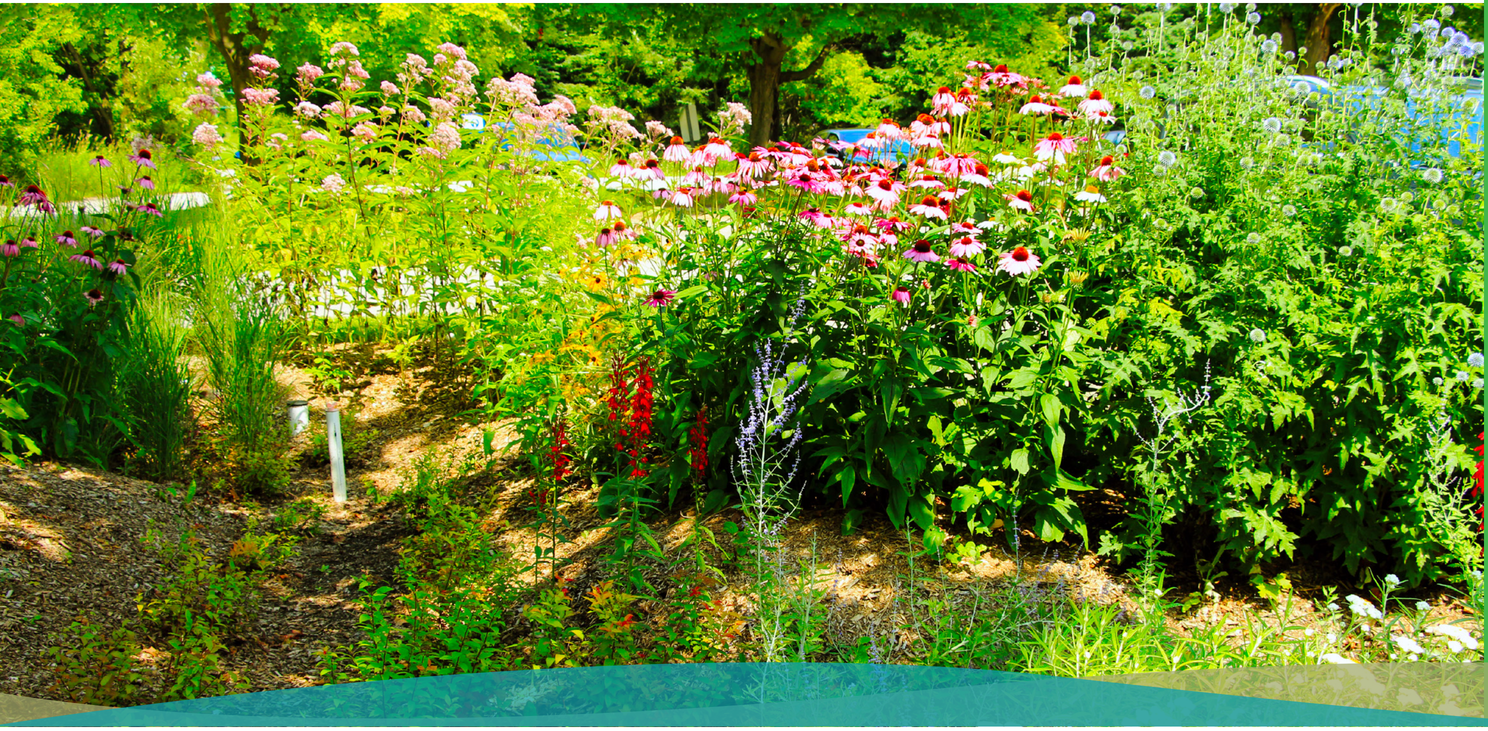
Performance Comparison of Surface and Underground Stormwater Infiltration Practices

TECHNICAL BRIEF

Low Impact Development Series



Bioretention and infiltration trenches are two of the most common Low Impact Development (LID) stormwater management practices. Bioretention consists of a shallow, excavated depression with layers of stone, prepared soil mix, mulch and native vegetation that is tolerant to salt and periodic inundation. Infiltration trenches are underground excavations filled with clear stone that occupy little to no space on the surface. Both practices treat runoff and promote infiltration, but only bioretention reduces runoff through evapotranspiration and utilizes the natural properties of soils and plants to remove pollutants.

