Evaluation of Permeable Pavements in Cold Climates

Kortright Centre, Vaughan

Prepared by: University of Guelph
Toronto and Region Conservation

Final Report 2012

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December 2012

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PUBLICATION INFORMATION

This research was undertaken collaboratively between the Toronto and Region Conservation Authority's (TRCA) Sustainable Technologies Evaluation Program (project lead: Tim Van Seters, B.Sc, MES and Glenn MacMillan, CET) and the University of Guelph, School of Engineering (project leads: Jennifer Drake, PhD candidate and Andrea Bradford, PhD, P.Eng). TRCA field support was provided by Christy Graham, Matt Derro, Paul Greck, Amanda Wilson and Caitlin Meanwell.

Report Citation: Drake, J., Bradford, A., Van Seters, T. 2012. Evaluation of Permeable Pavements in Cold Climates – Kortright Centre, Vaughan. Toronto and Region Conservation Authority.

Reports prepared under the Sustainable Technologies Evaluation Program (STEP) are available at www.sustainabletechnologies.ca. For more information about this project or STEP, please contact:

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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.

ACKNOWLEDGEMENTS

Financial support for this project was generously provided by the following organizations:

- Toronto and Region Remedial Action Plan
- Ontario Ministry of the Environment Best in Science Program
- Ontario Ministry of Transportation
- City of Toronto
- Region of Peel
- York Region
- Great Lakes Sustainability Fund
- Metrus Development Inc.
- Interlocking Concrete Paving Institute
- Morguard Investments
- Aecon

In kind-donations of services and materials were generously provided by the following organizations.

- Urban Ecosystems Limited (Engineering consulting services)
- Brown’s Concrete (Aquapave™)
- Unilock (Eco-Optiloc™)
- Lafarge (Hydromedia™ Pervious Concrete)
- Hanson (sampling vault)
- Ontario Ministry of the Environment (laboratory services)
- Armtec (pipes)
- Condrain (construction services)
- Dufferin Aggregates (aggregate base)
- Layfield Plastics (liner)
- Elgin (streetsweepers)

EXECUTIVE SUMMARY

Permeable pavements (PP) are one of several Low Impact Development practices that are being used to treat runoff and help increase infiltration in an effort to reproduce the pre-development hydrologic regime. Since PPs replace conventional asphalt, they are ideally suited to older built-up areas that lack stormwater management and have little to no space for conventional stormwater facilities. They can also be cost effective in new development areas where runoff reductions from infiltration can reduce or eliminate the need for sewer infrastructure beneath the pavement.

This three year study advances knowledge about the performance of PPs under Ontario climatic and geologic conditions by evaluating the functional, hydraulic and water quality effectiveness of three types of PPs and conventional asphalt. In addition, the study assesses the benefits of using PPs in areas with low permeability native soils, identifies critical cold climate factors that may influence performance, and compares the effectiveness of alternative pavement cleaning practices.

The research primarily centres on a new PP lot designed and constructed in 2009/10 by TRCA on the Living City Campus at Kortright in Vaughan, Ontario. The Kortright PP research facility provides the unique opportunity to simultaneous study multiple pavements subjected to the same local effects. This is the first research project of this scope to be conducted in Canada and under typical winter conditions. An underground sampling vault was installed downstream of the site to facilitate monitoring and drainage controls were designed to enhance infiltration into the silty clay native soils.

In order to assess the impact maintenance practices and in-situ conditions have on pavement performance, experiments were conducted on older PP parking lots within the Greater Toronto Area (GTA). Multiple types of proprietary street cleaners as well as labour intensive vacuuming and pressure washing on different types of PPs were examined. In-situ conditions were characterized according to drainage patterns, traffic use, age, and adjacent vegetation to evaluate impacts to pavement performance.

