phosphorus concentrations exceeded the Provincial receiving water guideline 69% of the time, but were similar to concentrations observed in local receiving waters (median = 0.05 mg/L). Although slightly elevated above asphalt runoff, nitrate nitrogen concentrations were always below the Canadian Environmental Sustainability Indicator for nitrate of 2.93 mg/L.
7. *Soil Moisture*: The moisture content of soils at 2 and 10 cm depths was significantly greater (α=0.05) in the non-vegetated (*i.e.* river stone) than vegetated areas of the bioretention cell. This suggests that bioretention cells without vegetation will have less capacity to reduce runoff through temporary soil moisture storage and evapotranspiration. Rain and runoff from the parking lot maintained soil moisture within the root zone at levels sufficient for plant survival and growth.
8. *Surface Temperature*: Relative to the asphalt pavement, average surface temperatures of the bioretention cell were warmer during the winter and considerably cooler during the summer. In the summer, peak bioretention soil temperatures were just over 25°C, compared to above 40°C on the asphalt. An ice layer formed on the surface of the cell during the winter, but further below the surface, temperatures were approximately 5°C warmer. These results show the benefit of bioretention in reducing urban heat island effects, and creating conditions that allow snow and ice to melt quickly during the spring.
9. *Effluent Temperature*: The reduction in runoff and cooler temperature of bioretention outflows helped to mitigate the thermal impact of urbanization on downstream aquatic communities. The maximum temperature of bioretention underdrain outflows during hot summer periods was just over 20°C, which was over 10°C lower than peak asphalt runoff temperatures during the same events.
10. *Operation and Maintenance*: Vegetation maintenance was conducted as part of the larger landscape maintenance activities at the site. Regular maintenance of the parking lot bioretention and bump-outs accounted for approximately $1500 of the annual budget. Manual irrigation was almost never required to supplement parking lot sources of water. Pipes and outlets remained clear of debris during the first 4 years of operation and there was no evident damage to vegetation from snow plowing and maintenance activities.

Recommendations

This study has demonstrated the viability of bioretention as a stormwater practice under Greater Toronto Area soil and climate conditions. The following recommendations on bioretention design and further research needs are offered based on the results of this study.

<u>Facility Design</u>

- 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.
- Underdrains should always be raised at least 30 cm in the cross section, 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, confirming that an area at least this size can be effectively treated without 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.

<u>Further Research Needs</u>

- 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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1.0 BACKGROUND AND OBJECTIVES

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 (ABL, 2006).

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 uses the natural properties of soils, plants and associated microbial activity to infiltrate water and remove pollutants from stormwater runoff. It typically 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. Bioretention systems installed on less permeable native soils may include an underdrain to facilitate drainage. They remove pollutants from runoff through filtration by soil media and uptake by plant roots. Runoff volumes are reduced through evapotranspiration and full or partial infiltration depending on the underlying soil permeability. The practice provides aesthetic benefits and can easily be modified to fit a wide variety of space and drainage contexts, making it one of the more common LID practices employed for reducing runoff volumes and achieving groundwater recharge targets on development sites.

This study evaluates the performance of a bioretention system that treats runoff from a commercial parking lot at the Earth Rangers facility, on the TRCA's Living City Campus in Vaughan. The specific objectives of the monitoring evaluation were to:

- (i) assess the capacity of the bioretention system to reduce runoff and reproduce the pre-development water balance;
- (ii) assess the quality of water discharged from the underdrain of the bioretention system relative to conventional asphalt runoff;
- (iii) evaluate seasonal changes in functional operational parameters and performance
- (iv) quantify surface and effluent temperatures relative to conventional asphalt
- (v) assess soil moisture conditions and differences between vegetated and non-vegetated areas within the bioretention cell, and
- (vi) identify and document operation and maintenance requirements.

Study results will be used to provide recommendations on design modifications to enhance performance and future monitoring and research needs.

2.0 PREVIOUS STUDIES

There have been a number of research studies and design guidelines on bioretention practices in cold climates, particularly within the last decade. The following sections provide a brief summary of previous literature on the hydrologic and water quality performance of the systems.

2.1 Hydrologic Performance

Nearly all studies on bioretention facilities in cold climates report good year-round infiltration and runoff reduction. In a study of a rain garden in Connecticut, sized to treat a 25 mm storm, a flow mass balance indicated that less than 1% of inflow water overflowed over the two year period of study, despite measurable frost being present in the bioretention media during winter months (Dietz and Clausen, 2006). Findings from studies of the performance of low impact development practices at the University of New Hampshire, including two types of bioretention systems, indicate a high level of functionality during winter months and that frozen filter media has not been a concern (Roseen *et al.*, 2009). Monitoring of a bioswale on a college campus parking lot in King City, Ontario also showed continuous infiltration throughout the winter during snowmelt and rain events (TRCA, 2008). Seasonal variation in infiltration rates through bioretention facilities have been observed, with reduced rates occurring in winter months, but differences between summer and winter are minimal (Emerson and Traver, 2008; Roseen *et al.,* 2009).

The hydrologic performance of four bioretention cells in Minnesota during cold climate conditions was examined by Davidson *et al.* (2008) over a three year period. The authors found that three of the four cells functioned for approximately 84% of the winter season. The fourth cell was constructed with poor draining in-situ soils without underdrains and did not function well even during warm weather. Recommendations for the design of bioretention cells to optimize performance in cold climates were made based on their observations. These included the use of engineered soils that are devoid of silt or clay particles, ponding depths less than 1 foot deep that draw down to the frost line within 12 hours to minimize potential for freezing, and installation of an underdrain system with a valve at the outlet that permits operation of the cell as either an infiltration system or filtration system (Davidson *et al.*, 2008).

Preliminary results from monitoring the performance of a newly installed rain garden in a residential community in North Carolina indicates that they can be effective infiltration practices, even on soils with high clay content (Estes, 2009). The rain gardens were located on sandy clay soil where infiltration rates ranged from 29-38 mm/hr, with an average rate of 33 mm/hr, and were designed to retain and infiltrate the two-year design storm (a 79 mm event). After 4.5 months of monitoring, including 37 storm events of up to 38 mm in size, the average infiltration rate through the facility was 7 mm/hr, with the rate increasing to 25 mm/hr in the underlying native soil, once water levels were past the bottom of the installed soil mixture and filter fabric (Estes, 2009).

Recent studies clearly indicate that bioretention systems can be effective at controlling peak discharge rates and reducing runoff volume, thereby helping to achieve the Low Impact Development objective of maintaining predevelopment hydrology. Typical peak flow reductions of 44 to 64% were observed from two underdrained facilities at the University of Maryland after two years of monitoring, and flow peaks were significantly delayed, usually by a factor of 2 or more (Davis, 2008). Investigations of the hydrologic performance of six underdrained bioretention cells in Maryland and North Carolina indicate that substantial delays in peak flow and decreases in runoff volume can be achieved (Li *et al*., 2009). Annual water budget analysis by Li *et al.* suggests that approximately 20-50% of runoff entering the bioretention cells was either infiltrated into the native soil or lost through evapotranspiration. Some facilities reduced runoff volumes by greater than 90% over the monitoring period, based on median ratios of influent to effluent volume over a 24 hour period (Li *et al.,* 2009).

2.2 Surface Water Quality

Bioretention systems remove pollutants through filtering, soil adsorption, microbial degradation, vegetative uptake and other processes. The soil media, and the surface mulch layer, are very effective in physically filtering TSS and removing oils from infiltrating runoff (Davis and McCuen, 2005). Performance results from both laboratory and field studies are promising and suggest that bioretention systems have the potential to be one of the most effective BMPs for pollutant removal.

In laboratory studies of bioretention system prototypes (Davis *et al.*, 2001) reductions in metal concentrations (lead, zinc and copper) were greater than 90%. Plant uptake accounted for approximately 5% removal by mass. Total Kjeldahl nitrogen (TKN) retention was 68% and ammonia nitrogen retention was 87%. The only nutrient not well retained was nitrate nitrogen which had a retention rate of only 24%.

Several field investigations of bioretention have been performed. In the Ontario study of a bioretention swale cited previously (TRCA, 2008), the effluent from the underdrain at one metre below the swale surface contained significantly lower concentrations of zinc than surface runoff from the asphalt, and other common roadway contaminants such as lead and PAHs were detected much less frequently. In Maryland, synthetic runoff was applied to two different bioretention areas (Davis *et al.*, 2003). Removal of lead, zinc and copper was greater than 95% at one site, with lower removal rates observed at the second site (70% for lead, 64% for zinc and 43% for copper). In New Zealand, Trowsdale and Simcock (2011) reported high removal of zinc, lead and TSS by an undersized bioretention cell draining polluted runoff from a heavily trafficked highway. High retention of metals has also been observed in facilities in New Hampshire (Roseen *et al.*, 2006), where 99% of zinc in runoff was retained, and in North Carolina (Hunt *et al.*, 2006) where retention rates of 81% for lead, 98% for zinc and 99% for copper were observed.

Improvements in parking lot runoff quality were documented by Davis (2007) for two bioretention cells at the University of Maryland. Overall composite median percent removals based on event mean concentrations for the two cells were 83% for lead, 62% for zinc, 57% for copper, 47% for total suspended solids and 76% for total phosphorus (Davis, 2007). Mass contaminant removal rates were higher than concentration based removal rates due to the attenuation of flow volume by the bioretention media. Much higher removal rates for total suspended solids, between 97-99%, have been documented through field tests at the University of New Hampshire Stormwater Center (Roseen *et al*., 2009). The University of Maryland bioretention cell was also effective at removing polycyclic aromatic hydrocarbon (PAH) pollutants from parking lot runoff. Event mean concentration reductions ranging from 31 to 99% were observed, with an average mass load reduction to the receiving waterbody of 87% (Diblasi *et al.,* 2009).

In an evaluation of metal retention and the fate of chloride in bioretention facilities receiving snow melt runoff from different types of urban roads in Norway, it was found that the facilities achieved excellent reductions in mass of metal contaminants from the snow to the outflowing melt water (Muthanna *et al.*, 2007). Mass reductions from 89% (for total copper) to 99% (for total lead) were observed, clearly demonstrating that bioretention can be used successfully to treat snowmelt from urban roads. The top mulch layer was responsible for the most significant metal retention (up to 74% for zinc). Uptake of dissolved metals by plants was estimated to be in the range of 2% to 8% (Muthanna *et al.*, 2007). However, concentrations of bioavailable (dissolved) copper and zinc in outflows from the bioretention cells were higher than in the input snowmelt. Further investigation is needed to determine means of achieving better retention for these contaminants (Muthanna *et al.*, 2007).

In cold climates, the application of de-icing salts (most commonly, sodium chloride) for winter road maintenance has been shown to increase the mobility of dissolved metal ions in the soil (Bäckström *et al.*, 2004). The specific processes responsible for this phenomenon are not well understood, but studies have suggested that high salt concentrations affect metal mobility primarily through ion exchange (Bauske *et al.*, 1993; Löfgren, 2001), the formation of water soluble complexes (Lumsdon *et al.*, 1995), and dispersion and mobilization of colloids (Norrström and Bergstedt, 2001; Norrström, 2005).

Field investigations of nutrient retention have produced more variable results. In a Connecticut study, an increase in total phosphorus was observed after infiltration through bioretention media (Dietz and Clausen, 2006). The export of total phosphorus from bioretention systems has been observed in other studies as well (Hunt *et al.*, 2006; TRCA, 2008). These findings have been attributed to high phosphorus content in the soil (Hunt *et al.*, 2006; TRCA, 2008; Denich, 2009) and leaching of phosphorus from the mulch and organic soil used as the planting media in these systems (TRCA, 2008, Bratieres et al. 2008). This is a significant concern if an underdrain discharges directly to sensitive receiving waters. Erickson *et al.* (2007) found better phosphorous retention at lower infiltration rates and with the addition of steel wool to provide P adsorption sites. Zhang *et al.* (2008) amended sandy bioretention media with 5% fly-ash to improve P removal. At the site evaluated in the present study, media with lower nutrient content (low P index) was selected, which some studies have shown to be a successful approach for reducing nutrient export (*e.g.* Hinman, 2009). Column tests also indicate that the species of plants used can have a significant effect on nutrient removal in bioretention systems (Bratieres *et al*, 2008; Read *et al*, 2008)

With the exception of the Connecticut study (Dietz and Clausen, 2006), nitrate nitrogen retention in bioretention systems has consistently been observed to be low, likely due to low adsorption of negatively charged nitrate ions to soil particles, and it is created through mineralization and nitrification of other forms of nitrogen between infiltration events (Dietz, 2007). There is also evidence to suggest that improvements to nitrogen removal can be achieved by designing facilities so that the bioretention media remains saturated for a significant period, which creates anaerobic conditions that promotes the conversion of NO_3-N to nitrogen gas through a bacterially mediated process called denitrification (Kim et al., 2003; Dietz and Clausen, 2006; Hunt et al., 2006). Vegetation has been shown to improve nitrogen removal in bioretention systems (Read et al, 2008; Lucas and Greenway, 2008).

Few data exists on the ability of bioretention areas to reduce bacteria concentrations, but preliminary results of a laboratory study report an average removal rate of 88% of fecal coliform bacteria in simulated bioretention columns (Rusicano and Obropta, 2005). In the King City study in Ontario, mean concentrations in the bioswale underdrain were only 35 CFU/100 mL, compared to 302 CFU/100 mL in asphalt runoff (TRCA, 2008). Both the mean and median concentrations of bioswale effluent were below the Provincial Water Quality Objective for swimming areas (100 CFU/100 mL). Initial studies of an underdrained bioretention cell treating parking lot runoff in Charlotte, North Carolina show significant reductions in event mean concentrations of fecal coliform and *E. coli*, in the order of 70% (Hunt *et al*., 2008).

Few studies have investigated the effect of bioretention facilities on runoff temperature. In Connecticut, no temperature difference was found between inflow and underdrain flow from a rain garden (Dietz and Clausen, 2005), while a North Carolina study found significant reductions in both maximum and median water temperatures between the inlet and outlet of two bioretention areas (Jones and Hunt, 2009). Of course, reductions in runoff volume that are achieved by bioretention facilities also effectively reduce thermal impacts to receiving waters.

2.3 Groundwater Quality and Soil Quality

There is a paucity of research on the effects of bioretention practices on groundwater quality and soil quality. This is of particular interest in cold climate applications where bioretention facilities may be used for snow storage and receive snow melt containing de-icing salt constituents, which could reduce the retention of some metals (*e.g.*, lead, copper and cadmium) in the soil and potentially increase metal concentrations in shallow groundwater.

Soil cores extracted from three bioretention facilities in the Greater Toronto Area ranging in age between 2 and 5 years showed metal and PAH levels comparable to nearby reference sites unimpacted by runoff (TRCA, 2008). All concentrations were below Ontario background soil concentrations. A repeat survey of one facility after two years showed no change in contamination. Depth profiles showed no consistent variation in contamination with depth (TRCA, 2008).

2.4 Bioretention Cell Maintenance

Particulates and associated contaminants are removed in the mulch and upper soil layers (e.g. Li and Davis, 2009), suggesting that maintenance which includes periodically removing and replacing surficial bioretention soils and mulch, may help to extend the life of bioretention systems. Plants and the biofilm within the media are believed to play important roles in the biodegradation, transformation and retention of some contaminants, but much remains to be learned about the complex interactions between plants, fungi, microbes and media properties (Lucas and Greenway, 2008).

An investigation of fifteen bioretention systems in Australia, ranging in age from 3 to 11 years, showed that maintenance costs for bioretention systems were not greater than other landscaped areas and, based on their current condition, would likely provide effective stormwater treatment for a period significantly longer than 10 to 15 years (Dalrymple, 2012). In Maryland, Ayers (2009) has also documented through a combination of modelling and surveys of existing bioretention systems of the role that biological organisms play in creating a self-maintaining soil eco-system that helps minimize manual maintenance.

3.0 STUDY SITE AND BIORETENTION DESIGN

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 (Figures 3.1 and 3.2). 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 contained monitoring equipment used to measure flow rates, volumes, water quality and water temperature.

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 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. A small forested area north of the parking lot drains to the east portion of the swale, but generates runoff only during the spring freshet and very large rain events in the summer (>35 mm). Drainage from the cell is directed to a vegetated ditch and stormwater pond, which discharges to Marigold Creek, a tributary of the Humber River.

The bioretention area at Earth Rangers was initially designed to comply with guidelines for this practice in the Greater Toronto Area (TRCA and CVC, 2010). However, some changes were made to the original design during construction, including a reduction in the filter media depth from 1 m to 0.6 m and an increase in the thickness of the granular reservoir below the filter media (from 0.2 m to 0.75 m). The ratio of the paved drainage area to the infiltration footprint of the cell is roughly 13 to 1. The east swale portion of the system covers roughly 84 m^2, and a drainage area to swale footprint ratio of just over 8 to 1. The entire paved drainage area is approximately 11 times larger than the combined bioretention cell and east swale. The biorention cell is approximately 1.35 m deep, from the surface to the native soil (Figure 3.2).

The filter media extends approximately 60 cm below the surface, and was specified to be composed of 85 to 88% sand, 8 to 12% soil fines and 3 to 5% organic matter, with a phosphorus index value in the range of 10 to 30 ppm and cation exchange capacity greater than 10 meq/100g. Tests of the media prior to installation indicated the media met this specification, however post installation tests showed the media to have a considerably higher proportion of fines (see section 4.5). Filter media was only placed in the center island portion of the cell. The east portion of the cell was filled with finer textured native soils.[1] The filter media is underlain by a 65 cm clear stone storage area with perforated underdrain raised in the cross section. A non-woven geotextile is used to separate the bioretention materials from the surrounding native soils. Although not specified in the original design, filter fabric was also added to the surface below the river stone as a weed barrier, and as a separation layer between the filter media and clean stone storage reservoir (Figure 3.2).

[1] This appears to have been the result of a misunderstanding by the contractor.

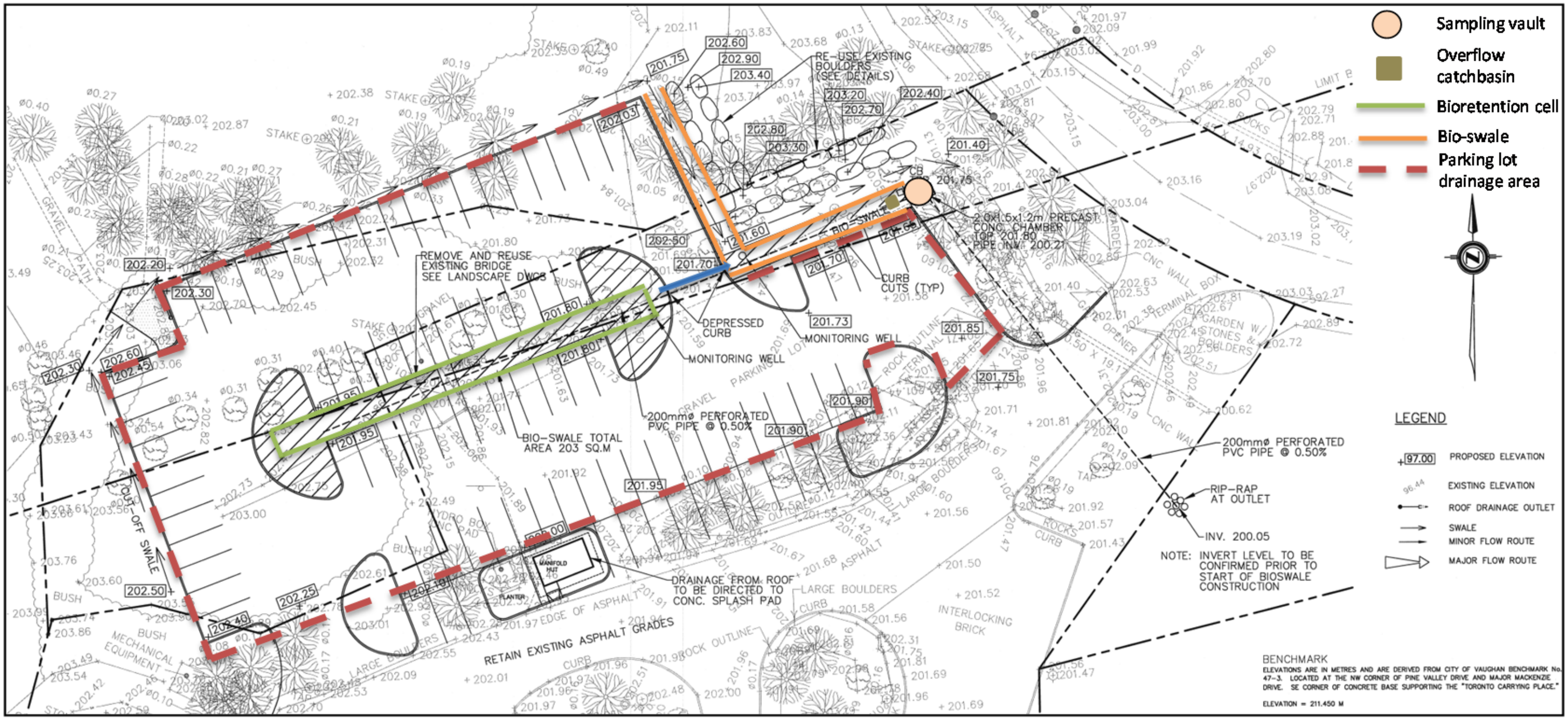

Figure 3.1: Study site showing parking lot drainage area, bioretention cell, bioswale, overflow catchbasin and sampling vault. Photos of the site are provided in Appendix A.