This study compares the hydrologic, water quality and functional performance of a bioretention cell and infiltration trench that drain runoff from a parking lot at the Living City Campus in Vaughan, Ontario. The practices have identical drainage and subsurface infiltration areas, and both receive runoff through geotextile-lined stone inlets. Key parameters examined include runoff volumes, runoff volume reduction, surface ponding and infiltration, water quality, effluent water temperatures, soil moisture and operation and maintenance requirements. Results showed that the bioretention cell and infiltration trench reduced runoff volumes by 90 and 80%, respectively. Effluent water quality from the two practices was not statistically different for most variables, with the exception of phosphorus and iron, which were exported from the bioretention cell at higher concentrations. Loads of most pollutants from the LID practices were significantly lower than asphalt due primarily to lower outflow volumes. Loading the inlets with street sweepings from other busy parking lots did not have a measurable effect on the quality of effluent from either practice over the short duration of testing. The results of this study suggest that infiltration systems with pre-treatment via a geotextile-lined stone inlet can provide comparable treatment and runoff reduction benefits to traditional bioretention systems while reducing costs and occupying substantially less surface area.

Proper design and regular inspections are required to ensure facilities are not ponding water for extended durations after rain events. Rectifying clogging issues in well designed systems can usually be done cheaply and effectively by non-specialized maintenance personnel.

INTRODUCTION

Implementing Low Impact Development practices is challenging in densely developed urban areas because of high land values and the lack of space for surface practices. Underground practices like infiltration trenches are attractive options for stormwater treatment in these settings because the land above them can be used for parking or other uses. Bioretention cells are another treatment option in parking lots, but require more surface area. Typical bioretention cell designs in Ontario occupy a space that is at least 7% of the contributing drainage area. A common assumption is that bioretention provides superior treatment of stormwater pollutants to underground infiltration systems due to filtration and retention by the filter media (soil) and decomposition and uptake by soil organisms and plants, but this assumption has never been verified through field tests.

In catchments that drain to waterbodies where the assimilative capacity for nutrients is low, selection of LID BMPs needs to consider their relative capacity to remove nutrients from runoff. Several studies of bioretention practices have shown elevated concentrations of nutrients due to leaching of these constituents from the filter media/planting bed (STEP, 2008; Dietz and Clauson, 2005; Hunt et al., 2006). The coarse granular material in infiltration trenches would not be expected to act as a source of nutrients, but there have been concerns that coarse filtration of runoff would not remove pollutants as effectively as BMPs that provide filtration through soils or feature filtering pretreatment devices.

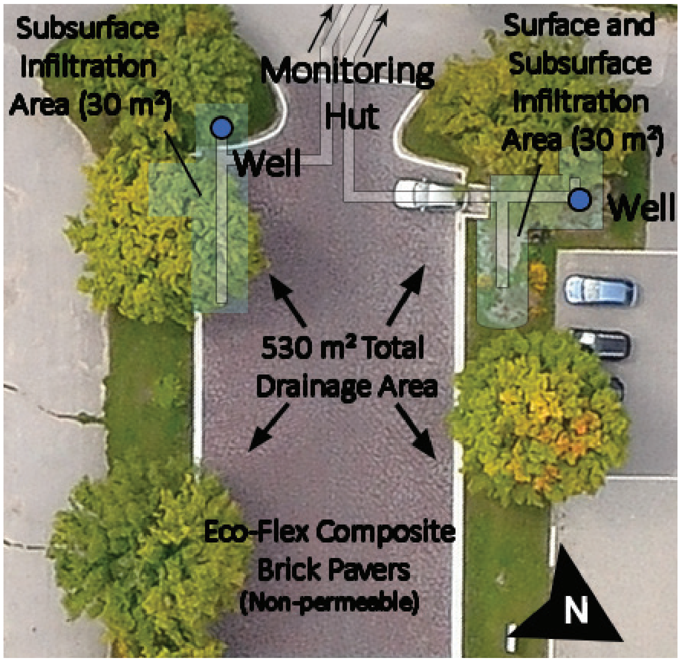


Figure 1 Plan view of the drainage area and treatment practices.

To make an informed decision regarding the most effective and affordable technology to implement in a certain context, it is of interest to better understand how their pollutant removal and runoff reduction performance compares to one another. While performance evaluation study results in the scientific literature for the various types of LID practices are often compared to one another, differences in the context in which the practices were located and their design objectives and material specifications make comparison of results between published studies subject to speculation.

This study compares the runoff reduction benefit, pollutant removal performance, and maintenance needs of an infiltration trench (underground infiltration practice) to that of a bioretention cell (surface infiltration practice) with identical sized drainage areas and infiltration footprints. Results from this comparison provide insight into the advantages and disadvantages of each type of practice, their design features and their suitability for application in low to medium traffic parking lot/road catchments.

STUDY SITE AND FACILITY DESIGN

This study was undertaken on the Visitor Centre parking lot at The Living City Campus in Vaughan, Ontario. To accommodate the study, the asphalt surface of a 530 m^2 portion of the parking lot was removed, regraded and resurfaced with non-permeable recycled tire-derived rubber composite brick pavers (Eco-flex® Churchill). Regrading of the pavement base created two parking lot surface catchments of 265 m^2 each that drain to a bioretention cell and infiltration trench. Both BMPs feature 30 m^2 infiltration bed footprints.

A plan view and cross section of the two practices are shown in Figures 1 and 2, respectively. Inlets to both systems consist of a 2 m^2 by 0.2 m deep layer of river stones, underlain by geotextile (Terrafix® 270R). The stones and geotextile in the bioretention inlet sit on top of a concrete pad graded to drain water into the 30 m^2 bioretention cell. In the infiltration trench, the stones and geotextile lie above a 55 cm deep 20 mm clear stone water reservoir wrapped with geotextile. The bioretention cell layering includes 75 mm of shredded hardwood mulch above a 40 cm deep filter media bed (60% sand, 40% silt and clay, and 5% organic matter by dry weight), and a 15 cm deep 20 mm clear stone gravel water reservoir wrapped with geotextile. Perforated drainage pipes (10 cm dia) are placed immediately on top of the geotextile and transition to solid pipe as they leave the infiltration beds. Anti-seepage collars were installed to prevent water from flowing along the gravel surrounding the pipes. Both practices drain to a monitoring hut where pipes are elevated to a level just below the base of the two infiltration beds.

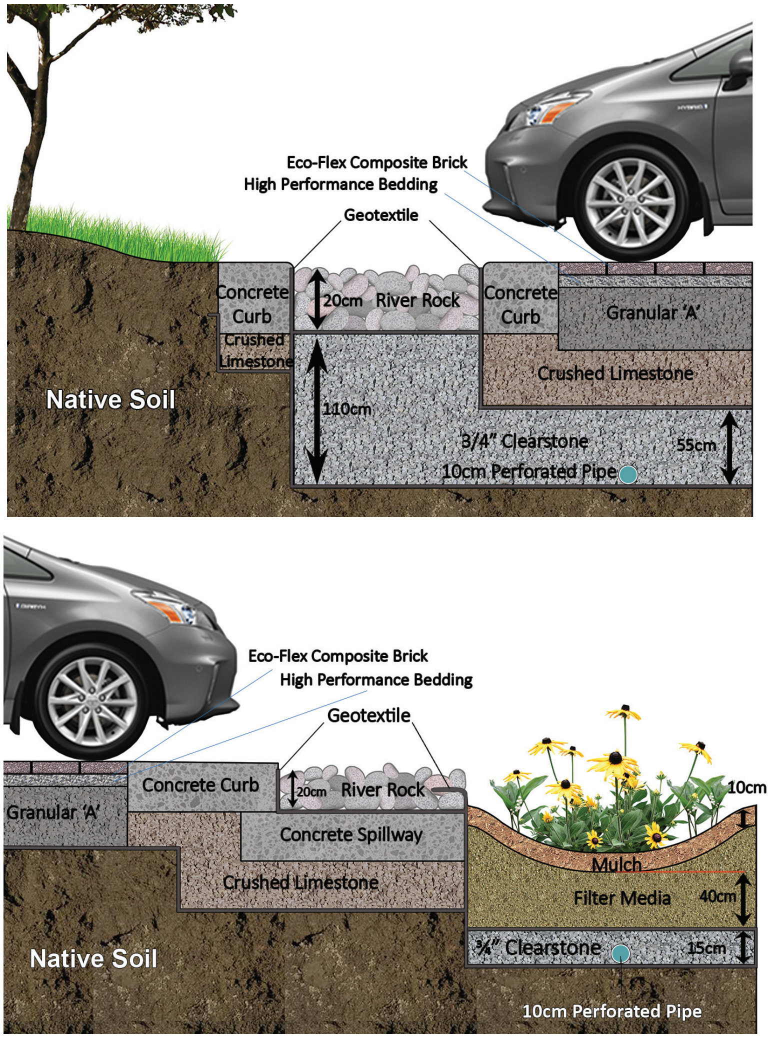


Figure 2. Cross-section of the infiltration trench (top) and bioretention cell (bottom).

APPROACH

The monitoring program was conducted from April to November over a two year period. Measurements included precipitation, flow, water quality, water temperature and functional attributes of the two stormwater treatment practices (e.g. clogging potential, maintenance requirements). Evapotranspiration was estimated based on actual measurements in a well vegetated field less than 1 km from the study site using the Bowen Ratio Energy Balance method. Flows from the parking lot drained laterally to concrete curbs and then into the inlets of the two practices. These flows could not be measured directly. Therefore, inflows to the system were estimated using unit area flow measurements from an adjacent asphalt reference site. A 1.5 mm abstraction factor was used to account for water losses through the interlocking pavers above what may have occurred via direct evaporation from the asphalt surface. There was a strong correlation between measured asphalt flow volumes and volume estimates based on pavement area and precipitation, lending further confidence to the inflow estimates. Outflow rates and volumes, water quality and water temperature were monitored in a surface sampling hut downstream of the site. Samples from the asphalt surface and infiltration practices were volume weighted to accurately represent the event mean concentration of the monitored events.