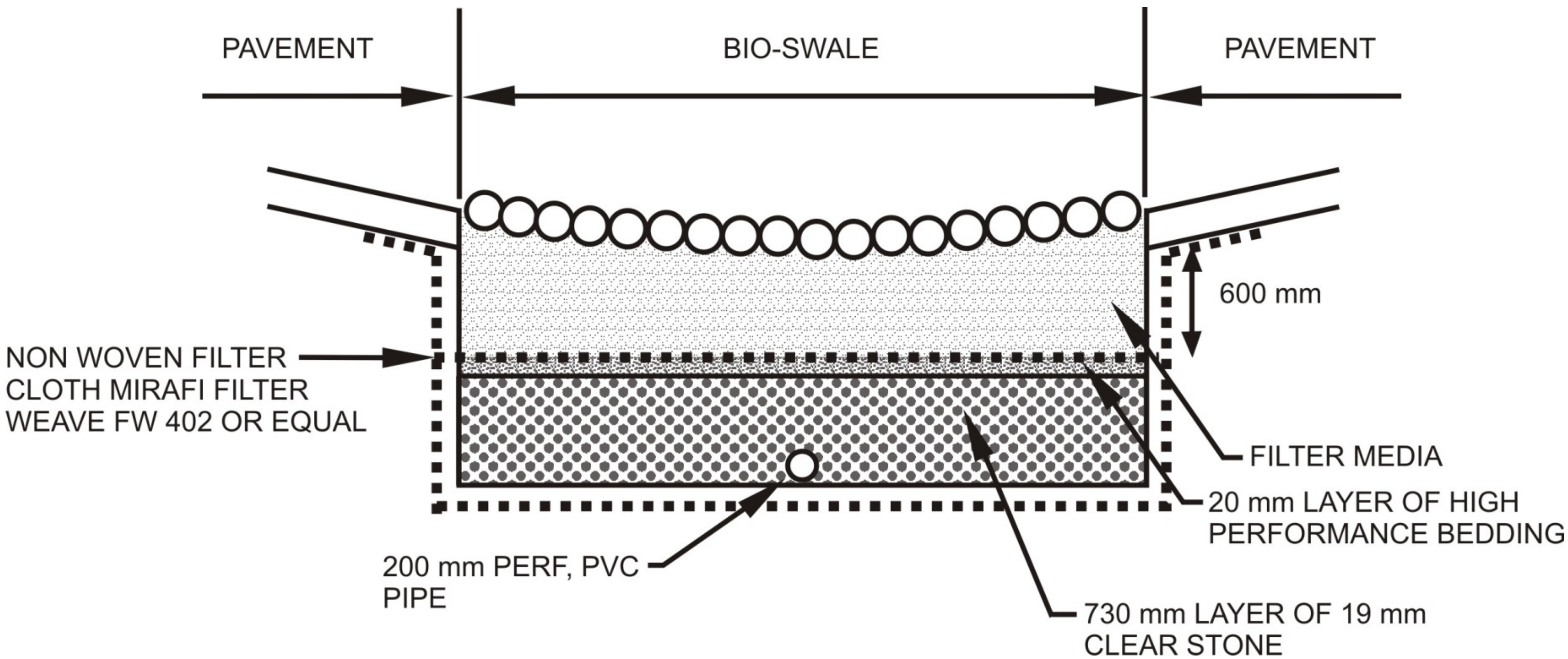

Figure 3.2: Cross section of the bioretention cell. The cell surface includes a combination of bioretention plants and river stone. Bump-outs are fully vegetated.

4.0 STUDY METHODS

4.1 Precipitation

Rainfall was measured on site with a tipping bucket rain gauge and manual rain gauge. Snowfall data were measured with a snow gauge at Albion Hills, approximately 30 km from the site. A meteorological station at the TRCA's Restoration Services Centre, roughly 2 km from the site was used as a secondary source of rain data.

4.2 Flow and Drainage

Both surface overflows and underdrainage were separately conveyed to a sampling vault, where a tipping bucket flow meter and automated sampler were installed to monitor underdrain flows and water quality. The tipping bucket flow gauge was calibrated prior to installation and midway through the study. The rate of flow through the underdrain was restricted by an adjustable ball valve in the sampling vault. The valve opening was set to promote infiltration by detaining water in the cell for a period of no more than 48 hours.

Inflow volumes (Q_i) were estimated based on measured precipitation depths and the catchment area, assuming an initial abstraction of 3 mm over the parking lot area, as follows

$$Q_i = ((P - I_a) \times A_P) + (P \times A_B) \quad \text{...equation 4.1}$$

where,

P = depth of precipitation (m)
I_a = initial abstraction (0.03 m)
A_P = Parking lot drainage area (2272 m^2)
A_B = Area of the bioretention cell and east swale (not including vegetated bumpouts) (207 m^2)

Events with less than 3 mm of rainfall were assumed to have generated no runoff. The well vegetated bumpouts did not receive drainage from the parking lot and were therefore assumed to produce negligible runoff.

The frequency and duration of surface overflows was measured using water level sensors at the surface of the cell and in the overflow catchbasin. Overflows occurred only when surface water levels rose above 25 cm, which caused a corresponding increase in overflow catchbasin water levels. Therefore, the volume of overflows (Q_o) was estimated as follows:

$$Q_o = P_o * A_E \quad \text{...equation 4.2}$$

where,
P_o = depth of precipitation (m) that fell when surface levels were greater than 25 cm

A_E = area draining to the east portion of the cell, plus the swale area itself (771 m^2)

Runoff draining to the center portion of the bioretention cell could overflow to the east portion of the cell, but only when the surface ponding area of the cell was full. Since this occurred only very rarely, if ever, event flow volumes entering the center cell were not included in the overflow calculation.

The volume of runoff reduced (Q_r) was estimated from total inflows and outflows as follows:

$$Q_r = \frac{Q_i - (Q_u + Q_o)}{Q_i} \quad \text{.......equation 4.3}$$

where,
Q_i = inflow runoff volumes (see equation 4.1)
Q_u = underdrain outflow volumes
Q_o = estimated overflow outflow volumes

Infiltration measurements on the surface of the cell were measured using a double ring infiltrometer and Guelph permeameter. These were used to characterize the infiltration capacity of the soils. Water level ponding on the cell surface at two locations was measured continuously at 10 minute recording intervals using a pressure transducer. These data were used to determine the frequency and duration of ponding during events of different intensities and assess whether the design objective for surface water ponding duration (max ≤ 24 hours) was being achieved.

Water levels in the lower stone filled reservoir were also measured continuously at 10 minute recording intervals with a pressure transducer. The time between the initiation of runoff and the rise in water level represents the time it takes for runoff to drain through the storage medium. Drawdown of the water level after underdrain flows have ceased also provides an indication of how quickly water is infiltrating into the native soils.

4.3 Moisture Content

The moisture content of soils was measured manually with a moisture probe at 20 locations throughout the bioswale both in planted and unplanted areas. The measurements were taken each day before and after rain events from June 23 to July 6, 2011 and from August 23, to September 28, 2011 to assess the variability in moisture content across the cell and the effect of plants on moisture availability. The probe was inserted at two depths (2 and 10 cm) below the surface to assess differences in moisture content at the surface (n=10) and within the plant root zone (n=10). The health of the vegetation was documented over the course of the study based on visual inspection. The cell was not irrigated over the monitoring period.

4.4 Water Quality

The quality of underdrain flows was measured using an automated sampler and flow meter in the vault at the downstream end of the facility. Runoff quantity and quality were measured over the same period at an asphalt parking lot roughly 300 meters away to provide an estimate of the quality of inflows to the bioretention facility.[2] The asphalt parking lot experienced similar traffic levels and would have been subject to similar contaminant sources from the surrounding area.

Water quality samples at both locations were proportioned according to flow volumes by measuring out a volume of water from each discrete sample bottle proportional to the volume of flow since the previous sample. The resulting flow volume proportioned composite samples for each event were subsequently prepared and delivered to the Ontario Ministry of the Environment (OMOE) laboratory in Etobicoke for analysis following OMOE lab preparation and submission protocols. The major variable groups analyzed are listed in Table 4.1. The list of variables was selected based on typical stormwater runoff contaminants in runoff from parking lots and roads.

Table 4.1: Water quality parameters

Parameter	
Solids and floatables	**General Chemistry**
Suspended solids	pH
Dissolve solids	Conductivity
Total solids	Alkalinity
Extractable solvents	Hardness
	Chloride
Nutrients	**Pathogens**
Ammonia + ammonium nitrogen	Escherichia coli
Nitrite nitrogen	Fecal streptococcus
Nitrite + nitrate nitrogen	Pseudomonas aeruginosa
Total kjeldahl nitrogen	
Phosphate phosphorus	
Total phosphorus	
Metals	
Aluminum	Molybdenum
Barium	Nickel
Beryllium	Lead
Calcium	Potassium
Cobalt	Sodium
Chromium	Strontium
Copper	Titanium
Iron	Vanadium
Magnesium	Zinc
Manganese	

The percentage of sample concentrations exceeding applicable receiving water quality guidelines were calculated for each variable. Descriptive statistics for all water quality variables were calculated for asphalt runoff and bioretention outflows. The percentage of concentrations below laboratory detection

[2] The asphalt flows and quality were conducted as part of a separate ongoing project evaluating the effectiveness of permeable pavements (TRCA, 2012).

limits was reported, and non-detect values were set at half the detection limit for statistical analysis. Normal and lognormal distributions of data were determined using goodness-of-fit statistics. Statistically significant differences in mean, geomean or median concentrations of selected variables with non-detect values less than or equal to 15% were evaluated using unpaired sample t tests for normal and log normal transformed data and the Mann Whitney U test for all other non-normal data. Most water quality variables that were selected for statistical analysis were detected in more than 85% of samples, and were associated with receiving water thresholds established by the Ontario Ministry of the Environment or Environment Canada.

Water quality improvements occurred primarily through the reduction in runoff volumes via infiltration and evapotranspiration. Pollutant loads (BL_i) entering the bioretention system over the monitoring period for each variable were estimated based on inflow volumes (Q_i – see equation 4.1 above) and the median event mean concentration (EMC) of asphalt runoff over the same period ($AEMC_{median}$):

$BL_i = Q_i * AEMC_{median}$ ……………………………………………………………………equation 4.4

This assumes that median asphalt EMCs were similar to EMCs of bioretention parking lot runoff, which is reasonable given the proximity of the two parking lots, and similarity in traffic volumes and pollutant sources.

Pollutant loads (BL_O) exiting the bioretention system over the monitoring period were estimated as:

$BL_O = (Q_u * BEMC_{median}) + (Q_o * AEMC_{median})$ ……………………………………………equation 4.5

where,
Q_u = total measured volume of underdrain outflows over the monitoring period
$BEMC_{median}$ = median event mean concentration of bioretention outflow concentrations for a given variable
Q_o = total volume of overflows over the monitoring period (see equation 4.2 above)

This calculation conservatively assumes that the quality of overflows was similar to untreated runoff from the asphalt surface.

The efficiency with which the mass of pollutants were removed by the bioretention system over the monitoring period (RE_{loads}) was estimated for each water quality variable as follows:

$RE_{loads} = \frac{BL_i - BL_o}{BL_i}$ ……………………………………………………………………equation 4.6

4.5 Filter Media

The bioretention filter media was tested prior to installation at a University of Guelph laboratory to determine whether it met the grain size and chemical specifications outlined in the design guidelines. The grain size and organic matter content tests were repeated on 4 cores taken from the cell after installation. Results presented in Table 4.2 show that the media tested prior to installation closely matched the target outlined in the TRCA/CVC LID guide (2010). However, in-situ soils contained considerably more fines, presumably due to contamination during the process of constructing the facility. Although the fines content is well above recommended values, surface ponding occurred only during large events and drained quickly (see chapter 5).

The pH and organic matter content of the pre and post installation soils generally met the guideline. The phosphorus content of 39 to 62 mg/ L of dry soil exceeded the recommended range of 10 to 30 ppm. The feasibility and practicality of the current phosphorus guideline for bioretention media is currently under review and may be raised in a future update of the guide.

Table 4.2: Bioretention media soil texture and organic matter test results

Soil texture	Size class	Sample prior to installation	*In-situ* samples post installation	Guideline (TRCA/CVC, 2010)
		Percentage	Percentage	
Gravel	> 4760 µm	0.6	0	
Sand	74 - 4760 µm	92.7	9.1	85-88%
Coarse	2000 – 4760 µm	2.0		-
Medium	420 – 2000 µm	37.2		-
Fine	74 – 420 µm	53.4		-
Silt	5 – 74 µm	4.4	55.6	8 - 12% silt/clay
Clay	1 – 5 µm	1.0	35.3	
Colloids	< 1 µm	0.6		-
Organic Matter		3.7%	2 – 5%	3 – 5%
pH		7.5	7.5	5.5 – 7.5

Notes: Pre and post soil analysis was conducted by the University of Guelph (n = 1) and the Ontario Ministry of the Environment (n = 5), respectively.

4.6 Soil and Water Temperature

A vertical profile of temperature sensors was installed at the surface of the cell to assess frost penetration depths and the benefit of bioretention in mitigating heat island effects. A similar temperature profile installed on a nearby asphalt pavement at the Kortright Centre was used for comparison.

The temperatures of effluents from the asphalt and bioretention system were also measured continuously during the final year of the study from May to September. These data were analyzed on an event basis during periods of active discharge.

5.0 RESULTS AND DISCUSSION

The bioretention system was monitored continuously from January 2011 to December 2012. A total of 237 events greater than 0.3 mm occurred over this period. The distribution of monitored events greater than 5 mm is shown in Figure 5.1. The following sections summarize data on runoff, infiltration, soil moisture, and water quality collected over this period.

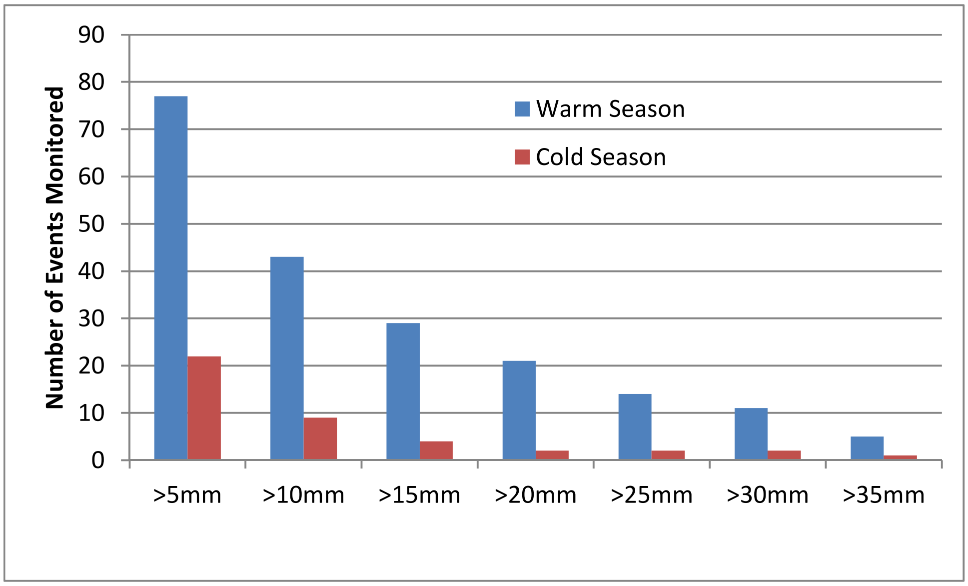

Figure 5.1: Distribution of precipitation events monitored during the warm (April to November) and cold (December to March) seasons.

5.1 Hydrologic Performance During the Warm Season (April to November)

Table 5.1 summarizes the hydrologic performance of the bioretention cell system during warm weather. The summary includes rainfall, estimated runoff volumes, surface ponding durations and outflows from the cell both as underdrain flows, and as surface overflows during larger rain events. Runoff reduction values are assessed based on the volume of runoff and outflows (the sum of underdrain flows and overflows). Results for individual precipitation events are provided in Appendix B.

Table 5.1: Hydrologic summary for rain events from April to November 2011 and 2012 (n= 169)

Parameter	Rainfall Depth (mm)	Parking Lot Runoff (m^3)	Surface Ponding Duration (hrs)	Underdrain Flow (m^3)	Overflow (m^3)	Runoff Reduction (%)
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

5.1.1 Surface Ponding and Infiltration

Bioretention systems are designed with surface storage where water can pond for up to 12 hours after large rain events. At the Earth Rangers site, surface ponding occurred 7 and 10 times from April to November in 2011 and 2012, respectively. Ponding usually occurred for less than 20 minutes. However, during the largest event (78 mm) water remained on the surface for 2.2 hours (Table 5.1). The relatively short duration of surface ponding indicate that water was infiltrating through the cell media at much more rapid rates than would be anticipated based on the texture of the soil media, which had a clay content of just over 30% (see section 4.5 above).

Surface infiltration rate tests using the Guelph permeameter did not provide a reliable indication of actual surface infiltration rates. Three permeameter tests at five different locations in the center cell indicated infiltration rates to be between 0.4 and 4.1 mm/h. Double ring infiltrometer tests produced similar results. Discontinuities within the soil matrix yielded in-determinate results during four other tests. As noted previously, drawdown of surface water levels up to 200 mm following storm events occurred over a period of less than 60 minutes, indicating that actual infiltration rates were much greater than measured during the tests. The surface was carefully examined for possible areas where infiltration may be more rapid, but none were found. The cause of differences between the rate of infiltration during the tests and during actual rain events requires further investigation.

5.1.2 Runoff Attenuation

Outflows from the system through the underdrain and surface overflow outlet occurred relatively infrequently during large or intense rain events. Total runoff draining into the cell over the study period was reduced by 91%, ranging from 65% to 100% during individual rain events. These runoff reduction rates are much higher than expected given the low permeability silty clay native soils underlying the facility. Rapid water level drawdown after rain events in the gravel trench at the base of the cell suggests that there may have been preferential drainage to a lens of gravel or sand below the base of the facility.

The total volume of underdrain and surface overflow volumes represented approximately 0.4 and 9 percent of total estimated inflow volumes over the study period, respectively. Low outflows from the perforated underdrain may be explained in part to the location of the perforated pipe roughly 15 cm above the native soil, which created an active storage area below the pipe for infiltration. This storage area was even greater in the first few months of the study when an upturned pipe was installed in the monitoring vault, forcing water levels in the lower storage reservoir to rise to 35 cm above the native soil before outflows were generated. On May 14th, the upturned pipe was removed to increase outflows and allow the sampling objectives of the study to be met. Had this not been done, flows from the underdrain would have been negligible.

Overflows occurred almost entirely in the east portion of the cell, which received direct flows from approximately one quarter of the total drainage area. As mentioned earlier, the less permeable, silty clay native soil was backfilled into this portion of the bioretention facility, resulting in more frequent surface ponding and overflows. The center portion of the cell, with more permeable media, rarely if ever generated sufficient surface ponding volumes to cause overflows. Use of a similar bioretention media in the east portion of the cell would have significantly reduced the volume of overflows, and allowed for a greater proportion of the runoff to be treated through infiltration.

5.1.3 Water balance

Figure 5.2 shows how runoff inputs to the bioretention cell over the growing season (April to November) were divided among evapotranspiration, infiltration and outflow. Evapotranspiration estimates were derived from actual measurements over the same period in a well vegetated field less than 1 km from the study site (see Delidjakova et al, 2014 for methods). The water balance analysis showed that evapotranspiration accounted for 8.9 and 9.6% of total runoff inputs in 2011 and 2012, respectively. A similar volume of water was discharged from the facility. Most of the runoff entering the facility infiltrated into the native soils.