The difference between total inflows (as measured from the asphalt reference site) and total outflows provided the basis for calculating the volume of runoff reduced through infiltration and evapotranspiration. The capacity of the two treatment systems to improve water quality was assessed through statistical analyses of the quality of outflows from each of the LID practice outlets and the quality of untreated runoff from an asphalt reference pavement, which had similar traffic density and sources of contamination. Load reduction factors were addressed based on event mean concentrations and measured runoff and outflow volumes from the three sites. Water quality variables analyzed included solids, general chemistry, nutrients and metals.

FINDINGS

Relative to the asphalt control, both practices reduced runoff by over 79%, despite the presence of low permeability subsoils. Table 1 shows the runoff reduction rates over the full study period, and after July 2013 when the elevation of the drainage outlets were lowered to generate more runoff for

Table 1. Water balance and % runoff reduction for the bioretention cell and infiltration trench over 4 different monitoring periods.

	Bioretention					Infiltration Trench				
Monitoring Period	Inflow Volume (mm)	Outflow Volume (mm)	Evapotranspiration (mm)	Groundwater Recharge (mm)	Runoff Reduction (%)	Inflow Volume (mm)	Outflow Volume (mm)	Evapotranspiration (mm)	Groundwater Recharge (mm)	Runoff Reduction (%)
Apr-Oct, 2013	437.7	30.4	41.4	365.9	93.0	437.7	64.2	11.2	362.3	85.3
Apr-Nov, 2014	306.3	41.1	48.2	217.0	86.6	306.3	88.4	2.6	215.3	71.2
Jul-Oct, 2013;Apr-Nov,2014	557.4	60.8	51.0	445.6	89.1	557.4	136.6	9.5	411.3	75.5
Apr-Oct, 2013; Apr-Nov,2014	744.0	71.5	89.6	582.9	90.4	744.0	152.6	13.9	577.6	79.5

Notes: In July, 2013, the elevations of the drainage outlets were lowered by 20 cm to generate more runoff for sampling purposes. Inflow volumes of both practices were estimated based on unit area measured flow measurements of an asphalt reference site.

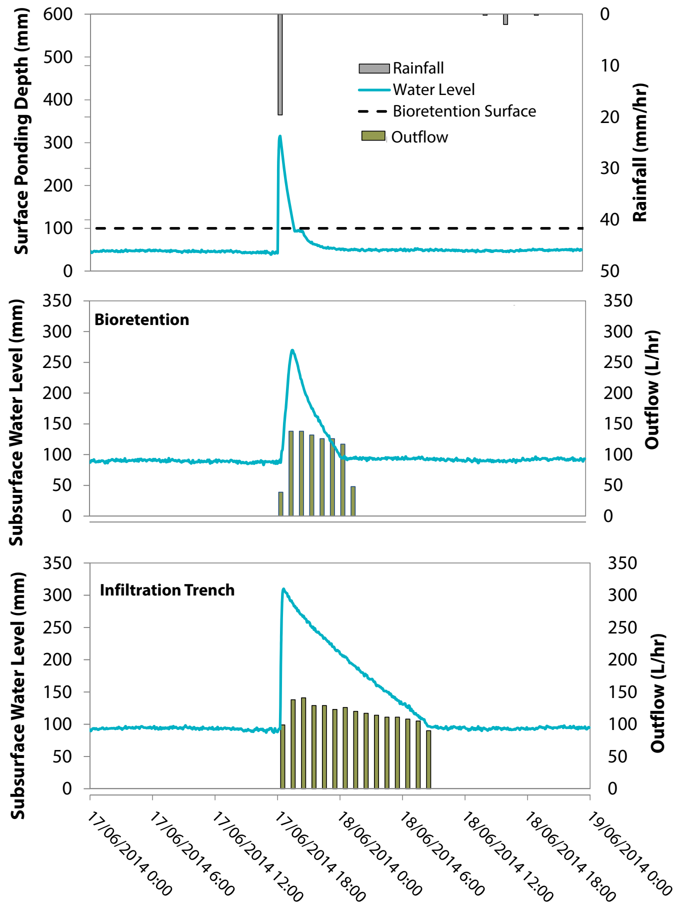


Figure 4. Runoff and water level response to a 19.6 mm rain event over one hour on June 17, 2014.

sampling purposes. Prior to July 2013, rain events less than 20 mm in depth were not producing outflows, even though the drainage pipe was only elevated 20 cm above the native subsoils. Both practices generated outflows for most events with more than 10 mm of rain after the outlets were lowered to correspond with the base of the two infiltration practices. Outflows during rain events greater than 20 mm represented 81% and 59% of total outflows from the bioretention and infiltration trench, respectively. The two practices also delayed and attenuated peak flows, resulting in a flow regime that closely replicates rainfall retention and overland flow patterns observed in natural landscapes.

It was estimated that approximately 14% and 3% of total runoff inputs were evapotranspired by the bioretention cell and infiltration trench between April and November, respectively. Evapotranspiration estimates were derived from Bowen Ratio Energy Balance measurements over the same period in a well vegetated field less than 1 km from the study site. Data gaps were estimated based on a Thornthwaite and Mather energy balance model using coefficients derived from measured data over a three year period (Delidjakova et al, 2014). Comparing the two practices reveals that most of the difference in outflow volumes between the two practices could be accounted for by differences in evapotranspiration (Table 1 and Figure 3). The two practices had similar groundwater recharge volumes. The capacity of the bioretention soils to retain runoff is particularly evident for events less than 15 mm in size, during which outflow volumes from the bioretention cell were less than one fifth of those observed from the infiltration trench.

Throughout the summer, water ponded on the surface of the bioretention cell only during events with more than 10 mm of rain and remained on the surface for an average duration of 3 hours. Ponded water remained on the surface for close to 17 hours during the largest event on July 27, 2014. During this event, ponding depths reached a maximum of 29 cm above the low point of the cell surface. Infiltration after rainfall events occurred relatively quickly, at a rate of over 100 mm/h (Figure 4). Winter ponding was rare because there were few melt events and none of these were combined with rain. Previous studies have shown that prolonged winter ponding can occur during rain on snow events, and are caused by the formation of a thin layer of ice at the surface (Van Seters and Graham, 2014). Throughout the study period, the parking lot remained free of standing water because the overflow elevation was below that of the pavement surface.

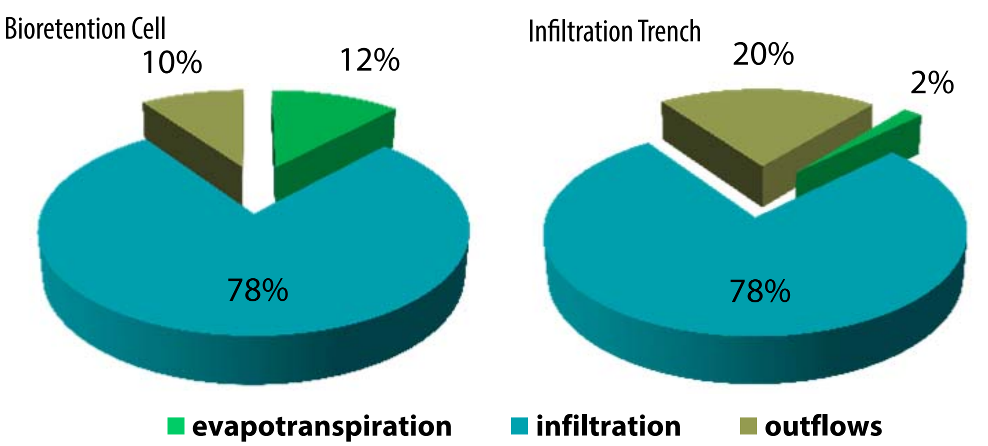


Figure 3. The proportion of runoff entering the bioretention cell (left) and infiltration trench (right) that infiltrated, evapotranspired, or was discharged to receiving waters from April to October 2011 and April to November 2012.