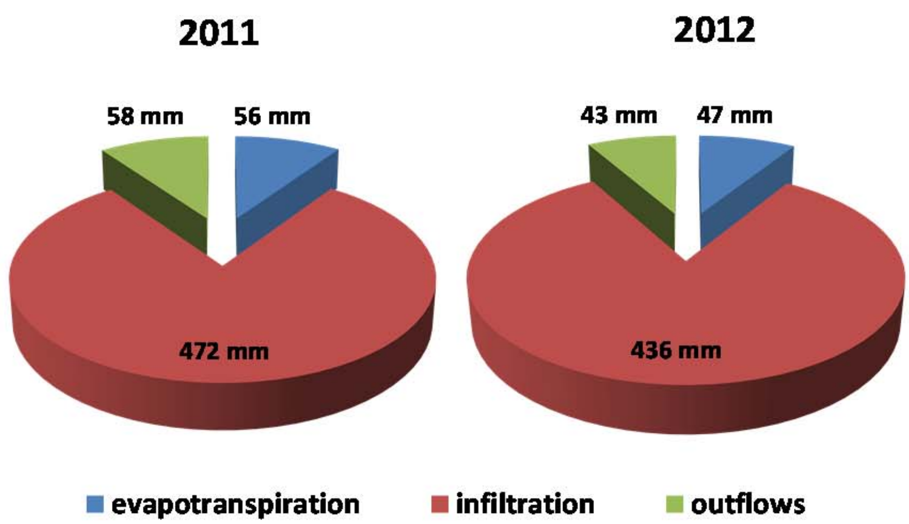

Figure 5.2: The proportion of runoff entering the bioretention system that infiltrated, evapotranspired, or was discharged to receiving waters from April to November in 2011 and 2012.

5.1.4 Sample Warm Season Events

Figures 5.3a and 5.3b shows the hydrologic response of the cell to two large summer rain events of different intensities. Similar graphs for other summer events are provided in Appendix C.

The event on November 28, 2011 generated 48 mm over 27 hours. The first 8 mm of rain over 7 hours did not generate a water level or flow response as runoff was absorbed by the bioretention soils. Once the soils were saturated, runoff drained through to the gravel reservoir at the base of the cell. As the reservoir filled, the perforated underdrain started to flow. Water accumulated in the surface wells as rainfall intensity increased, but water levels did not rise above the surface. There was a 35 to 55 minute delay between each of the rainfall, surface water level and subsurface water level peaks. As expected, the timing of underdrain flow peaks corresponded closely to those of subsurface water levels. Surface overflows from the eastern portion of the cell (not shown) occurred over a 5 hour period generating approximately 4 m^3 of water. Ninety five percent of all runoff during the event either infiltrated or was absorbed by the bioretention soils.

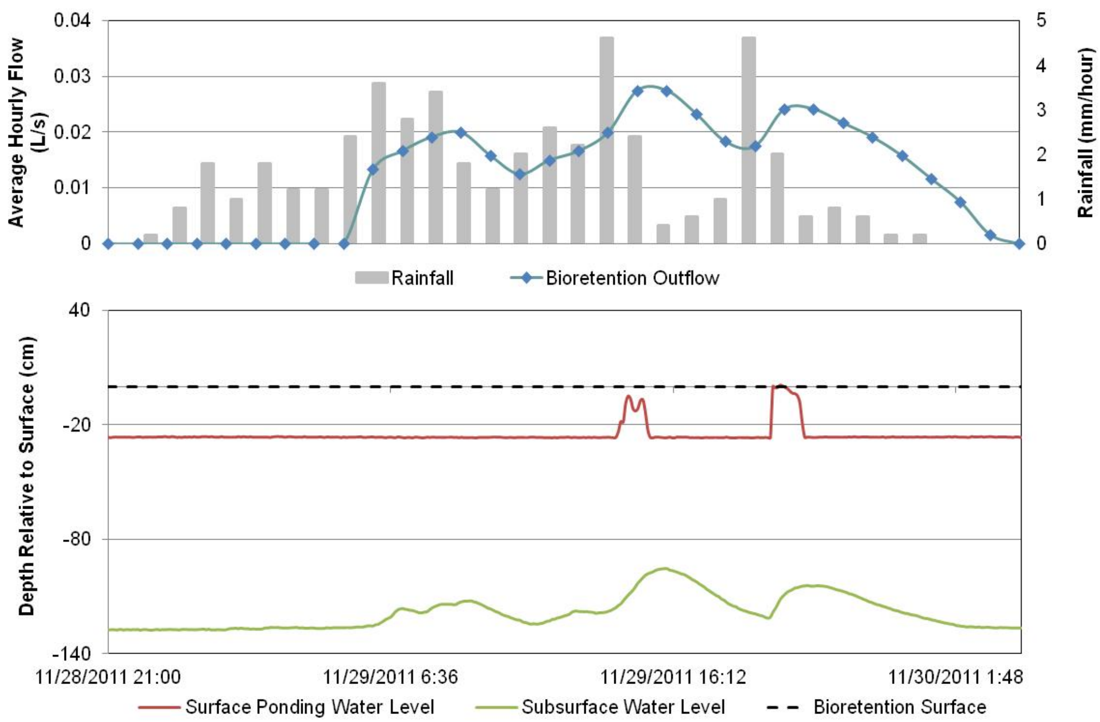

Figure 5.3a: Runoff and water levels during a 48 mm rain event on November 28, 2011. Note that ponding depths below the surface (dashed line) represent water level changes in the monitoring well embedded approximately 22 cm into the surface soils.

During the event on September 4, 2012 (Figure 5.3b) a total of 43 mm fell over 11 hours, and the maximum hourly rainfall was 30 mm. As in the previous event, the first 6.8 mm of rainfall runoff was absorbed by the soils. Surface ponding occurred when the intensity of rainfall increased (6.4 mm fell over 5 minutes). Outflows started between 10 and 15 minutes later. Surface ponding lasted approximately 50 minutes (longer in the eastern portion of the cell) and produced an estimated 23 m^3 of overflow. 77 percent of runoff was infiltrated or absorbed by soils during this event.

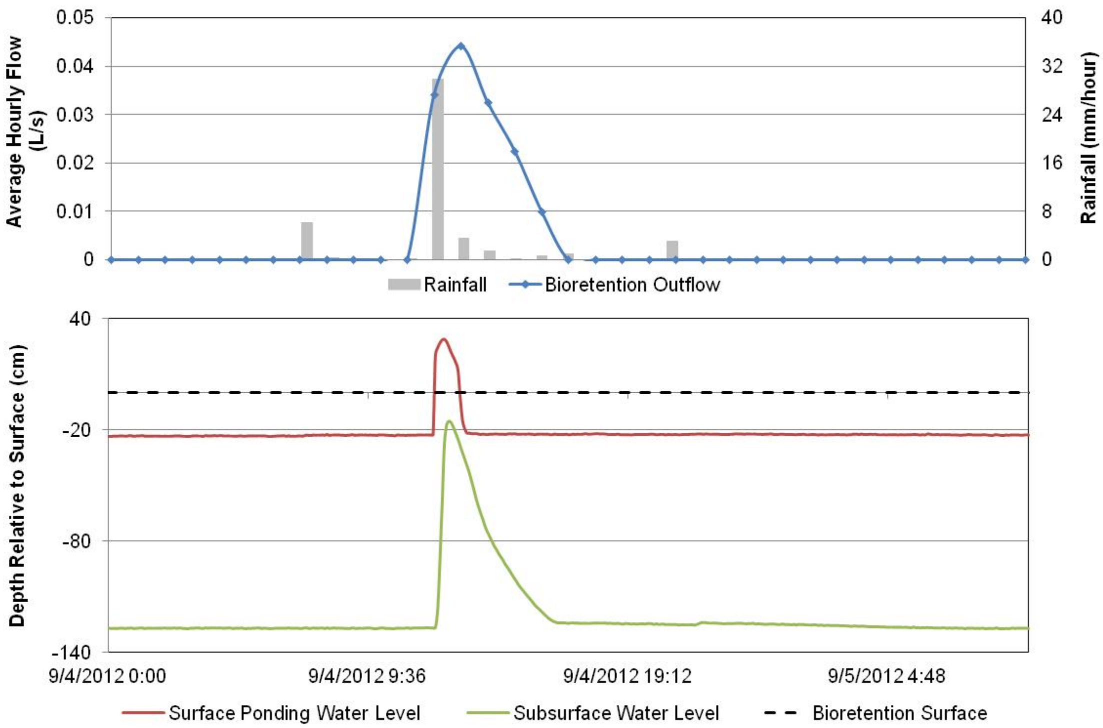

Figure 5.3b: Hydrologic response to a 43 mm rain event on September 4, 2012. Note that ponding depths below the surface (dashed line) represent water level changes in the monitoring well embedded approximately 22 cm into the surface soils.

Figure 5.4: Surface water ponding following a 5 mm high intensity rainfall event on August 15, 2012. The ponded water infiltrated within 20 minutes.

5.2 Hydrologic Performance During the Cold Season (December to March)

Table 5.2 summarizes the hydrologic performance of the bioretention cell system during cold weather. The Table shows precipitation, runoff volumes, the duration of surface ponding and outflows from the cell both as underdrain flows, and as surface overflows during rain and snow melt events. Runoff reduction rates are assessed based on the volume of parking lot runoff and outflows. Performance summaries for individual winter events are provided in Appendix B.

Table 5.2: Hydrologic summary for runoff events from January to March 2011, and December to March, 2012 (n= 63)

Parameter	Rainfall Depth (mm)	Parking Lot Runoff (m^3)	Surface Ponding Duration (hrs)	Underdrain Flow (m^3)	Overflow (m^3)	Runoff Reduction (%)
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	23.0	96

5.2.1 Surface Ponding and Infiltration

During the winter, rain events resulted in longer ponding times due to a thin layer of ice at the surface (Table 5.2). Although infrequent, surface ponding during the winter occurred for up to 38 hours. The occasional presence of water on the bioretention cell surface during the winter did not interfere with normal operation of the parking lot because overflow grates were located below the elevation of the pavement surface.

5.2.2 Runoff Attenuation

Snow was plowed into piles surrounding the parking lot and adjacent to the bioretention cell. When temperatures rose above zero, some of this snow melted, and combined with rain to generate significant runoff volumes. During most of the winter, however, runoff entered the cell slowly over long time periods, allowing water to infiltrate through the media and into the native soils. This pattern of precipitation and runoff resulted in less ponding of water, and fewer overflows than were observed during the summer. Underdrain flow and overflow volumes represented approximately 0.1 and 4.2% of inflow volumes, respectively. Overall cold season runoff was reduced by 96%.

5.2.3 Sample Cold Season Events

Two winter events are presented in Figures 5.5a and 5.5b. The winter event on March 9, 2011 produced 49.4 mm of rain over two days. Snow piles adjacent to the bioretention cell generated additional runoff in the form of melt water. During this event, surface ponding of rain and melted snow occurred for approximately 38 hours. The initial precipitation recorded by the gauge was probably a combination of rain and wet snow that was partially absorbed within the swale, and therefore did not produce any change in surface or subsurface water levels. As temperatures rose further during the day, snow melt increased resulting in some ponding on the surface. As mentioned previously, the initial jump in surface water levels represents water filling the 30 cm deep well containing the sensor, which is embedded into the surface of the bioretention cell. Subsurface water levels below the perforated underdrain indicate that infiltration was occurring throughout the event, but with a delay. Observations revealed that infiltration through the filter media was inhibited initially by a layer of ice near the surface.

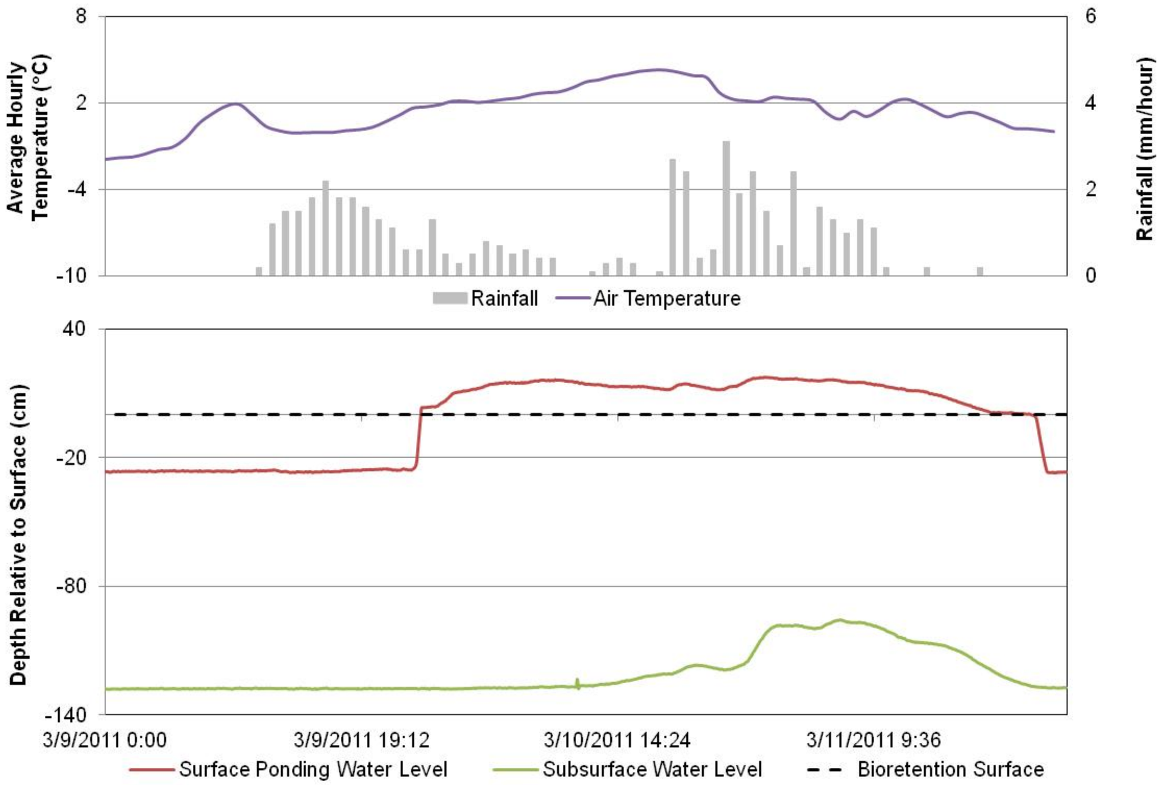

Figure 5.5a: Rainfall, air temperatures and water levels in the bioretention cell during a rain and snowmelt event on March 9, 2011. There was no outflow during this event, in part because the outlet to the monitoring vault was raised 20 cm higher than during the period after May 14, 2011, which created a large sump for storage and infiltration.

During a winter rain and snowmelt event on January 23, 2012, air temperatures increased, followed by 6.5 mm of rain. Surface water levels rose rapidly, and receded much more slowly than during the summer because of the presence of ice on the surface. Outflows from the underdrain during the first part of the event represented only 1.4% of the rainfall runoff volume generated from the parking lot (snowmelt volumes of were not measured). All of the flow was generated during the first few hours of the event when water was ponded on the surface. Unlike the previous event, subsurface water levels increased only slightly, and these occurred nearer to the beginning of the event.

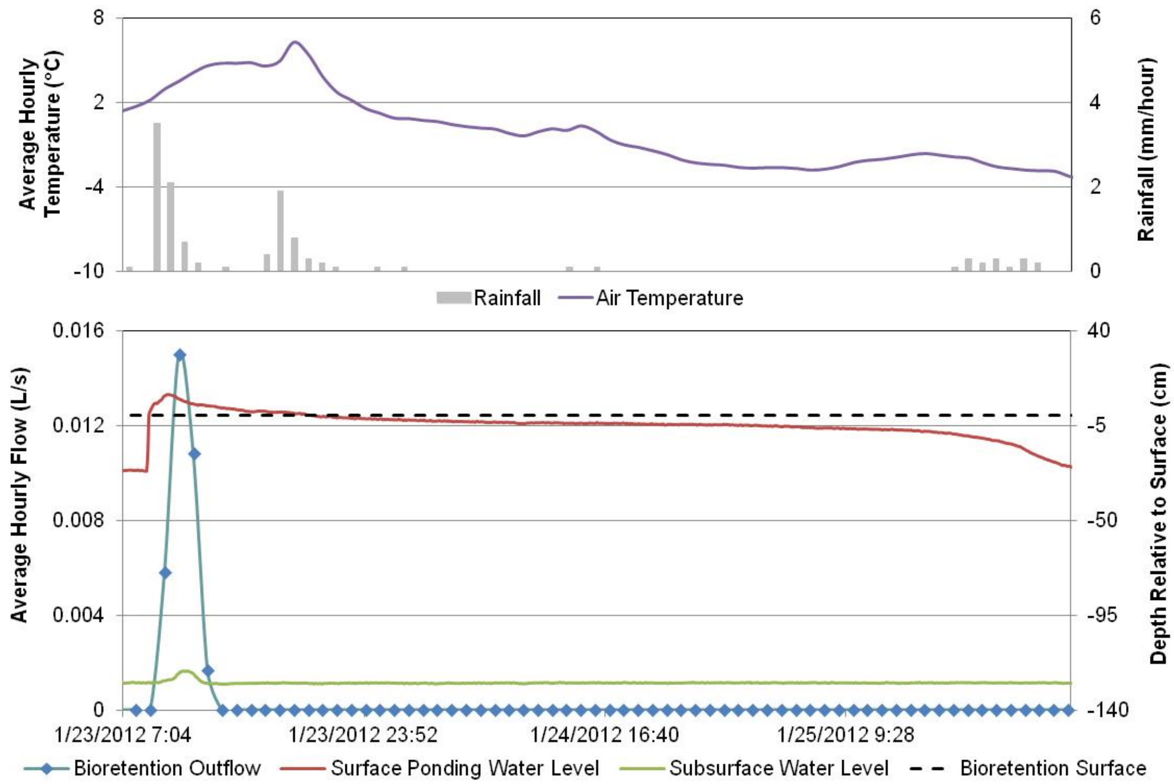

Figure 5.5b: Rainfall, air temperatures and water levels during a rain and snowmelt event on January, 23, 2012.

Figure 5.6: Ponding during winter snowmelt and rain events on February 28 and March 9, 2011. Ponded water remained on the surface during these events over a period of 15 and 38 hours, respectively.

5.3 Water Quality

Twenty six flow volume proportioned water quality samples of underdrain outflows were collected between June 4, 2011 and October 30, 2012. Flow volume proportioned samples of runoff (n = 41) from a nearby conventional asphalt surface were collected over the same period for comparative purposes. The asphalt and bioretention parking lots had similar traffic levels and sources of contamination as the parking. Surface overflows were not sampled as these were assumed to have undergone no treatment. Tables 5.3a and b present summary statistics for key variables and comparisons to receiving water quality guidelines. Figures 5.7a and 5.7b show box plots for selected variables, including total suspended solids, general chemistry, nutrients and metals.

Underdrain outflows had significantly ($\alpha \leq 0.05$) lower concentrations of several variables relative to asphalt runoff, including total suspended solids, total phosphorus and phosphate, ammonia nitrogen (NH_3 + NH_4), total kjeldahl nitrogen, aluminum, iron, manganese and lead. 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. Other studies (e.g. Read et al, 2008; Lucas and Greenway, 2008) have shown that increasing the amount of vegetation can help to remove nitrate nitrogen. Phosphorus concentrations from the bioretention system were similar to levels observed in area streams (TRCA, 2013), despite exceeding the provincial guideline 69% of the time.

Copper and zinc concentrations were not significantly different in asphalt and bioretention underdrainage. Outflow concentrations of some metals, such as nickel, chromium, molybdenum and beryllium were never above guideline thresholds for these variables. *E.coli* and fecal streptococcus densities varied substantially during individual events but were generally higher than asphalt runoff, and *E.coli* exceeded the 100 CFU/100 mL threshold for recreational uses 44% 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). On a per unit area basis, contaminant loading to receiving waters from the bioretention system was much lower than the asphalt surface, largely because more than 90% of runoff from the parking lot was reduced through infiltration and evapotranspiration. Even for variables where bioretention concentrations were higher, such as *E coli*, loads to receiving waters were over 85% lower.