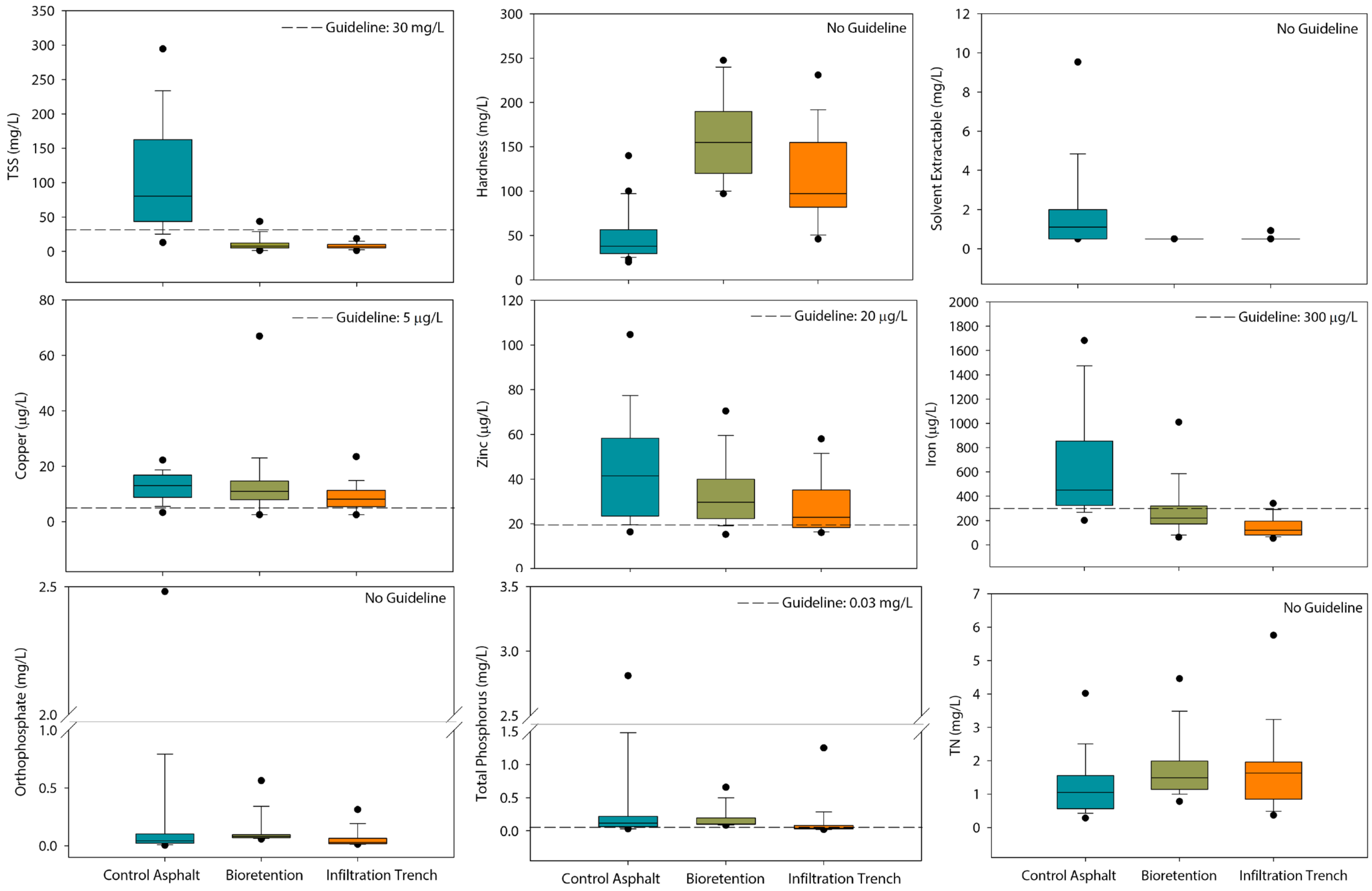


Figure 5. Box plots of selected stormwater pollutants.

The concentrations of several pollutants in the outflows of both practices were significantly lower (α=0.05) than in asphalt runoff. Figure 5 compares effluent from the asphalt, infiltration trench and bioretention cell for several common stormwater pollutants. Significant differences among the sites are presented in Table 2 for these and other water quality variables. While the biorention and trench had lower concentrations of TSS, lead, iron, copper, zinc and oil and grease, asphalt runoff had lower or not significantly different concentrations of several nutrients (e.g. total nitrogen, ortho-phosphate, nitrate). Only total phosphorus concentrations from the trench were lower than asphalt runoff. Although nitrate nitrogen was higher in the bioretention and trench samples, concentrations were consistently below the Canadian Environmental Sustainability Indicator of 2.93 mg/L. Hardness and alkalinity were higher in bioretention and infiltration trench outflows, which is considered to be beneficial, as higher values of these variables helps to reduce the toxicity of some heavy metals to aquatic life (e.g. lead). Median pH concentrations of all outflows exhibited a narrow range of between 7.6 and 8.0, which is considered to lie within an acceptable range for the protection of aquatic life.

The concentrations of most pollutants in the bioretention and infiltration trench outflows were not significantly different. Notable exceptions included ortho-phosphate, total phosphorus and iron, all of which were significantly higher in bioretention outflows than in those of the infiltration trench (Table 2). The filter media soil was believed to be the source of phosphorus. All of the sites exhibited sharp increases in dissolved phosphorus during the fall when plants died off and leaves accumulated in the inlets and catchbasin.

On a unit area basis, the mass of contaminants discharged from the bioretention and infiltration trench facilities was over 75% less than that discharged from the conventional asphalt control for most water quality variables. Exceptions included nitrogen variables, particularly nitrate, and metals such as nickel that were found to have very low concentration in asphalt

Table 2. Statistically significant differences at the 95% confidence level between effluent concentrations from the Asphalt pavement (A), Infiltration Trench (IT) and Biotention Cell (BR).

Variable	A vs IT	A vs BR	BR vs IT
TSS	A>IT	A>BR	Not sig
pH	IT>A	BR>A	Not sig
Alkalinity	IT>A	BR>A	BR>IT
Hardness	IT>A	BR>A	Not sig
Oil and Grease*	A>IT	A>BR	Not sig
Total Phosphorus	A>IT	Not sig.	BR>IT
Ortho-phosphate	Not sig.	BR>A	BR>IT
Total Nitrogen	Not sig.	BR>A	Not sig
Total Kjedahl N	Not sig.	Not sig.	Not sig
Ammonia	A>IT	A>BR	Not sig
Nitrate	IT>A	BR>A	Not sig
Lead	A>IT	A>BR	Not sig
Iron	A>IT	A>BR	BR>IT
Copper	A>IT	Not sig.	Not sig.
Zinc	A>IT	Not sig.	Not sig.
Nickel	IT>A	BR>A	Not sig.

* Not detected in more than 15% of samples at one or more sampling stations.

runoff samples (Table 3). The bioretention cell reduced loads more effectively than the infiltration trench for zinc and oil/grease, while the infiltration trench achieved better treatment of phosphorus, nitrogen variables (e.g. TKN, nitrate), iron and copper. In both cases, pollutant loads were largely reduced through runoff volume reductions associated with infiltration and evapotranspiration.

Enhancing the contaminant load entering the infiltration trench and bioretention cell did not result in a measurable decline in effluent water quality from either practice. Since the parking lot drainage area for the evaluation was not heavily trafficked, there was an interest in assessing the effect of higher contaminant loading on the quality of effluent from the two practices. To evaluate this scenario, 18.4 kg of dry sediment and dirt was collected from the surface of several high use commercial parking lots in the Greater Toronto Area. On October 14, 2014, 9.2 kg of the collected sediment was placed in each of the inlets. This amount is roughly equivalent to loading from nine 25 mm rain events with an inlet TSS event mean concentration of 150 mg/L. The sediment was placed at the upstream opening of the inlets to ensure runoff entering the practices flowed through and across the sediment prior to entering their respective infiltration areas. A 5.2 mm rain event occurred shortly after application of the sediment, but the event was too small to generate outflow from either facility. Two water quality samples were collected during subsequent rainfall events on October 16 and November 23rd, 2014, prior to decommissioning of monitoring equipment for the winter period. Water quality results from the two events did not show distinct variations in effluent quality from the time period prior to loading, suggesting that the capacity of the two stormwater practices to treat water is not strongly influenced by sediment loading rates. Further investigations are needed to determine the effect of enhanced sediment loading on effluent quality over an extended time period.

Maximum effluent temperatures of the bioretention cell and infiltration trench were 5.3°C cooler than the asphalt during the summer, thereby providing a more suitable thermal regime for downstream aquatic life. This represents an important benefit of these practices over other treatment systems, such as ponds, which have been shown to increase runoff temperatures by 5 to 9°C. The maximum temperature of bioretention and infiltration outflows during hot summer periods was 26.1°C and 27.8°C, respectively. The bioretention temperature is considerably warmer than observed in other bioretention systems (e.g. Van Seters and Graham, 2014). The difference is likely attributable to the thermal properties of the recycled rubber composite pavers. The rubber composite pavers were found to be 12°C warmer than asphalt on one hot summer day. It should be noted, however, that while the bioretention and infiltration trench outflows were above the desired level for protection of cool water fisheries, the thermal load from these practices would have been very low due to significant reductions in runoff volumes. Unlike stormwater ponds, which often discharge warm water even during dry weather, the LID treatment systems virtually eliminated dry weather flows.

After two years of operation, the systems continue to infiltrate and drain very well. Maintenance of the bioretention cell has been limited to routine weeding, pruning and spring planting, with both practices needing annual cleaning of the inlets. Manual irrigation of the bioretention cell was required during the first year to aid with initial establishment of plants, but only rarely during the second year of operation. Regular maintenance of the parking lot bioretention cell cost approximately $2000 per year, mainly due to weeding, while the infiltration trench cost only about $200 to maintain. Pipes and outlets remained clear of debris and there was no damage to vegetation from snow plowing or winter parking lot maintenance activities. Surface infiltration rates have remained stable over the first two years of operation.

The bioretention cell was approximately 13% more expensive to construct than the infiltration trench construction

Table 3. Estimated loads and load reduction rates for several common stormwater pollutants

Water Quality Variable	Bioretention Cell			Infiltration Trench		
	Loads In (g)	Loads Out (g)	Contaminant Load Reduction (%)	Loads In (g)	Loads Out (g)	Contaminant Load Reduction (%)
Total Suspended Solids	7766.3	207.2	97	7766.3	166.0	98
Ammonia+ammonium - N	16.3	1.5	91	16.3	1.6	90
Nitrate + nitrite - N	34.3	31.9	7	34.3	25.3	26
Total Kjeldahl - N	71.7	24.9	65	71.7	16.6	77
Total Nitrogen	101.8	56.4	45	101.8	40.6	60
Total Phosphorus	21.8	1.9	91	21.8	1.6	93
Phosphate	11.1	1.3	88	11.1	0.7	93
Oil and Grease	91.6	6.5	93	91.6	12.2	87
Copper	1.0	0.2	80	1.0	0.2	83
Iron	47.5	5.3	89	47.5	3.1	93
Lead	0.2	0.0	92	0.2	0.0	85
Nickel	0.2	0.1	42	0.2	0.2	11
Zinc	3.2	0.4	88	3.2	0.5	84