Table 5.3a: Water quality summary statistics – nutrients and general chemistry

				Asphalt Runoff								Bioretention Effluent										
Variable	**Units**	**MDL**	**GL**	**%>dl**	**N**	**Min**	**Max**	**Mean**	**Median**	**St. Dev.**	**%>GL**	**%>dl**	**N**	**Min**	**Max**	**Mean**	**Median**	**St. Dev.**	**%>GL**	**Median Conc. % Diff.**	**Pollutant Load % Diff.**	**Conc Diff. α ≤ 0.05**
Solids; suspended	mg/L	2.5	30	100	41	12.9	232	68.5	54.1	55.2	73	100	26	6.3	42.4	18.4	16.2	10.9	15	70.1	92.0	As > Bio
Soilds; total	mg/L	50		100	41	53.0	68600	3318	173	11903	--	100	26	251	440	358	373	58	--	-115	91.4	--
Solids; dissolved	mg/L	50		73	41	25.0	68500	3244	98	11896	--	100	26	240	424	340	352	53	--	-259	90.9	--
Conductivity	uS/cm	5		100	41	47.0	96200	4862	144	17119	--	100	26	370	4970	695	549	876	--	-281	90.8	--
pH	none		6.5-9.5	100	41	7.3	7.9	7.7	7.7	0.2	0	100	26	7.79	8.6	8.1	8.1	0.2	0	--	--	As < Bio
Alkalinity	mg/L $CaCO_3$	2.5		100	41	17.4	255.0	48.0	35.8	39.1	--	100	26	60.6	259.0	187.4	191.0	50.7	--	--	--	--
Nitrogen; NH_3+NH_4	mg/L	0.01	1.4	100	41	0.06	3.90	0.55	0.34	0.68	7	92	26	0.005	0.75	0.07	0.03	0.14	0	90.4	92.1	As > Bio
Nitrogen; nitrite	mg/L	0.005	0.06	100	41	0.01	0.28	0.06	0.04	0.06	34	73	26	0.003	0.16	0.02	0.01	0.03	4	79.5	92.0	--
Nitrogen; NO_2+NO_3	mg/L	0.025		100	41	0.1	3.1	0.7	0.5	0.6	--	100	26	0.384	2.3	1.3	1.3	0.5	--	-158	91.2	As < Bio
Phosphorus; PO_4	mg/L	0.003		98	41	0.001	1.03	0.09	0.03	0.21	--	100	26	0.006	0.07	0.02	0.02	0.01	--	47.2	91.9	As > Bio
Phosphorus; total	mg/L	0.01	0.03	100	40	0.1	1.4	0.3	0.2	0.3	100	85	26	0.005	0.11	0.04	0.05	0.03	69	73.9	92.0	As > Bio
Nitrogen; TKN	mg/L	0.1	3.2	100	40	0.4	9.7	1.7	1.3	1.6	10	96	26	0.05	1.2	0.6	0.6	0.3	0	54.3	91.9	As > Bio
Escherichia coli	c/100 mL		100	100	27	4.0	600	57	4	144	11	100	18	4	3400	397	70	803	44	-1650	86.4	--
Fecal streptococcus	c/100 mL			100	27	12.0	2900	851	440	869	--	100	18	190	15000	3046	2150	3722	--	-389	90.5	--
Calcium	mg/L	0.01		100	41	8.2	167.0	35.5	17.6	41.7	--	100	26	20.9	88.9	61.6	64.1	17.1	--	-264	90.9	--
Magnesium	mg/L	0.01		100	41	0.5	14.9	2.3	1.1	3.0	--	100	26	2.11	10.7	7.7	7.8	2.3	--	-636	89.7	--
Potassium	mg/L	0.06		100	41	0.4	59.8	3.9	1.1	9.9	--	100	26	0.85	20.5	11.3	10.7	4.5	--	-864	88.9	--
Hardness	mg/L	1		100	41	22.0	480.0	98.1	47.0	115.1	--	100	26	61	260.0	185.4	190.0	49.4	--	--	--	As < Bio
Solvent extractable	mg/L	1		85	41	0.5	9.1	2.0	1.5	1.6	--	4	26	0.5	1.2	0.5	0.5	0.1	--	66.7	92.0	--
Chloride	mg/L	1	120	88	41	0.5	41400	2046.6	4.2	7501	22	96	26	0.5	149.0	20.5	4.7	37.1	4	-11.9	91.7	--
Sodium	mg/L	0.04		100	41	0.3	27900	1309.8	3.5	4908	--	100	26	5.1	82.8	22.6	14.2	20.4	--	-308	90.8	--

Note: N = number of observations. GL = provincial or federal water quality guidelines. MDL = method detection limit. Conc. Diff = Difference in concentration at the 0.05 level of significance (α). The percent difference in loads represents an approximation of the mass of pollutants reduced by the biorention system over the course of the monitoring period. See methods section for an explanation of how loads were determined.

Table 5.3b: Water quality summary statistics - metals

Variable	Units	MDL	GL	Asphalt Runoff %>dl	N	Min	Max	Mean	Median	St. Dev.	%>GL	Bioretention Effluent %>dl	N	Min	Max	Mean	Median	St. Dev.	%>GL	Median Conc. % Diff.	Pollutant Load % Diff.	Conc Diff. α ≤ 0.05
Aluminum	ug/L	1	100	100	41	107.0	1310	335.8	263.0	239	100	100	26	94.8	473.0	209.5	181.5	102	96	31.0	91.9	As > Bio
Antimony	ug/L	0.5		93	41	0.3	1.7	0.9	0.8	0.3	--	85	26	0.25	0.9	0.7	0.8	0.2	--	0.0	91.8	--
Arsenic	ug/L	1		12	41	0.5	8.7	0.9	0.5	1.5	--	0	26	0.5	0.5	0.5	0.5	0.0	--	0.0	91.8	--
Barium	ug/L	0.5		100	41	7.1	329.0	38.8	15.9	70.2	--	100	26	41.2	189.0	135.9	137.5	37.2	--	-765	89.3	--
Beryllium	ug/L	0.5	11	0	41	0.3	0.3	0.3	0.3	0.0	0	0	26	0.25	0.3	0.3	0.3	0.0	0	0.0	91.8	--
Boron	ug/L	10		29	41	5.0	60.0	11.5	5.0	13.1	--	92	26	5	129.0	71.9	68.0	37.7	--	-1260	87.7	--
Cadmium	ug/L	0.5	0.8	0	41	4.0	0.4	0.4	0.4	0.0	0	0	26	0.3	0.4	0.4	0.4	0.0	0	0.0	91.8	--
Chromium	ug/L	5	8.9	22	41	2.5	2.5	2.5	2.5	0.0	0	0	26	2.5	2.5	2.5	2.5	0.0	0	0.0	91.8	--
Cobalt	ug/L	1	0.9	2	41	0.5	5.4	1.2	1.1	1.0	100	4	26	0.5	1.1	0.5	0.5	0.1	4	54.5	91.9	--
Copper	ug/L	5	5	100	41	5.1	121.0	17.7	13.5	18.9	100	100	26	6.9	75.7	20.4	16.7	14.1	100	-23.3	91.7	no diff.
Iron	ug/L	30	300	100	41	140	2100	612	420	500	63	100	26	90	440	205	185	91	12	56.0	91.9	As > Bio
Lead	ug/L	0.5	1 - 5	98	41	0.3	10.6	3.9	2.6	3.0	44	100	26	0.6	5.1	1.9	1.5	1.1	4	42.3	91.9	As > Bio
Manganese	ug/L	0.5		100	41	18.5	845.0	122.7	73.6	150.0	--	100	26	7.1	51.3	19.9	16.4	11.7	--	77.8	92.0	As > Bio
Molybdenum	ug/L	0.5	40	22	41	0.3	4	0.5	0.3	0.7	0	92	26	0.25	3.6	1.0	0.9	0.6	0	-260.0	90.9	--
Nickel	ug/L	2	25	56	41	1.0	19.8	3.8	2.5	4.4	0	92	26	1	6.7	3.8	3.4	1.6	0	-36.0	91.6	--
Selenium	ug/L	5		0	41	2.5	2.5	2.5	2.5	0.0	--	0	26	2.5	2.5	2.5	2.5	0.0	--	0.0	91.8	--
Silver	ug/L	0.5		0	41	0.3	0.3	0.3	0.3	0.0	--	0	26	0.25	0.3	0.3	0.3	0.0	--	0.0	91.8	--
Strontium	ug/L	1		100	41	39	1790	264	130	385	--	100	26	2510	13300	9845	10450	2577	--	-7938	65.9	--
Thallium	ug/L	0.5		0	41	0.3	0.3	0.3	0.3	0.0	--	0	26	0.25	0.3	0.3	0.3	0.0	--	0.0	91.8	--
Titanium	ug/L	5		39	41	2.5	24.7	5.5	2.5	5.0	--	65	26	2.5	14.1	5.3	5.5	2.7	--	-118.0	91.4	--
Uranium	ug/L	0.5		0	41	0.3	0.3	0.3	0.3	0.0	--	19	26	0.25	0.7	0.3	0.3	0.2	--	0.0	91.8	--
Vanadium	ug/L	0.5	7	100	41	1.2	10.6	3.8	3.2	2.2	7	77	26	0.25	1.4	0.7	0.8	0.3	0	75.0	92.0	--
Zinc	ug/L	2	20	100	41	14.3	471.0	77.9	46.9	94.5	83	100	26	17.2	158.0	51.9	33.8	35.6	96	27.9	91.9	no diff.

Note: N = number of observations. GL = provincial or federal water quality guidelines. MDL = method detection limit. Conc. Diff = Difference in concentration at the 0.05 level of significance (α). The percent difference in loads represents an approximation of the mass of pollutants reduced by the biorention system over the course of the monitoring period. See methods section for an explanation of how loads were determined.

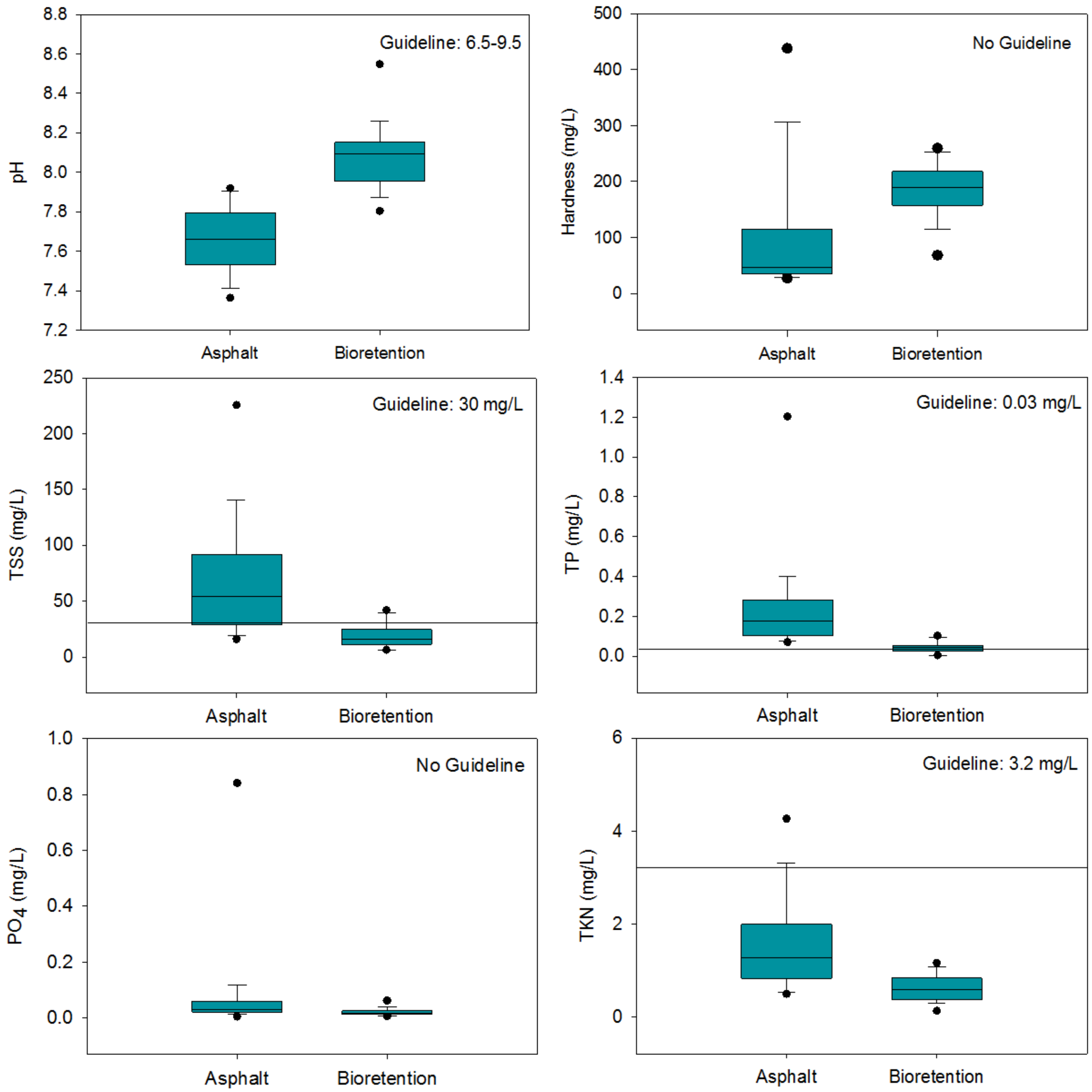

Figure 5.7a: Box plots and receiving water guidelines for selected water quality variables. The whiskers represent the 10th and 90th percentiles, and the individual points are the 5th and 95th percentiles.

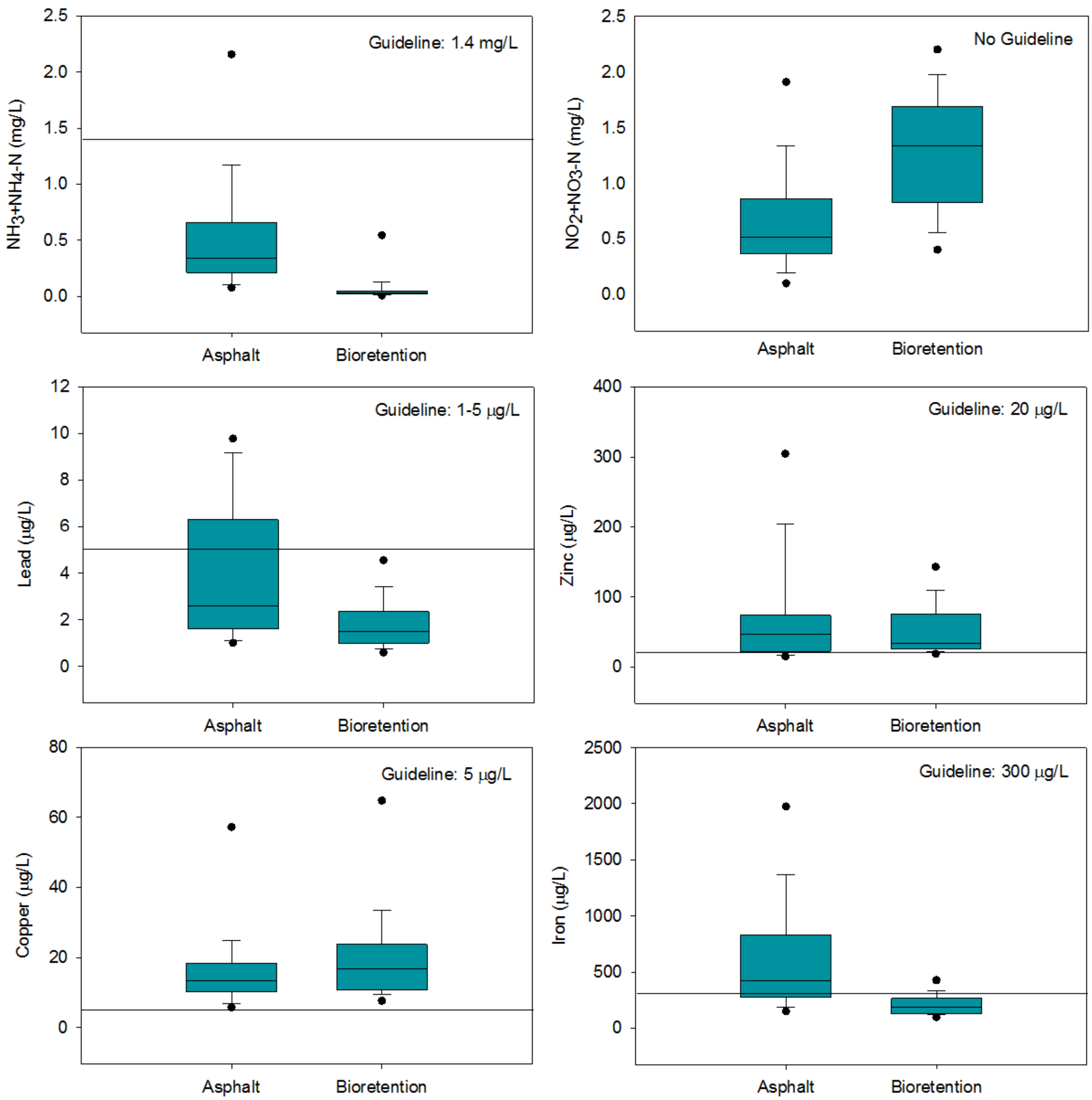

Figure 5.7b: Box plots and receiving water guidelines for selected water quality variables. The whiskers represent the 10th and 90th percentiles, and the individual points are the 5th and 95th percentiles.

5.4 Surface Temperature

Surface temperatures were monitored at four depths throughout the winter within a nearby conventional asphalt and base, and within the upper soil horizon of the bioretention cell. The cumulative frequency distribution of temperatures is presented in Figure 5.7. The deepest sensor is not included because there was some missing data, and therefore comparisons could not be made over the same time period.

The graph shows substantial differences in temperature between the two surfaces. In the winter, the bioretention soil temperatures were warmer than asphalt temperatures, but the magnitude of difference may not be as shown because of the presence of ice around the bioretention sensor (the temperature of ice is zero degrees Celsius). Ice at the surface provides insulation, which may have contributed to the lower amplitude of temperature fluctuations at lower depths. The higher bioretention temperatures in the winter may also be attributed to the natural insulating properties of soil, the overlying snow layer, and heat generated from microbial activity within the filter media.

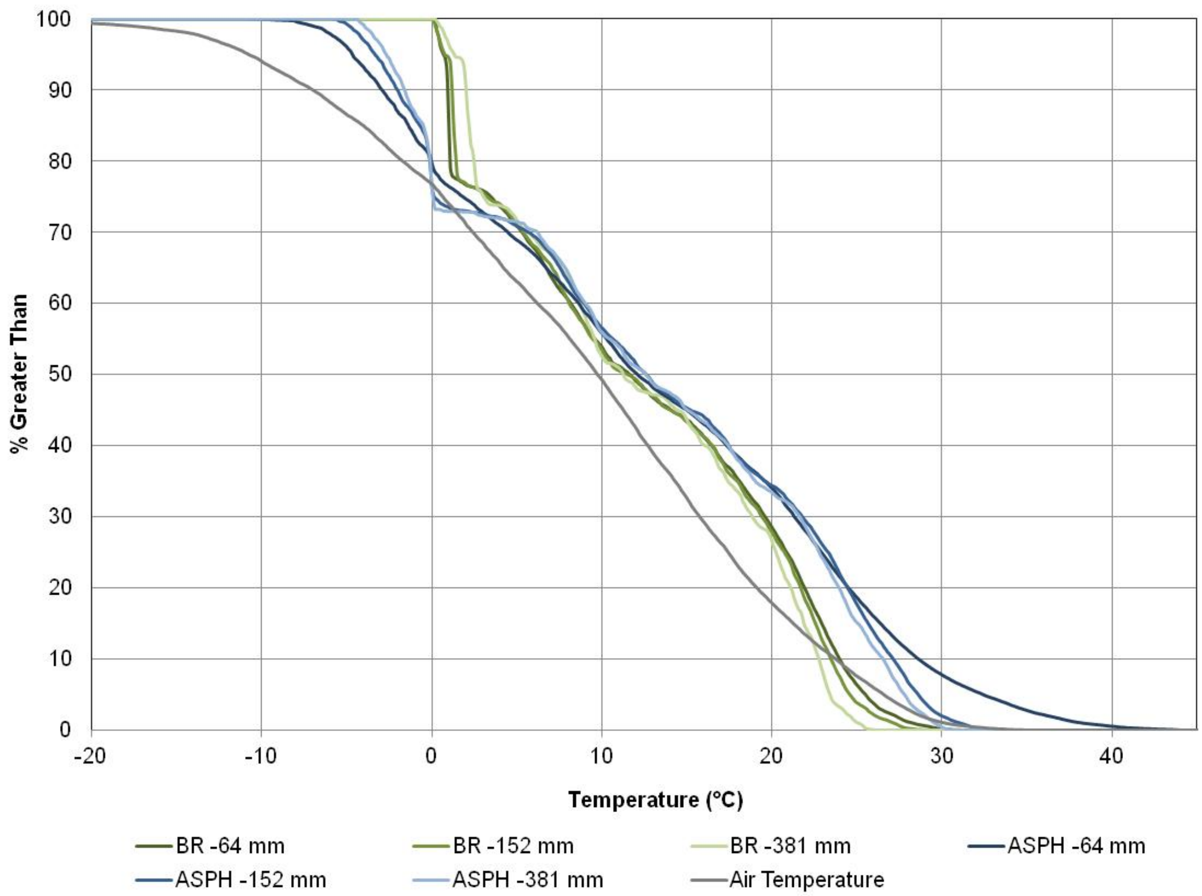

Figure 5.8: Cumulative frequency distributions of bioretention and asphalt temperatures at 64, 152 and 381 mm below the surface.

During the warm season, the temperature of bioretention soils at all depths were considerably cooler than the asphalt, rarely rising above 25°C. The asphalt temperatures were on average 4°C higher. Differences were greatest near the surface, where the maximum asphalt temperature rose to above 40°C. The presence of moisture in the soils and their capacity to release heat through evaporative cooling, combined with shading from herbaceous plants, maintains soil temperatures well below air temperatures during warm periods, and thereby helps to mitigate urban heat island effects.

5.5 Water Temperature

The lower volumes of bioretention outfows and cooler temperatures of filter media significantly reduce the impact of stormwater runoff on the temperature of receiving waters, and helps to protect aquatic organisms that are sensitive to even small changes in thermal conditions. This represents an important benefit of bioretention over other treatment systems, such as ponds or constructed wetlands, which have been shown to significantly increase the temperature of stormwater.

Since outflows occur only during medium to large rainfall events, differences in temperatures were analyzed on an event basis. Sample events are shown in Figure 5.8. The three water temperature sensors were installed in the well at the cell surface, and in the asphalt and bioretention outflow pipes. Since the outflow sensors are always submerged in water, the initial temperature reflects the temperature of air in the vault (with which the water equilibrates over time). When there is flow, the temperature changes as the stagnant water is replaced with new water. After the event, the water temperature gradually declines until it is the same as the air temperature in the monitoring vaults. The surface temperature remains elevated for less time because eventually all of the water in the well infiltrates, leaving the sensor open to the atmosphere.

On June 21, 2012, a 22 mm event was preceded by a warm period with air temperatures above 32°C. The initial asphalt temperature was above 32°C, followed by declining temperatures over the course of the event as the pavement cooled and air temperatures fell. Surface ponding on the bioretention cell coincided with peak runoff, resulting in an increase in temperature to 28°C. Flow through the perforated underdrain occurred later during the event. Underdrainage temperatures were approximately 20°C, which was 12°C lower than peak asphalt temperatures during the same event.

The 12 mm rain event on July 15, 2012 shows a similar pattern. During this event rainfall occurred during two periods roughly 6 hours apart. The event was preceded by a warm period with air temperatures above 29°C. The asphalt runoff increased to 32°C during the initial period of runoff, falling to 30°C during the second runoff peak. Accumulation of water on the bioretention cell surface caused the water temperature to increase until water in the well had fully infiltrated. Underdrain outflows occurred later in the event, after the second runoff peak. The rise in temperatures to 20°C reflects this period of increased flow.

These results combined with the substantial reductions in runoff volumes resulting from infiltration highlight the benefits of bioretention systems in mitigating the thermal impacts of stormwater runoff and maintaining stream temperatures within the upper tolerance limits for cool water fisheries (<21°C).

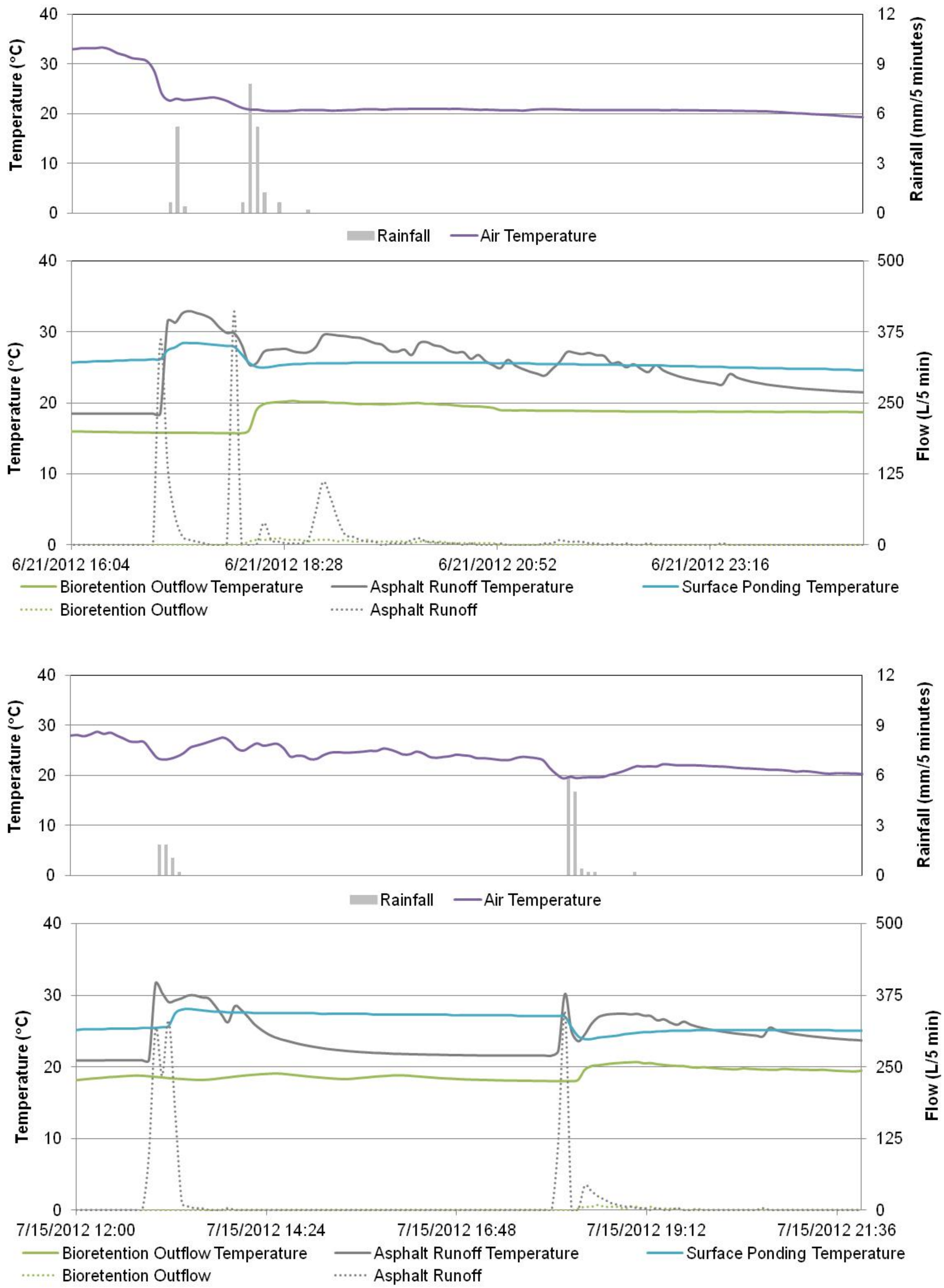

Figure 5.8: Temperatures of asphalt runoff, surface water on the bioretention cell and bioretention outflow during two rain events on June 21 and July 15, 2012.

5.6 Soil Moisture Content

The moisture content of soils was measured at 20 locations before and after rain events from June 23 to July 6, 2011 and from August 23 to September 28, 2011. Point measurements were taken at 2 and 10 cm below the surface in vegetated (n=10) and non-vegetated areas (n=10). Results are shown as time series graphs with rainfall in Figures 5.9a and b, and as box plots in Figure 5.10.

Key observations from the soil moisture measurements include the following:

- Vegetated areas had significantly lower moisture content ($\alpha=0.05$) than non-vegetated areas at both test depths, likely due to higher rates of evaporative losses, but also because non-vegetated areas tended to be located at slightly lower elevations near the middle of the cell where water accumulates.
- As expected, the surface soils of both areas were drier than the deeper soils, as the latter were more affected by direct evaporation from the surface.
- Following rain events, the vegetated and non-vegetated surfaces dried at similar rates, but within the root zone at 10 cm below the surface, the vegetated area dried more quickly, presumably due to plant uptake of soil moisture.
- Rain and runoff from the parking lot maintained soil moisture within the root zone at levels sufficient for plant survival and growth. Manual irrigation was almost never required to supplement parking lot sources of water.

These results confirm the beneficial effect of vegetation in reducing soil moisture content and creating greater capacity for runoff to be stored and returned to the atmosphere through evapotranspiration.

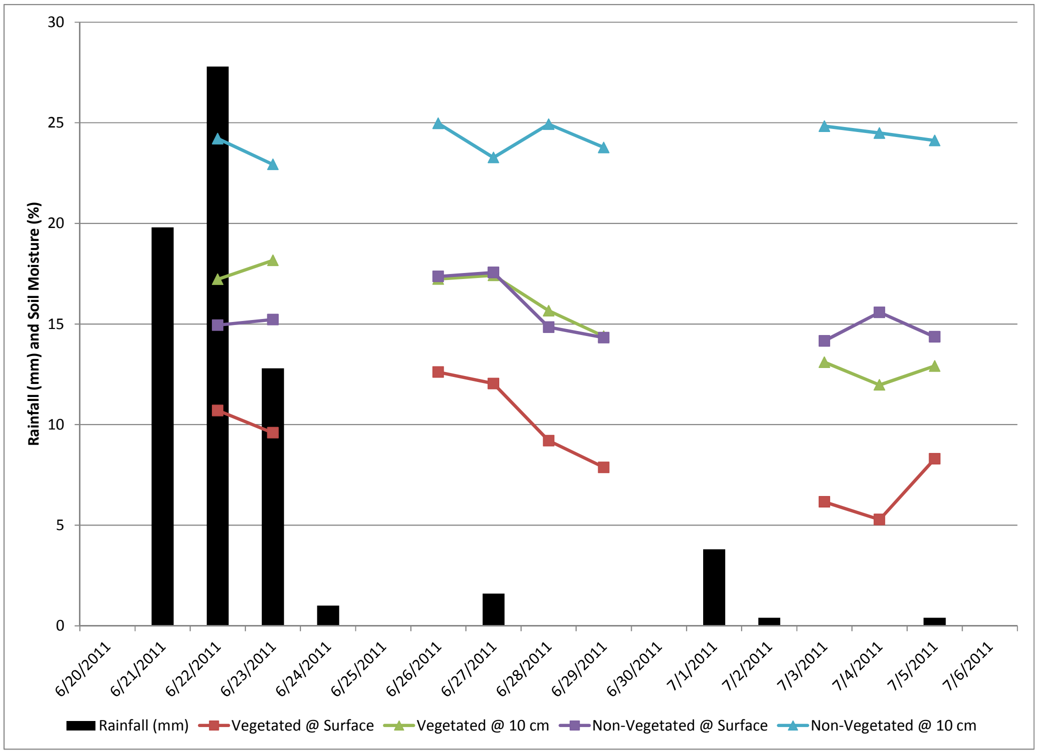

Figure 5.9a: Soil moisture and rainfall at the surface and 10 cm below the surface in vegetated (n=10) and non-vegetated (n=10) areas within the bioretention cell (June 21 to July 6, 2011).

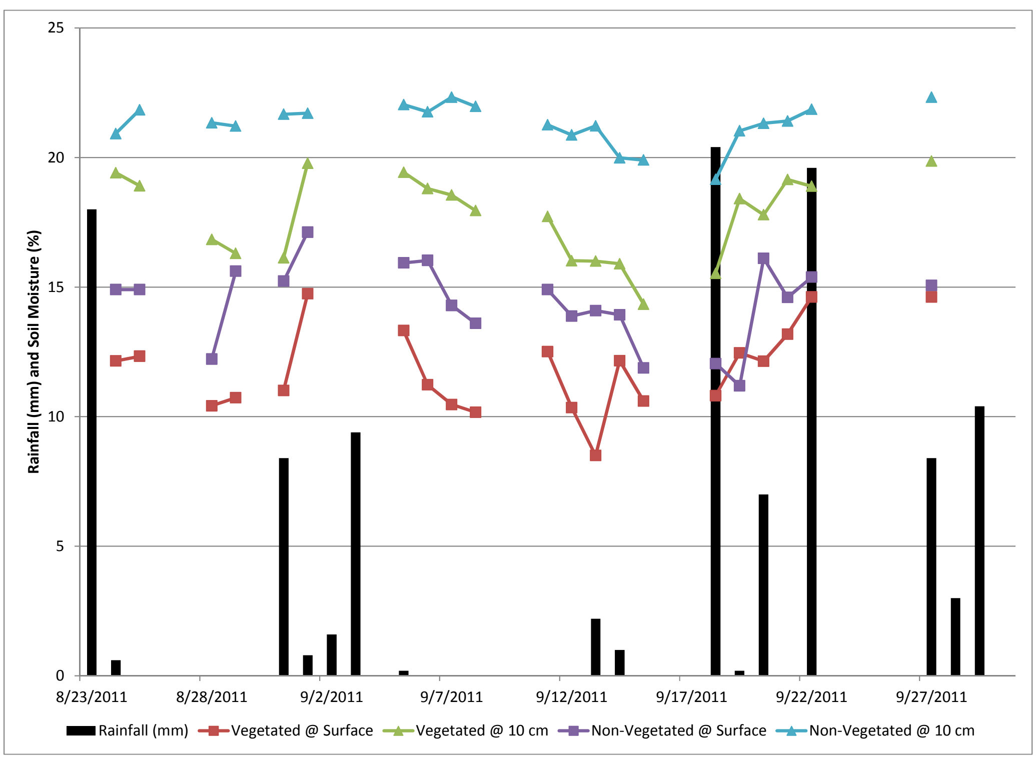

Figure 5.9b: Soil moisture and rainfall at the surface and 10 cm below the surface in vegetated (n=10) and non-vegetated (n=10) areas within the bioretention cell (August 23 to September 28, 2011)

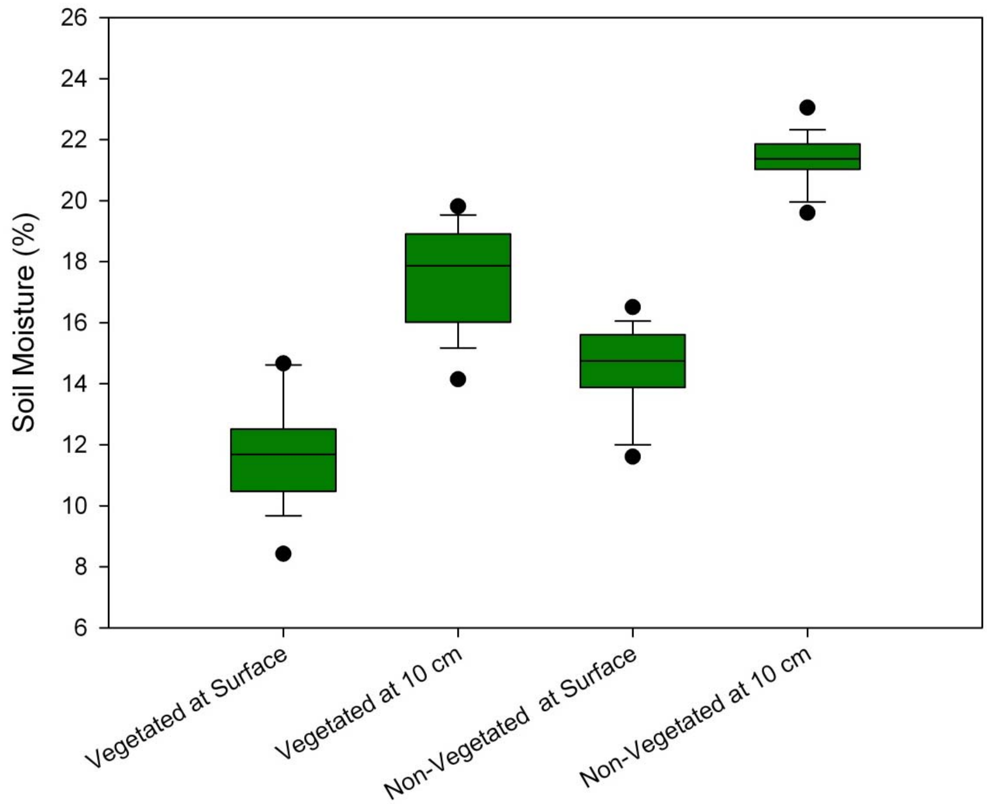

Figure 5.10: Box plots of soil moisture content at the surface and 10 cm below the surface of vegetated and non-vegetated areas within the bioretention cell.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This study has shown that bioretention systems can significantly improve the management of stormwater runoff from parking lots and other small drainage areas relative to conventional treatment practices. Despite the presence of low permeability native soils, runoff volumes were reduced by over 90%. Runoff infiltrated well throughout the winter and vegetation remained healthy year round with limited need for manual irrigation. Even during the largest observed storm (78 mm, of which 46 mm occurred over less than two hours), the bioretention system reduced runoff volumes by approximately 81%.

Reducing the volume and rate of runoff to watercourses helped to attenuate the impact of flooding on downstream infrastructure, but also played a significant role in improving water quality. On a per unit area basis, the mass of contaminants discharged from the bioretention facility was estimated to be between 65 and 92 percent less than that discharged from the asphalt control. The concentrations of most constituents in bioretention underdrainage were also significantly lower than in asphalt runoff (α=0.05), including total suspended solids, total phosphorus, ammonia nitrogen, total kjeldahl nitrogen, lead, iron, and aluminum. Exceptions included nitrate nitrogen, which was higher in bioretention effluent, as well as copper and zinc, which were not significantly different (α=0.05).

The lower runoff volumes and cooler temperatures of runoff from the bioretention system play a critical role in mitigating the thermal impact of urbanization on downstream aquatic communities. The maximum temperature of bioretention outflows during hot summer periods was just over 20°C, which was over 10°C lower than peak asphalt runoff temperatures during the same events.

The following recommendations on bioretention design and further research needs are offered based on the results of this study.

<u>Facility Design</u>

- 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.
- Underdrains should always be raised at least 30 cm in the cross section, 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, confirming that an area at least this size can be effectively treated without 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.