Notes: Influent loads are determined from monitoring of an asphalt reference site.

costs and will have higher landscape maintenance and long term rehabilitation costs. Since construction of the parking lot LID features included laying pavers and other components of the drainage and monitoring system, the contractor was unable to specify costs for the bioretention cell and infiltration trenches alone. Therefore, costs for the design, construction and materials of the two practices were estimated based on a life cycle costing tool developed by STEP for the Greater Toronto Area (Uda et al., 2013; STEP, 2013). Using this tool, initial construction of the two practices was approximately $517/m² for the bioretention cell and $450/m² for the infiltration trench. The life cycle cost includes routine maintenance activities and estimated rehabilitation costs incurred over a 50 year evaluation period, assuming a discount rate of 5%. Life cycle costs are expressed as 'net present values' (NPV), which represent the value of the future stream of costs (i.e. cell maintenance, rehabilitation) discounted to the present value via a 'discount rate' which reflects the investor's time value of money. Life cycle costs were $8000 higher for the bioretention cell due to filter media and plant material costs and annual maintenance of the landscape features and the assumption that the filter media would need to be partially rehabilitated after 25 ears.

CONCLUSIONS AND RECOMMENDATIONS

This study compared the hydrologic and water quality benefits of two practices with different surface footprints and filter media. Results showed that both practices reduced runoff by more than 79%, despite the presence of low permeability native subsoils. The bioretention cell retained 10% more water than the trench due to higher water retention by the filter media and plants, which resulted in higher rates of evapotranspiration, and improved overall runoff reduction. Effluent water quality from the two practices was similar, with the exception of phosphorus and iron, which were exported from the bioretention cell at higher concentrations. Low contaminant loads from both practices were strongly influenced by the capacity of the practices to retain and infiltrate runoff. The results of this study suggest that infiltration systems with pre-treatment via a geotextile-lined stone inlet can provide comparable treatment and runoff reduction benefits to traditional bioretention systems while reducing costs and occupying substantially less surface area. Ontario communities interested in a wider range of aesthetic, heat island mitigation, storage and rapid infiltration benefits should consider hybrid designs that combine the functions of both practices.

The following recommendations on bioretention and infiltration design and further research needs are offered based on the findings from this study.

Facility Design

- The 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 bioretention filter media was tested prior to installation, but in situ tests on the delivered media revealed the media to have a finer texture, suggesting that a different material was delivered, or the material was not uniformly mixed. Contracts with soil mixing companies should include clauses that guarantee that the material delivered meets pre-delivery test specifications.
- Despite the presence of 40% fines, runoff infiltrated well through the surface, with ponding occurring for relatively short durations. While further long term observations are needed, this finding lends support to landscape design professionals that suggest the current specification of 85-88% sand content in bioretention filter media may be lowered to allow for a more diverse range of plants, and reduced irrigation maintenance.

- The low permeability silty clay native subsoils at this site were sufficiently permeable to allow both practices to promote significant groundwater recharge. This finding further corroborates evidence from other STEP studies (Young et al., 2013a; Young et al., 2013b) showing that significant runoff volume reduction from infiltration is possible even on fine-textured native soils with limited capacity to infiltrate water. Further reductions in discharge volumes could have been achieved by raising the outlet to provide more opportunity for temporary water storage and infiltration from the granular reservoirs of both facilities.
- Current TRCA/CVC guidelines (2010) on bioretention systems recommend that the impervious drainage area to these facilities should be less than 15 times the size of their infiltration footprint to ensure optimal performance over the life of the facility. In this study, the bioretention cell functioned well with impervious to pervious area ratio of 9:1, confirming that an area at least this size can be effectively treated without erosion or pre-mature sediment clogging.
- Geotextile-lined river stone inlets were used in both practices evaluated in this study to remove coarse sediment and, in the case of the bioretention cell, prevent erosion of mulch and filter media. Large accumulations of sediment were removed each year from these pretreatment devices. The process of removal involved removing the stone and shaking out the underlying geotextile, a process that took about 4 hours for both practices. Where space permits, these types of inlets are recommended as an effective and low maintenance option that can extend the time interval required for major rehabilitation of these practices.

Further Research Needs

- The influence of pollutant loading on the quality of effluents from practices such as bioretention and infiltration trenches is not well understood. Research on the effectiveness of these practices at different loading rates is needed to assess how well practices may function in different land use contexts.
- Further research is needed on the long-term operation and maintenance requirements of bioretention cells and infiltration trenches, and changes in functional performance over time.

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Toronto and Region Conservation for The Living City