<u>Further Research Needs</u>

- 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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APPENDIX A

Site Photos

Bioretention Cell

Bio-Swale

Overflow Catchbasin and sampling vault

APPENDIX B

Hydrologic Summary Tables

Table A1: Summer events

Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Rainfall Duration (hours)	Rainfall Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
April 3, 2011	13.4	24.1	1.9	52.9	0	0	150	30.7	0	0	100.0
April 10, 2011	3.0	7.6	0.6	12.0	0	0	0	0	0	0	100.0
April 16, 2011	11.4	14.8	0.8	29.9	0	0	24	39.9	0	1	95.9
April 17, 2011	1.1	2.8	1.6	0.6	0	0	0	0	0	0	100.0
April 19, 2011	16.6	15.6	1.6	31.9	0	0	158	15.5	0	4	85.9
April 22, 2011	12.2	8.2	0.6	13.5	0	0	0	0	0	0	100.0
April 25, 2011	5.8	4.6	0.2	4.6	0	0	0	0	0	0	100.0
April 26, 2011	7.0	9	2	15.5	0	0	25	11.0	0	1	93.0
April 26, 2011	1.3	0.8	0.2	0.2	0	0	0	0	0	0	100.0
April 27, 2011	0.8	3	1.8	0.6	0	0	0	0	0	0	100.0
April 28, 2011	7.5	2.8	0.4	0.6	0	0	0	0	0	0	100.0
April 29, 2011	0.9	0.6	0.2	0.1	0	0	0	0	0	0	100.0
May 1, 2011	5.7	3	0.6	0.6	0	0	0	0	0	0	100.0
May 2, 2011	0.8	1	0.2	0.2	0	0	0	0	0	0	100.0
May 3, 2011	11.2	7.2	0.2	11.0	0	0	0	0	0	0	100.0
May 6, 2011	0.4	1.2	0.4	0.2	0	0	0	0	0	0	100.0
May 6, 2011	1.7	2.4	0.4	0.5	0	0	0	0	0	0	100.0
May 14, 2011	39.0	45.6	1.2	106.2	0	0	222	16.6	0.903	6	93.0
May 17, 2011	4.1	2	0.4	0.4	0	0	0	0	0	0	100.0
May 18, 2011	3.9	5	0.6	5.6	0	0	0	0	0	0	100.0
May 18, 2011	6.4	13.6	3	26.9	2.3	0.1	228	25.7	0.414	5	79.5
May 23, 2011	0.5	0.8	0.6	0.2	0	0	0	0	0	0	100.0
May 23, 2011	5.7	5.6	2.8	7.1	0	0	30	5.7	0.003	0	100.0
May 25, 2011	4.0	10	1	18.0	0	0	126	8.7	0.102	0	99.4
May 26, 2011	1.8	5	0.6	5.6	0	0	32	11.2	0	0	100.0
May 26, 2011	8.7	4.2	0.4	3.6	0	0	22	8.4	0	0	100.0
May 29, 2011	4.7	0.8	0.2	0.2	0	0	0	0	0	0	100.0
May 29, 2011	2.2	3	0.4	0.6	0	0	20	3.4	0	0	100.0
June 4, 2011	2.7	13.8	1	27.4	0	0	131	2.7	0.105	0	99.6
June 7, 2011	1.8	5.4	1	6.6	0	0	18	2.1	0	0	100.0
June 8, 2011	0.7	26.4	6.6	58.6	133.4	0.8	684	5.3	0	11	80.5
June 11, 2011	3.3	21	6.6	45.2	173.3	1.0	629	8.2	0	8	81.6
June 22, 2011	2.3	3	1.4	0.6	0	0	0	0	0	0	100.0
June 22, 2011	2.7	20.2	7.2	43.3	29.1	0.8	605	2.9	0.168	11	75.0
June 23, 2011	1.7	23.2	7.4	50.7	162.3	0.8	904	7.2	0	15	71.1
June 23, 2011	3.5	2.2	0.2	0.5	0	0	0	0	0	0	100.0

Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Rainfall Duration (hours)	Rainfall Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
June 24, 2011	3.0	11	4.4	20.5	91.9	0.4	438	7.5	0	7	64.5
June 24, 2011	0.2	0.6	0.2	0.1	0	0	0	0	0	0	100.0
June 25, 2011	2.7	1	0.2	0.2	0	0	0	0	0	0	100.0
June 28, 2011	0.4	1.6	1	0.3	0	0	0	0	0	0	100.0
July 2, 2011	2.0	4.2	1.2	3.6	0	0	0	0	0	0	100.0
July 22, 2011	1.8	3.8	1	2.6	0	0	0	0	0	0	100.0
July 25, 2011	3.0	25	4.2	55.2	0	0	372	8.3	0.249	9	83.0
July 26, 2011	0.8	5.2	1.8	6.1	0	0	43	3.2	0.012	0	99.8
July 29, 2011	0.3	0.6	0.2	0.1	0	0	0	0	0	0	100.0
July 29, 2011	0.5	1	0.2	0.2	0	0	0	0	0	0	100.0
August 1, 2011	0.3	7.6	3.8	12.0	0	0	61	2.7	0.012	0	99.9
August 3, 2011	3.0	15.2	1.2	30.9	0	0	87	9.7	0.072	0	99.8
August 3, 2011	0.6	0.8	0.2	0.2	0	0	0	0	0	0	100.0
August 7, 2011	3.6	1.6	0.4	0.3	0	0	0	0	0	0	100.0
August 7, 2011	0.3	9.4	2.8	16.5	0	0	279	3.4	0.081	3	79.8
August 9, 2011	4.9	16	2.6	32.8	0	0	262	6.4	0.009	6	80.7
August 14, 2011	3.0	38.6	7.6	88.9	100	0.7	1242	12.7	0.489	22	74.6
August 14, 2011	2.8	1.6	0.2	0.3	0	0	0	0	0	0	100.0
August 17, 2011	2.2	1	0.4	0.2	0	0	0	0	0	0	100.0
August 21, 2011	2.9	0.8	0.4	0.2	0	0	0	0	0	0	100.0
August 21, 2011	4.6	15	5	30.4	0	0	461	3.0	0.183	5	81.6
August 24, 2011	2.5	5.8	1.2	7.6	0	0	14	1.3	0	2	79.6
August 24, 2011	7.3	12.6	1.2	24.4	0	0	233	5.9	0.147	2	90.5
September 1, 2011	2.0	8.4	3.6	14.0	0	0	35	1.4	0.006	0	100.0
September 2, 2011	1.0	0.8	0.4	0.2	0	0	0	0	0	0	100.0
September 3, 2011	0.3	1.4	0.8	0.3	0	0	0	0	0	0	100.0
September 4, 2011	2.3	9.4	4.6	16.5	0	0	150	2.7	0.078	0	99.5
September 14, 2011	6.1	3.2	0.2	1.1	0	0	0	0	0	0	100.0
September 19, 2011	11.2	20.6	1.2	44.3	0	0	0	0	0.078	0	99.8
September 21, 2011	5.7	6.8	0.8	10.0	0	0	128	5.2	0	0	100.0
September 23, 2011	8.3	19.6	1.4	41.8	0	0	277	11.4	0.174	6	86.3
September 28, 2011	5.8	7.6	1.2	12.0	0	0	14	1.2	0	0	100.0
September 28, 2011	1.1	0.6	0.2	0.1	0	0	0	0	0	0	100.0
September 29, 2011	0.9	0.8	0.2	0.2	0	0	0	0	0	0	100.0
September 29, 2011	0.7	1.8	1	0.4	0	0	15	1.6	0	0	100.0
September 30, 2011	4.8	10	1	18.0	0	0	132	6.1	0	0	100.0

Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Rainfall Duration (hours)	Rainfall Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
October 2, 2011	1.2	2.2	0.4	0.5	0	0	0	0	0	0	100.0
October 3, 2011	5.4	5.4	0.6	6.6	0	0	28	2.2	0	0	100.0
October 3, 2011	6.5	1.8	0.2	0.4	0	0	0	0	0	0	100.0
October 12, 2011	15.1	10.4	0.4	19.0	0	0	0	0	0	0	100.0
October 14, 2011	5.7	2.6	0.4	0.5	0	0	0	0	0	0	100.0
October 14, 2011	4.6	6.4	2.2	9.0	0	0	26	2.5	0	0	100.0
October 19, 2011	1.1	1.4	0.4	0.3	0	0	0	0	0	0	100.0
October 19, 2011	21.2	33.8	1	77.0	0	0	239	21.7	0.573	2	96.6
October 20, 2011	1.5	1	0.2	0.2	0	0	0	0	0	0	100.0
October 24, 2011	4.3	2.4	0.6	0.5	0	0	0	0	0	0	100.0
October 25, 2011	31.3	26	0.6	57.6	0	0	121	27.6	0.198	0	99.7
November 8, 2011	1.9	1.2	0.4	0.2	0	0	0	0	0	0	100.0
November 9, 2011	7.4	5.4	0.4	6.6	0	0	0	0	0	0	100.0
November 14, 2011	1.0	3.4	1.8	1.6	0	0	0	0	0	0	100.0
November 14, 2011	1.7	4.4	0.4	4.1	0	0	0	0	0	0	100.0
November 22, 2011	13.0	13.8	0.4	27.4	0	0	13	3.2	0	0	100.0
November 27, 2011	4.6	3.8	0.4	2.6	0	0	0	0	0	0	100.0
November 27, 2011	5.7	2.8	0.2	0.6	0	0	0	0	0	0	100.0
November 28, 2011	26.7	48	1.2	112.2	0	0	321	26.1	1.4	4	94.9
November 30, 2011	0.9	0.6	0.2	0.1	0	0	0	0	0	0	100.0
November 30, 2011	1.2	1.8	0.2	0.4	0	0	0	0	0	0	100.0
April 1, 2012	3.4	2.0	0.4	0.4	0	0	0	0	0	0	100.0
April 15, 2012	0.4	0.8	0.2	0.2	0	0	0	0	0	0	100.0
April 20, 2012	5.5	9.4	0.4	16.5	0	0	0	0	0	0	100.0
April 23, 2012	23.9	16.4	0.4	33.8	0	0	0	0	0	0	100.0
April 26, 2012	3.2	1.4	0.2	0.3	0	0	0	0	0	0	100.0
April 30, 2012	9.5	11	0.4	20.5	0	0	0	0	0	0	100.0
May 2, 2012	0.1	0.6	0.4	0.1	0	0	0	0	0	0	100.0
May 3, 2012	1.2	2	1.2	0.4	0	0	0	0	0	0	100.0
May 3, 2012	4.1	25.2	3.2	55.7	28.2	0.1	388	12.2	0.375	4	91.3
May 8, 2012	5.7	6.4	0.4	9.0	0	0	0	0	0	0	100.0
May 9, 2012	4.9	2.8	0.4	0.6	0	0	0	0	0	0	100.0
May 13, 2012	2.7	1.6	0.2	0.3	0	0	0	0	0	0	100.0
May 16, 2012	0.8	1	0.4	0.2	0	0	0	0	0	0	100.0
June 1, 2012	18.8	31.2	1.2	70.5	0	0	63	7.3	0.099	0	99.9
June 2, 2012	0.1	1	0.6	0.2	0	0	0	0	0	0	100.0

Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Rainfall Duration (hours)	Rainfall Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
June 3, 2012	1.6	1.2	0.4	0.2	0	0	0	0	0	0	100.0
June 9, 2012	4.3	4.4	1.8	4.1	0	0	0	0	0	0	100.0
June 11, 2012	9.6	14.8	1.2	29.9	0	0	0	0	0	0	100.0
June 12, 2012	0.2	2.2	0.8	0.5	0	0	0	0	0	0	100.0
June 21, 2012	1.6	21.8	7.8	47.2	59.0	0.2	534	2.8	0.216	5	89.1
June 22, 2012	0.2	1.2	0.6	0.2	0	0	0	0	0	0	100.0
June 24, 2012	1.8	12.8	2.4	24.9	0	0	164	1.6	0.072	0	99.7
June 24, 2012	0.3	2.8	1.8	0.6	0	0	0	0	0	0	100.0
July 7, 2012	2.0	8.4	2.6	14.0	0	0	0	0	0	0	100.0
July 15, 2012	0.2	4.8	1.8	5.1	0	0	0	0	0	0	100.0
July 15, 2012	0.8	12	6	22.9	0	0	234	1.3	0.081	0	99.6
July 22, 2012	1.9	0.6	0.6	0.1	0	0	0	0	0	0	100.0
July 22, 2012	0.5	2.4	1.6	0.5	0	0	0	0	0	0	100.0
July 22, 2012	0.9	2.4	1	0.5	0	0	0	0	0	0	100.0
July 23, 2012	1.7	0.8	0.2	0.2	0	0	0	0	0	0	100.0
July 25, 2012	13.7	77.8	10.6	186.1	210	2.2	1344	13.4	0.324	34	81.3
July 26, 2012	1.3	0.8	0.2	0.2	0	0	0	0	0	0	100.0
July 28, 2012	2.0	1	0.2	0.2	0	0	0	0	0	0	100.0
July 31, 2012	2.3	30.4	3.4	68.5	84	0.4	862	4.7	0.363	6	90.5
August 4, 2012	0.7	5.2	2.4	6.1	0	0	0	0	0	0	100.0
August 5, 2012	3.3	3	1	0.6	0	0	0	0	0	0	100.0
August 9, 2012	10.8	6.2	0.4	8.6	0	0	0	0	0	0	100.0
August 10, 2012	4.4	7.2	0.8	11.0	0	0	0	0	0	0	100.0
August 10, 2012	1.8	16	2.8	32.8	0	0	427	3.5	0.234	3	89.9
August 11, 2012	2.8	1.8	0.2	0.4	0	0	17	0.6	0	0	100.0
August 11, 2012	1.4	5.2	1	6.1	0	0	0	0	0.015	0	99.8
August 11, 2012	0.2	1.2	0.6	0.2	0	0	0	0	0	0	100.0
August 13, 2012	5.8	8.4	1	14.0	0	0	13	0.2	0	0	100.0
August 14, 2012	5.1	2.2	0.2	0.5	0	0	0	0	0	0	100.0
August 15, 2012	0.2	5	2.6	5.6	91	0.3	411	2.2	0.168	1	77.6
August 27, 2012	4.0	7.2	1.6	11.0	0	0	0	0	0	0	100.0
September 4, 2012	10.7	43.4	6.4	100.8	231	0.8	1123	955.0	*0.3*	23	76.6
September 8, 2012	11.9	34.6	1.2	79.0	0	0	363	19.8	0.429	0	99.5
September 14, 2012	3.8	9.8	1.6	17.5	0	0	0	0	0	0	100.0
September 18, 2012	8.9	35	2.8	79.9	159	0.8	696	15.7	0.501	21	72.5
September 22, 2012	5.3	14.4	0.8	28.9	0	0	0	0	0.072	0	99.8

Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Rainfall Duration (hours)	Rainfall Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
September 23, 2012	3.3	2	0.6	0.4	0	0	0	0	0	0	100.0
September 29, 2012	4.0	1.8	0.4	0.4	0	0	0	0	0	0	100.0
October 3, 2012	5.0	2.4	1.4	0.5	0	0	0	0	0	0	100.0
October 5, 2012	7.7	4.2	0.4	1.3	0	0	0	0	0	0	100.0
October 10, 2012	1.4	1	0.2	0.2	0	0	0	0	0	0	100.0
October 11, 2012	2.7	0.6	0.2	0.1	0	0	0	0	0	0	100.0
October 13, 2012	15.2	9.8	0.8	17.5	0	0	0	0	0	0	100.0
October 14, 2012	0.3	1	0.4	0.2	0	0	0	0	0	0	100.0
October 17, 2012	1.8	2.6	0.4	0.5	0	0	0	0	0	0	100.0
October 18, 2012	6.4	10.4	0.6	19.0	2	0.1	0	0	0.039	0	99.8
October 20, 2012	4.6	3.8	0.8	2.6	0	0	18	0.9	0	0	100.0
October 23, 2012	13.4	19.8	0.6	42.3	0	0	41	18.7	0.015	0	100.0
October 24, 2012	0.7	0.8	0.2	0.2	0	0	0	0	0	0	100.0
October 26, 2012	7.7	2.2	0.2	0.5	0	0	0	0	0	0	100.0
October 27, 2012	12.7	31	0.6	70.0	25	0.2	181	23.1	0.591	0	99.2
October 28, 2012	22.3	15.8	0.4	32.4	0	0	0	0	0	0	100.0
October 29, 2012	2.0	2	0.4	0.4	0	0	89	12.2	0	0	100.0
October 29, 2012	5.3	7.6	0.6	12.0	65	0.8	0	0	0.108	0	99.1
October 30, 2012	12.1	9.8	3.6	17.5	0	0	213	6.0	0.153	0	99.1
October 31, 2012	21.7	8.6	0.2	14.5	0	0	34	23.5	0	0	100.0
November 02, 2012	1.7	0.6	0.2	0.1	0	0	0	0	0	0	100.0
November 02, 2012	6.8	1	0.2	0.2	0	0	0	0	0	0	100.0
November 10, 2012	0.4	1.2	0.6	0.2	0	0	0	0	0	0	100.0
November 12, 2012	7.3	6.4	0.4	9.0	0	0	0	0	0	0	100.0
November 23, 2012	1.2	0.8	0.2	0.2	0	0	0	0	0	0	100.0
Minimum	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**65**
Maximum	**39.0**	**77.8**	**10.6**	**186.1**	**231.0**	**2.2**	**1344.2**	**955.0**	**1.4**	**34.4**	**100**
Average	**5.0**	**8.5**	**1.3**	**15.7**	**9.7**	**0**	**95.9**	**8.9**	**0**	**1.4**	**97**
Median	**3.0**	**4.2**	**0.6**	**3.6**	**0**	**0**	**0**	**0**	**0**	**0**	**100**
Total	**--**	**1438**	**--**	**2662**	**--**	**--**	**--**	**--**	**10**	**231**	**90.9**

Notes: **1.** The first 3 mm of rainfall was assumed to generate no runoff from the parking lot surface. During events less than 3 mm, runoff volumes are based on rain falling directly on the 130 m^2 cell area. **2.** Prior to May 14th, 2011, the underdrain outflow pipe was 20 cm higher than during the remainder of the monitoring period. **3.** See text for method used to calculate overflow volumes.

Table A2: Winter events

Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Precipitation Duration (hours)	Precipitation Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
January 6, 2011	0.2	2	1.8	0.4	0	0	0	0.0	0	0	100.0
January 10, 2011	1.5	2.8	1.8	0.6	0	0	0	0.0	0	0	100.0
January 13, 2011	1.5	0.6	0.4	0.1	0	0	0	0.0	0	0	100.0
January 14, 2011	2.7	1.4	0.2	0.3	0	0	0	0.0	0	0	100.0
January 18, 2011	7.0	5	1	5.6	0	0	0	0.0	0	0	100.0
January 20, 2011	5.7	1.3	0.1	0.3	0	0	0	0.0	0	0	100.0
January 22, 2011	4.2	0.9	0.1	0.2	--	--	0	0.0	0	3	--
January 24, 2011	10.7	2.5	0.1	0.5	--	--	0	0.0	0	0	100.0
February 2, 2011	17.9	11.7	0.5	22.2	--	--	0	0.0	0	9	60.9
February 5, 2011	4.4	9.2	0.5	16.0	0	0	0	0.0	0	0	100.0
February 12, 2011	2.7	0.6	0.1	0.1	0	0	0	0.0	0	0	100.0
February 17, 2011	0.7	1.3	0.3	0.3	0	0	0	0.0	0	0	100.0
February 20, 2011	5.3	3.4	0.2	0.7	0	0	0	0.0	0	0	100.0
February 25, 2011	3.2	1.7	0.2	0.4	0	0	0	0.0	0	0	100.0
February 26, 2011	9.2	3.2	0.2	0.7	0	0	0	0.0	0	0	100.0
February 27, 2011	9.8	12.9	0.4	25.2	141.3	14.9	0	0.0	0	0	100.0
March 4, 2011	37.2	31.8	0.4	72.0	109.9	21.0	84.7	19.2	0	0	100.0
March 9, 2011	49.2	49.4	0.6	115.6	115.7	38.4	321.6	39.6	0	10	91.1
March 12, 2011	2.0	0.8	0.1	0.2	0	0	0	0.0	0	0	100.0
March 16, 2011	10.6	6	0.2	5.8	0	0	17.3	26.5	0	0	100.0
March 21, 2011	6.7	4.3	0.6	1.6	0	0	8	19.7	0	0	100.0
March 23, 2011	2.6	2.2	0.2	0.5	0	0	0	0.0	0	0	100.0
March 23, 2011	6.7	5.2	0.2	6.1	0	0	0	0.0	0	0	100.0
March 31, 2011	3.9	0.6	0.1	0.1	0	0	0	0.0	0	0	100.0

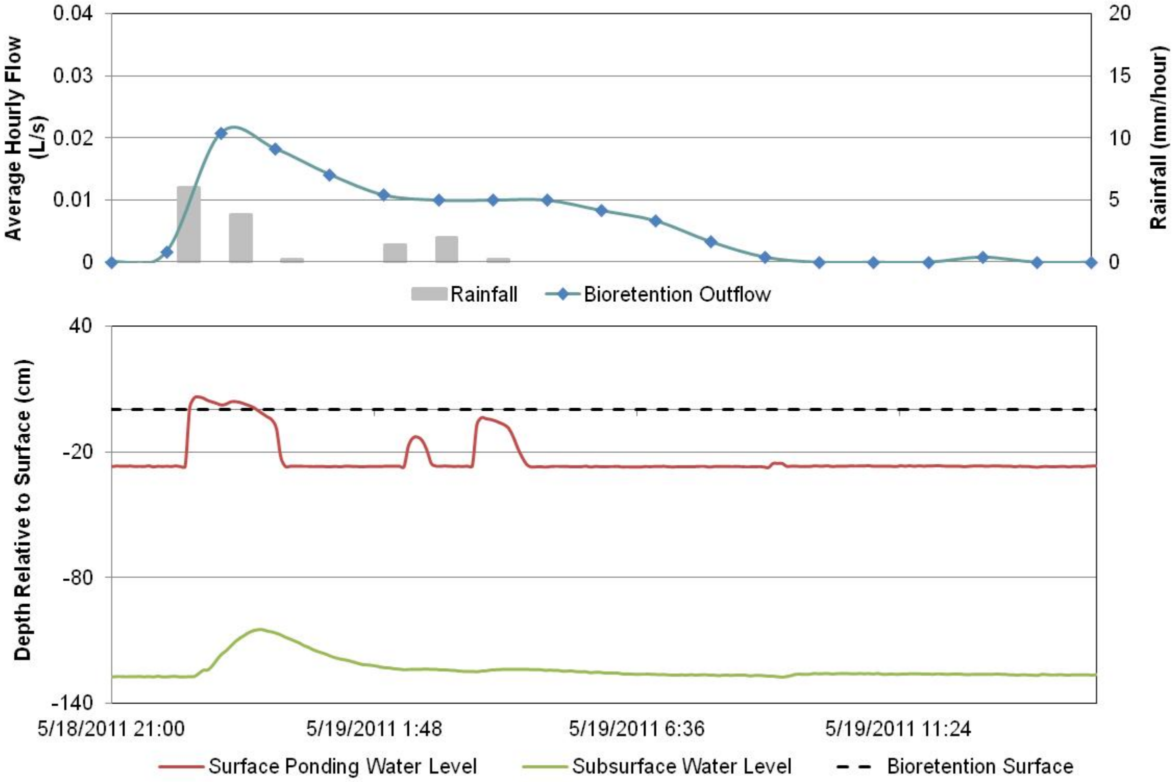
Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Precipitation Duration (hours)	Precipitation Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
December 2, 2011	0.6	2.4	0.4	0.5	0	0	0	0.0	0	0	100.0
December 4, 2011	13.9	6.6	0.4	9.5	0	0	0	0.0	0	0	100.0
December 5, 2011	23.4	12.2	0.3	23.4	0	0	21.6	46.5	0	0	100.0
December 6, 2011	1.7	1.5	0.4	0.3	0	0	0	0.0	0	0	100.0
December 14, 2011	23.3	16.2	0.6	33.3	0	0	0	0.0	0	0	100.0
December 21, 2011	8.8	11.1	1.9	20.7	0	0	27.1272	2.3	0	0	100.0
January 1, 2012	12.6	8.3	0.5	13.8	0	0	13.1	14.8	0	0	100.0
January 2, 2012	2.4	0.6	0.1	0.1	0	0	0.0	0.0	0	0	100.0
January 12, 2012	19.0	8.6	0.2	14.5	0	0	0.0	0.0	0	0	100.0
January 16, 2012	1.6	0.7	0.1	0.1	0	0	0.0	0.0	0	0	100.0
January 17, 2012	11.2	9.4	0.5	16.5	0	0	0.0	0.0	0	0	100.0
January 19, 2012	3.8	2.3	0.2	0.5	0	0	0.0	0.0	0	0	100.0
January 20, 2012	4.1	0.9	0.1	0.2	0	0	0.0	0.0	0	0	100.0
January 23, 2012	3.2	6.5	0.5	9.3	35	2	60.7	3.7	0.12	0	98.7
January 23, 2012	5.7	3.7	0.7	2.4	0	0	0.0	0.0	0	0	100.0
January 25, 2012	5.7	1.5	0.1	0.3	0	0	0.0	0.0	0	0	100.0
January 26, 2012	16.2	15.1	0.3	30.6	27	3.8	0.0	0.0	0.06	1	95.1
January 28, 2012	11.1	3.8	0.1	2.6	0	0	0.0	0.0	0	0	100.0
January 30, 2012	5.9	4.9	0.2	5.3	0	0	0.0	0.0	0	0	100.0
January 31, 2012	9.2	0.8	0.1	0.2	0	0	0.0	0.0	0	0	100.0
February 10, 2012	13.9	2.7	0.1	0.6	0	0	0.0	0.0	0	0	100.0
February 12, 2012	0.7	0.7	0.2	0.1	0	0	0.0	0.0	0	0	100.0
February 14, 2012	7.5	1.3	0.1	0.3	0	0	0.0	0.0	0	0	100.0
February 16, 2012	3.3	1.5	0.1	0.3	0	0	0.0	0.0	0	0	100.0

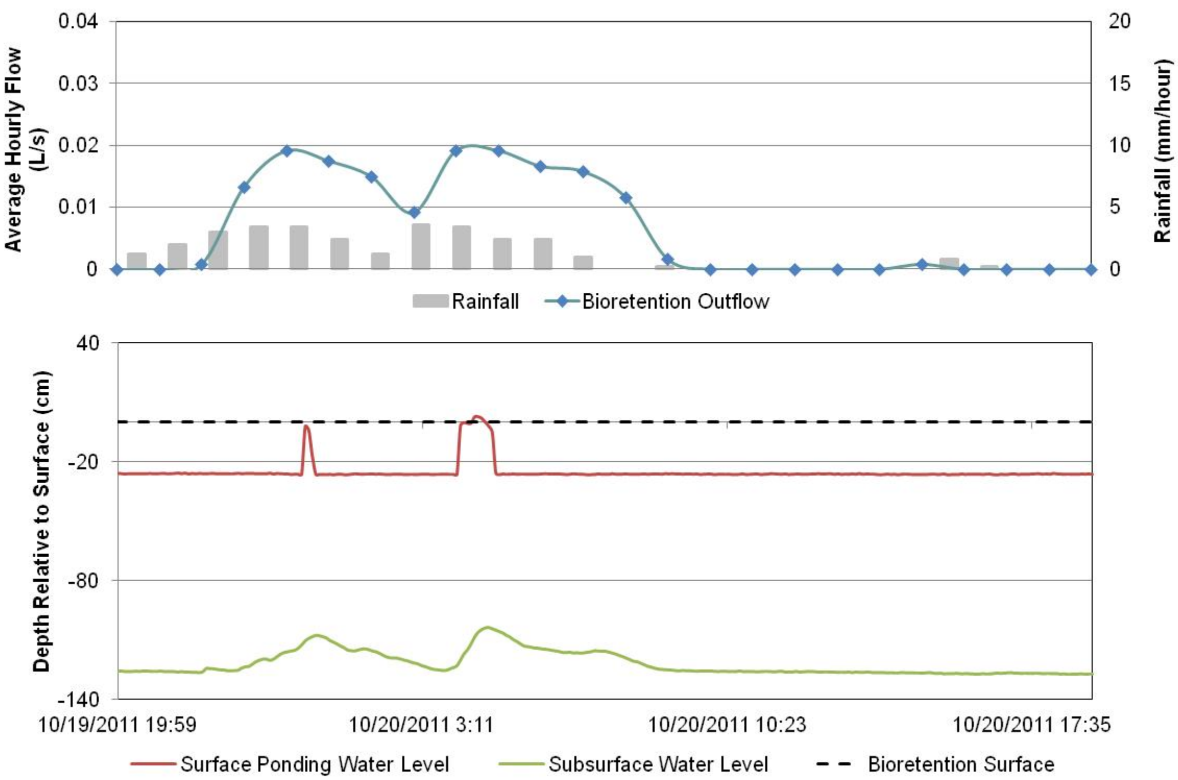
Event Date	Rainfall			Parking Lot	Bioretention Cell						Runoff Reduction (%)
					Surface Water Levels		Subsurface Water Levels		Outflows		
	Precipitation Duration (hours)	Precipitation Depth (mm)	Max. Rainfall Intensity (mm/5 min)	Runoff Volume (m^3)	Maximum Water Level above Surface (mm)	Duration (hours)	Maximum Water Level above Native Soil (mm)	Duration (hours)	Underdrain Flow Volume (m^3)	Estimated Overflow Volume (m^3)	
February 16, 2012	2.1	0.3	0.1	0.1	0	0	0.0	0.0	0	0	100.0
February 17, 2012	0.4	0.3	0.1	0.1	0	0	0.0	0.0	0	0	100.0
February 18, 2012	11.0	7.7	0.3	12.3	0	0	0.0	0.0	0	0	100.0
February 21, 2012	11.3	2.2	0.1	0.5	0	0	0.0	0.0	0	0	100.0
February 24, 2012	10.0	12.5	0.5	24.2	0	0	0.0	0.0	0.06	0	99.5
February 29, 2012	10.1	8.1	0.3	13.3	0	0	0.0	0.0	0	0	100.0
March 1, 2012	6.6	9.3	0.6	16.2	0	0	0.0	0.0	0	0	100.0
March 2, 2012	14.8	8.3	0.8	13.8	0	0	59.1	5.0	0.24	0	98.3
March 3, 2012	3.6	0.9	0.2	0.2	0	0	0.0	0.0	0	0	100.0
March 7, 2012	12.1	2.5	0.3	0.5	0	0	0.0	0.0	0	0	100.0
March 9, 2012	2.1	0.6	0.2	0.1	0	0	0.0	0.0	0	0	100.0
March 12, 2012	4.5	0.4	0.1	0.1	0	0	0.0	0.0	0	0	100.0
March 13, 2012	2.2	5.7	0.7	7.3	0	0	0.0	0.0	0	0	100.0
March 15, 2012	0.4	0.7	0.3	0.1	0	0	0.0	0.0	0	0	100.0
March 23, 2012	1.1	1.8	0.6	0.4	0	0	0.0	0.0	0	0	100.0
Minimum	**0**	**0.3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**61**
Maximum	**49.2**	**49.4**	**1.9**	**115.6**	**141.3**	**38.4**	**321.6**	**46.5**	**0**	**10.3**	**100**
Average	**8.1**	**5.5**	**0**	**8.7**	**7.2**	**1.3**	**9.7**	**2.8**	**0**	**0**	**99**
Median	**5.7**	**2.5**	**0**	**0.5**	**0**	**0**	**0**	**0**	**0**	**0**	**100**
Total	**--**	**345.4**	**--**	**549.8**	**--**	**--**	**--**	**--**	**0.48**	**23.0**	**96**

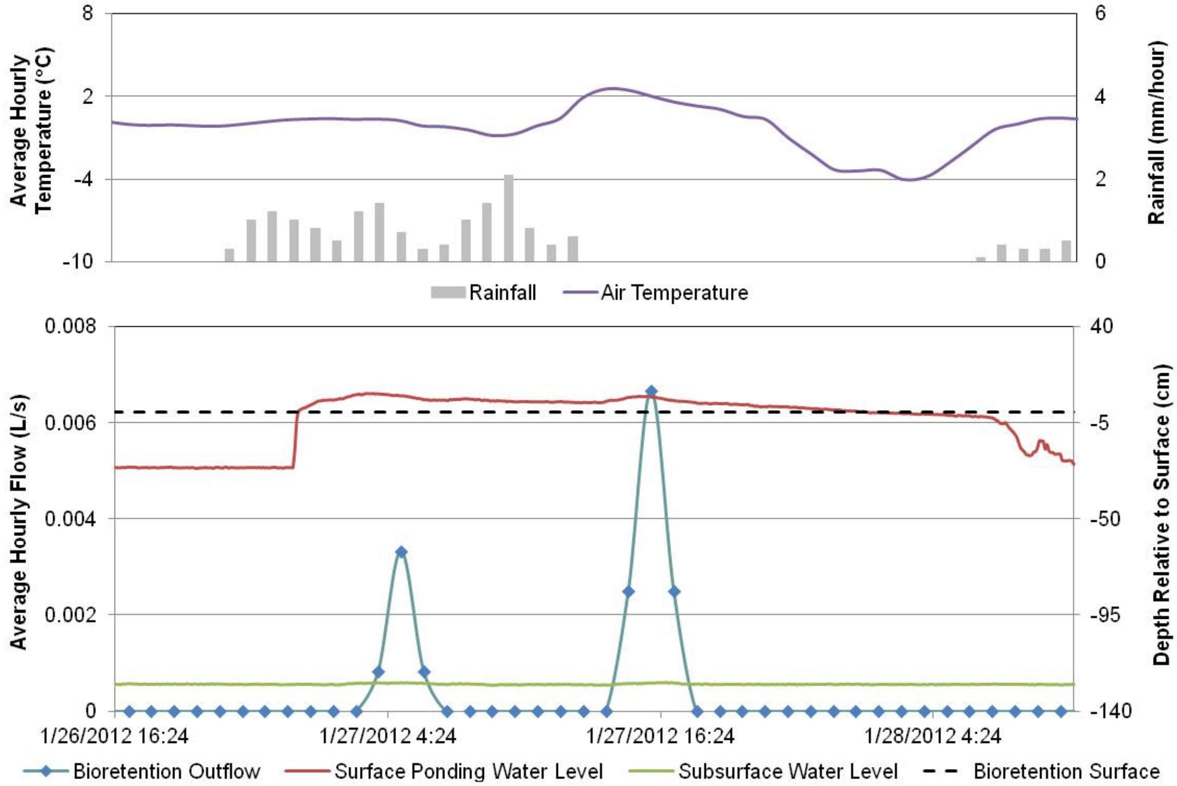
Notes: 1. The first 3 mm of rainfall was assumed to generate no runoff from the parking lot surface. During events less than 3 mm, runoff volumes are based only on precipitation falling directly on the 130 m^2 cell area. **2.** Winter snow data are presented as the equivalent depth of water. Melting of snow accumulated during previous events is not accounted for in the individual event runoff volumes. Likewise, snow that accumulated is shown as runoff volume on the day that it fell, rather than as melt during a future event. **3.** See text for the method used to estimate overflow volumes **4.** Prior to May 14th, 2011, the underdrain outflow pipe was 20 cm higher than during the remainder of the monitoring period. **5.** Underdrain flow data were not available from December 21 to December 31, 2011.

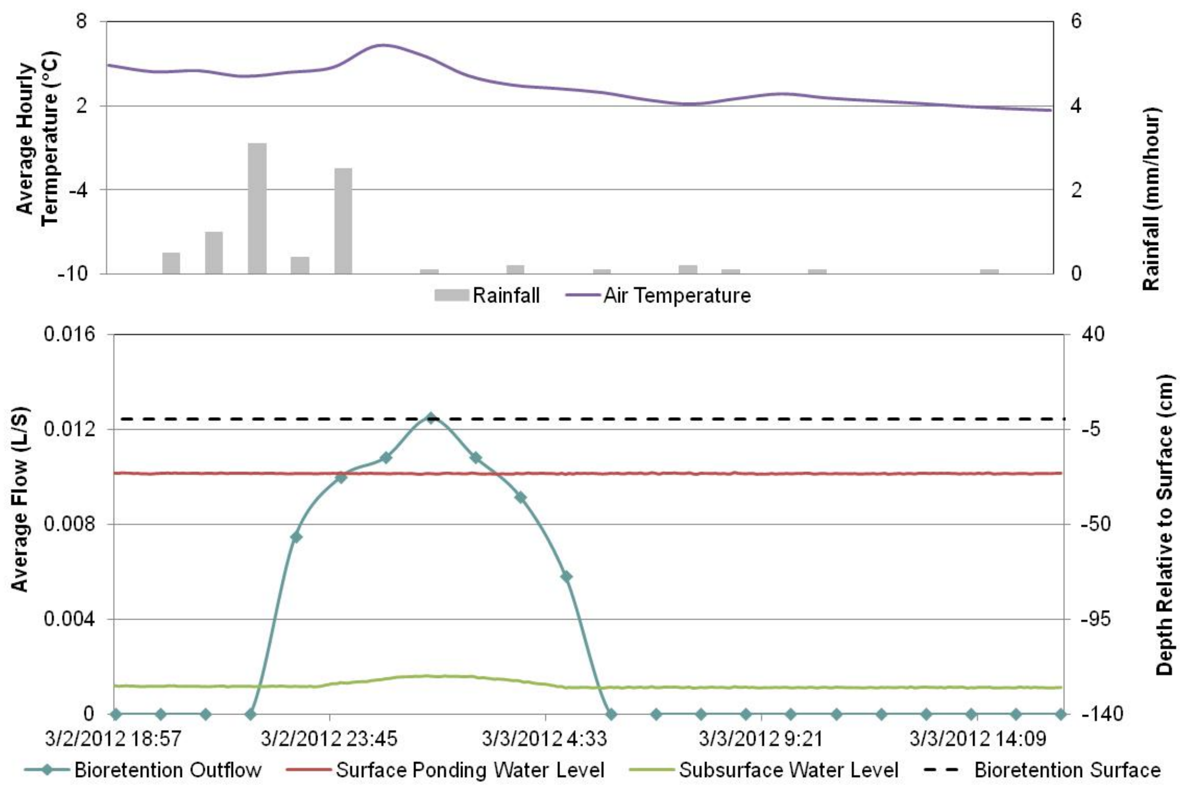
APPENDIX C

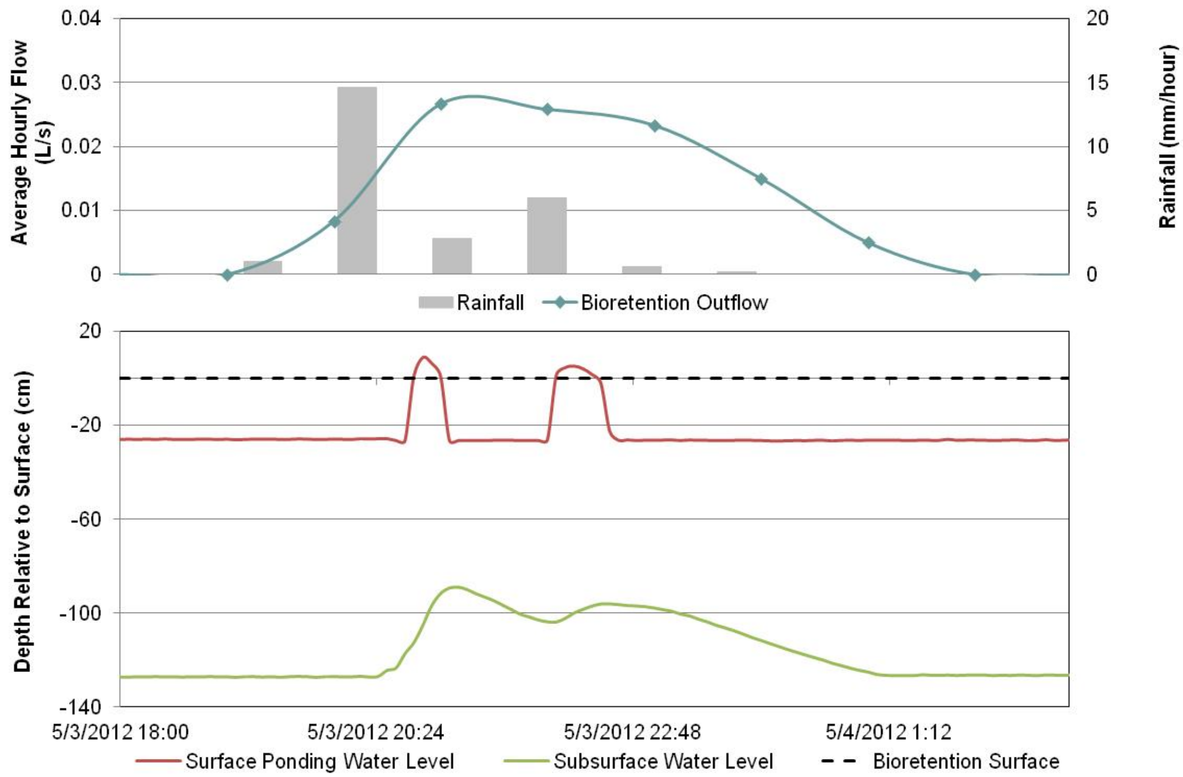
Hydrographs and Hyetographs


0.04
0.03
0.02
0.01
0
Average Hourly Flow (L/s)
20
15
10
5
0
Rainfall (mm/hour)
Rainfall
Bioretention Outflow
40
-20
-80
-140
Depth Relative to Surface (cm)
5/18/2011 21:00
5/19/2011 1:48
5/19/2011 6:36
5/19/2011 11:24
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface

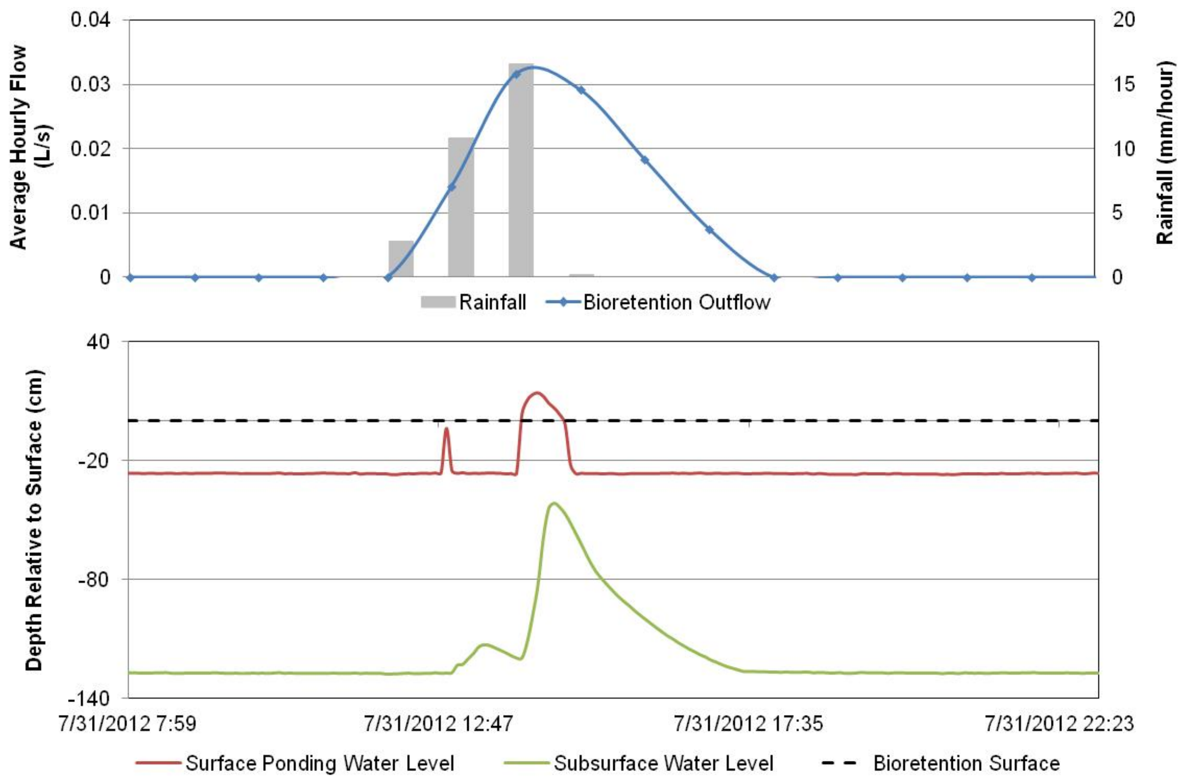

0.04
0.03
0.02
0.01
0
Average Hourly Flow (L/s)
20
15
10
5
0
Rainfall (mm/hour)
Rainfall
Bioretention Outflow
40
-20
-80
-140
Depth Relative to Surface (cm)
10/19/2011 19:59
10/20/2011 3:11
10/20/2011 10:23
10/20/2011 17:35
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface


Average Hourly Temperature (°C)
Rainfall (mm/hour)
Rainfall
Air Temperature
Average Hourly Flow (L/s)
Depth Relative to Surface (cm)
1/26/2012 16:24
1/27/2012 4:24
1/27/2012 16:24
1/28/2012 4:24
Bioretention Outflow
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface

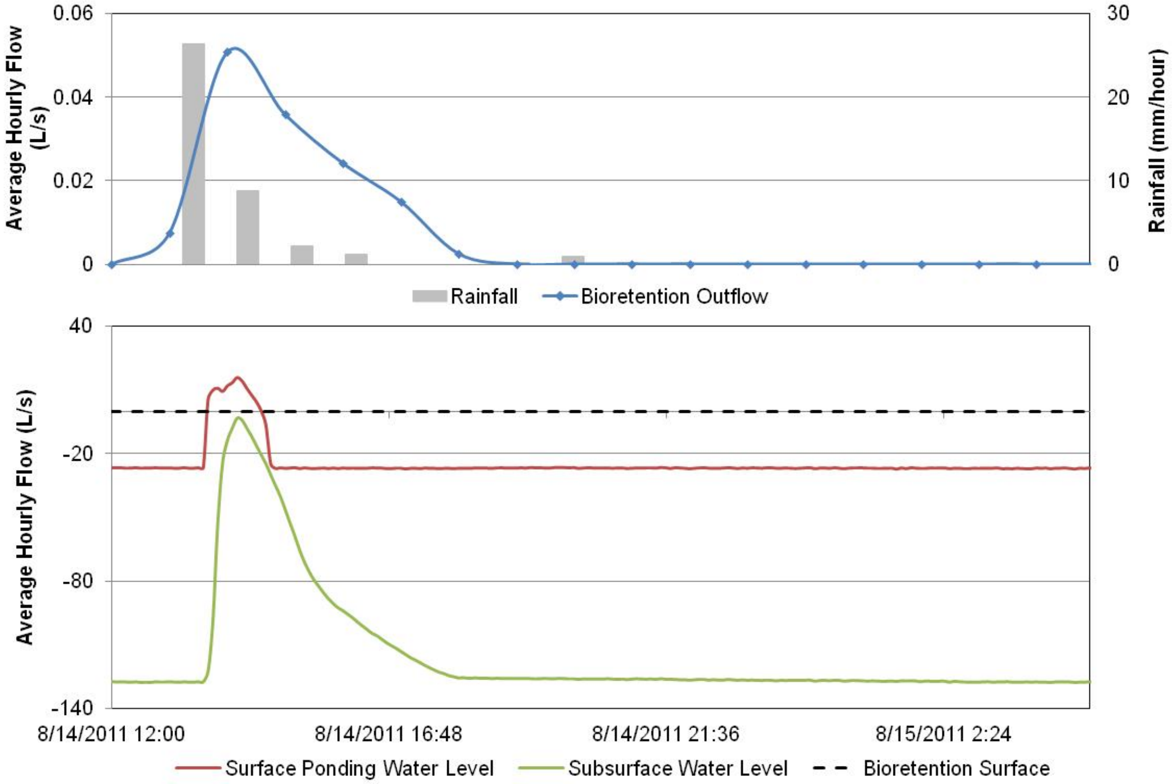

Average Hourly Termperature (°C)
Rainfall (mm/hour)
Rainfall
Air Temperature
Average Flow (L/S)
Depth Relative to Surface (cm)
3/2/2012 18:57
3/2/2012 23:45
3/3/2012 4:33
3/3/2012 9:21
3/3/2012 14:09
Bioretention Outflow
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface



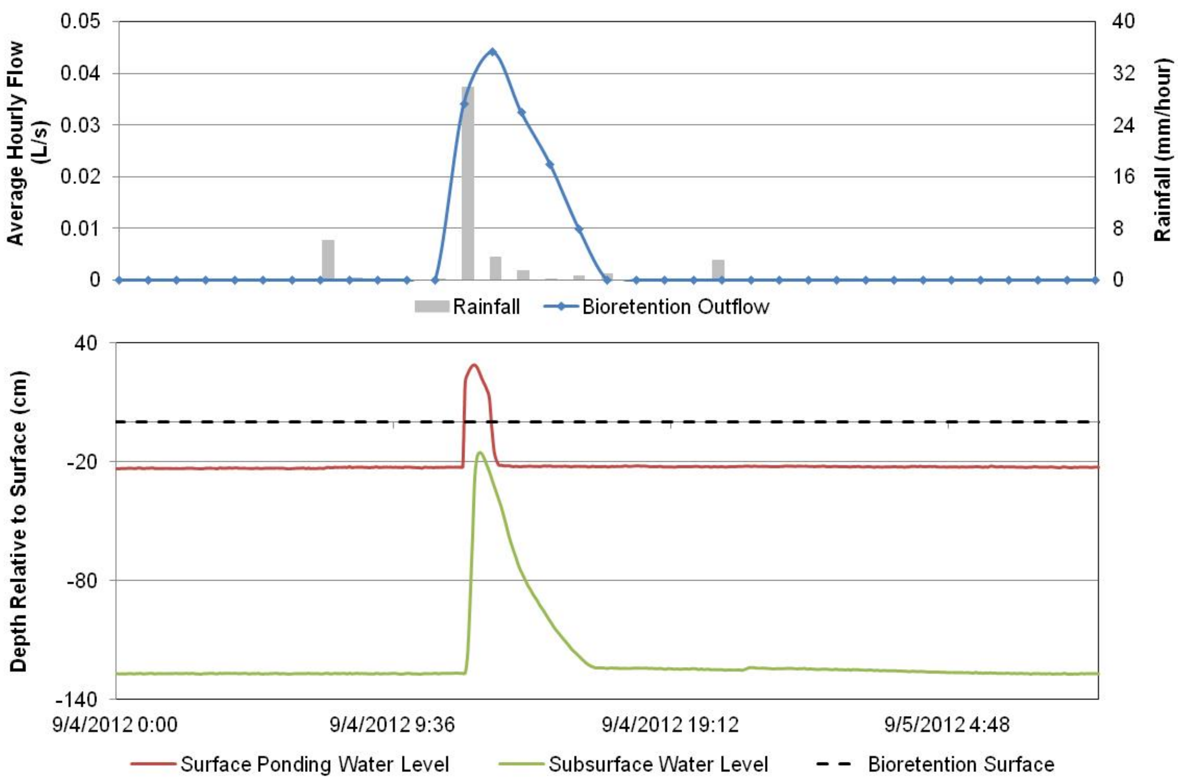
Average Hourly Flow (L/s)
0.04
0.03
0.02
0.01
0
Rainfall (mm/hour)
20
15
10
5
0
Rainfall
Bioretention Outflow
Depth Relative to Surface (cm)
20
-20
-60
-100
-140
5/3/2012 18:00
5/3/2012 20:24
5/3/2012 22:48
5/4/2012 1:12
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface



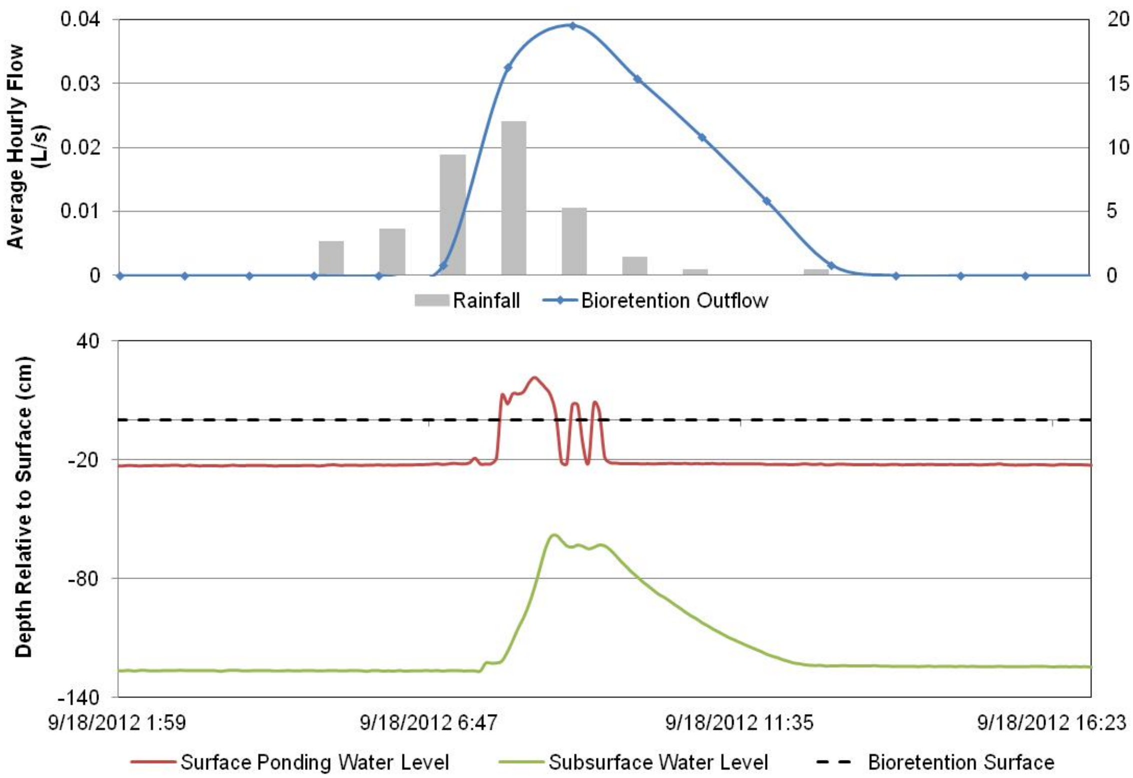
Average Hourly Flow (L/s)
0.04
0.03
0.02
0.01
0
Rainfall (mm/hour)
20
15
10
5
0
Rainfall
Bioretention Outflow
Depth Relative to Surface (cm)
40
-20
-80
-140
7/31/2012 7:59
7/31/2012 12:47
7/31/2012 17:35
7/31/2012 22:23
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface

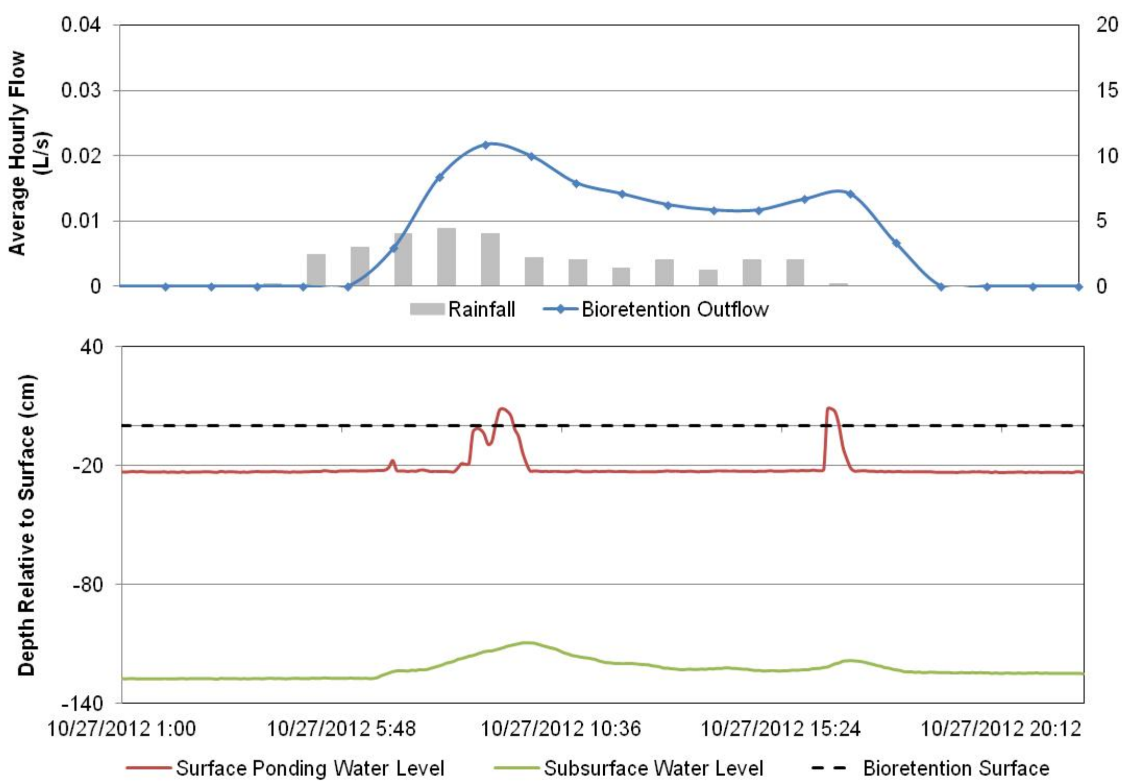


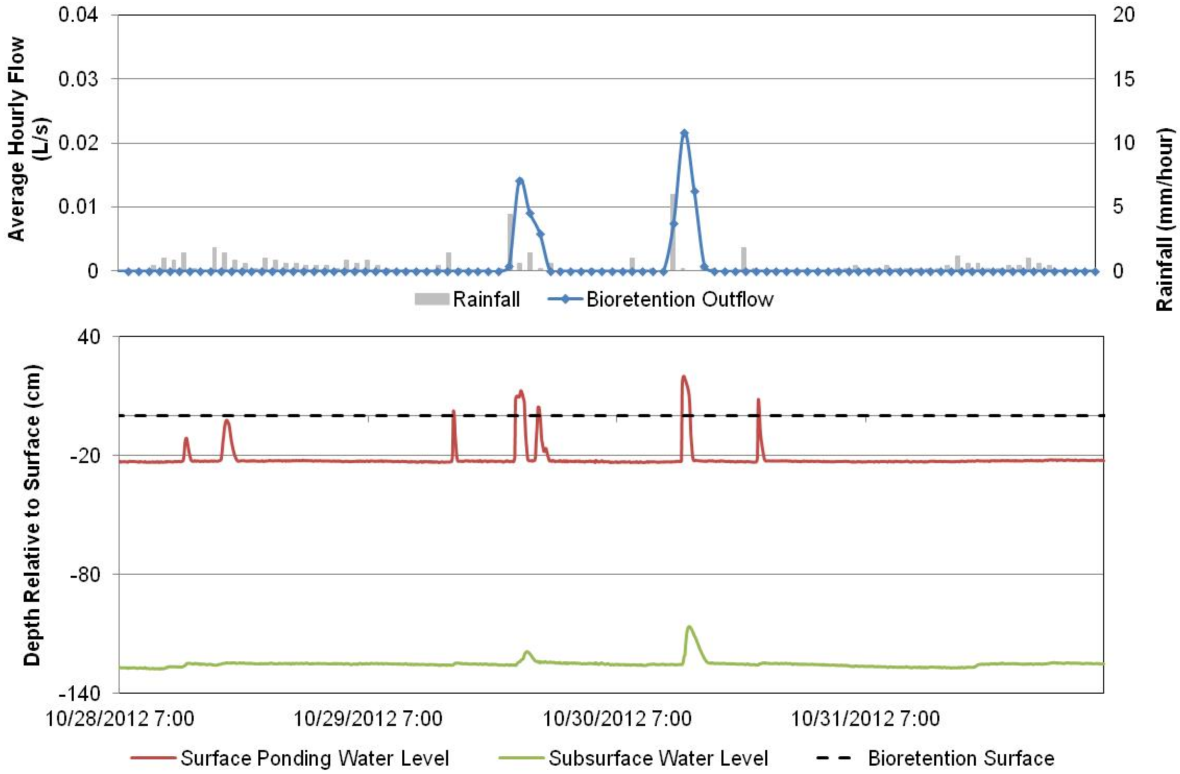
Average Hourly Flow (L/s)
Rainfall (mm/hour)
0.06
0.04
0.02
0
30
20
10
0
Rainfall
Bioretention Outflow
Average Hourly Flow (L/s)
40
-20
-80
-140
8/14/2011 12:00
8/14/2011 16:48
8/14/2011 21:36
8/15/2011 2:24
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface



Average Hourly Flow (L/s)
Rainfall (mm/hour)
0.05
0.04
0.03
0.02
0.01
0
40
32
24
16
8
0
Rainfall
Bioretention Outflow
Depth Relative to Surface (cm)
40
-20
-80
-140
9/4/2012 0:00
9/4/2012 9:36
9/4/2012 19:12
9/5/2012 4:48
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface


0.04
0.03
0.02
0.01
0
Average Hourly Flow (L/s)
20
15
10
5
0
Rainfall (mm/hour)
Rainfall
Bioretention Outflow
40
-20
-80
-140
Depth Relative to Surface (cm)
9/18/2012 1:59
9/18/2012 6:47
9/18/2012 11:35
9/18/2012 16:23
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface


0.04
0.03
0.02
0.01
0
Average Hourly Flow (L/s)
20
15
10
5
0
Rainfall (mm/hour)
Rainfall
Bioretention Outflow
40
-20
-80
-140
Depth Relative to Surface (cm)
10/27/2012 1:00
10/27/2012 5:48
10/27/2012 10:36
10/27/2012 15:24
10/27/2012 20:12
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface


Average Hourly Flow (L/s)
0.04
0.03
0.02
0.01
0
Rainfall (mm/hour)
20
15
10
5
0
Rainfall
Bioretention Outflow
Depth Relative to Surface (cm)
40
-20
-80
-140
10/28/2012 7:00
10/29/2012 7:00
10/30/2012 7:00
10/31/2012 7:00
Surface Ponding Water Level
Subsurface Water Level
Bioretention Surface