Study Findings

Results of this study show that PPs offer significant benefits for the treatment and management of stormwater over conventional asphalt-to-catchbasin collection systems. A key advantage of PPs is the capacity of these systems to reduce outflow volumes even when applied to areas with low permeability soils. The three evaluated PPs, AquaPave™ (AP), Eco-Optiloc™ (EO) and Hydromedia™ Pervious Concrete (PC), did not produce direct surface runoff throughout the 22 month monitoring period of this study. Overall, the PPs reduced the volume of stormwater outflow by 43% and were shown to be capable of completely capturing (i.e. infiltrating and evaporating) the stormwater produced from rainfall events up to 7 mm in depth. This reduction of stormwater volume mitigates the adverse impact of the urban landscape on receiving surface water systems.

In addition to reducing outflow volumes, the PPs delayed and reduced peak flows. Attenuation was observed throughout all seasons, including the winter, over the duration of the study. On average, PP peak flows were 91% smaller than peak runoff flows from the asphalt pavement. A median 14 hour attenuation (or 2.9 lag ratio) of outflow was observed from the PPs. The slower and more controlled outflow closely mimics natural interflow and reduces the risk of flooding and erosion in downstream receiving waters.

Winter data showed the PP systems to function well even during freezing temperatures. Elevation surveys indicated that freezing temperatures did not cause significant surface heaving or slumping. A substantial spring thaw was observed in March 2011, during which the PP delayed the outflow of melt water by three days and greatly reduced peak flows. Increases in outflow volume were occasionally observed during the winter and spring due to the delayed release of stormwater stored within the aggregate reservoir.

Surface infiltration measurements revealed substantial reductions in permeability over the course of the study, although even at reduced permeability levels, all of the pavements continued to maintain sufficient capacity to rapidly infiltrate all rainfall from the observed storms. Between June 2010 and May 2012, permeability reductions of the narrow jointed permeable interlocking concrete pavement (PICP) (AP), wide jointed PICP (EO) and PC were 87%, 70% and 43%, respectively. These results indicate that PPs with larger surface opening may sustain critical infiltration capacity longer without maintenance than PPs with small surface openings.

The PC pavement continued to have extremely high infiltration capacity even after two years, with median infiltrations rates of 1,072 cm/hr at the end of the study in 2012. By contrast, the median surface infiltration rate of the narrow jointed PICP was only 20 cm/hr after 2 years. Vacuum sweeping provided only partial restoration of surface permeability for the PICPs. No benefit was observed from vacuum sweeping for the PC at Kortright, although the pavement retained a high infiltration capacity. Vacuum sweeping on other PP parking lots produced highly variable results and did not provide consistent removal of embedded fines within PICP joints and PC pavements.

Over the monitoring period, median/mean concentrations of several pollutants in PP outflow were significantly lower than median/mean concentrations in asphalt runoff, including suspended solids, extractable solvents (oil & grease), ammonia-ammonium nitrogen (NH_3, NH_4^+), nitrite, total kjeldahl nitrogen (TKN), total phosphorus, copper, iron, manganese and zinc. The PPs also generated a net reduction in total pollutant mass for all of these constituents in addition to dissolved solids, chloride, sodium, phosphate, and nitrates. Seasonality was more pronounced in runoff than in PP outflow. In the winter the concentration of pollutants associated with road salting were considerably higher in runoff than in PP outflow. The reduction in concentration is attributed to the detention and dilution of winter stormwater provided by the PP systems. Water quality data collected below native soils indicated that sodium and chloride will migrate onwards to groundwater systems, although further investigation is needed to determine how the presence of these constituents may affect the mobility of other stormwater contaminants, such as metals.

The PICP and PC pavements introduced different constituents into stormwater outflow as a result of leaching of materials within the pavement system. In the case of the PC this led to a gradual improvement in water quality over the course of the study, as mobile pollutants were ultimately flushed from the pavement. Throughout the first year of monitoring the PC effluent contained elevated levels of phosphate and released highly alkaline stormwater, which are undesirable characteristics for aquatic ecosystems.

Further investigation is needed to explore the implications of pollutant leaching on stormwater quality from large newly constructed PP installations. The long term change in water quality of outflows from these PPs is being investigated in a second phase of this project.

Recommendations

Results of this study indicate that PPs can be effective measures for maintaining or restoring infiltration functions on parking lots and other low volume traffic areas, even in areas with low permeability soils. The following recommendations are based on study findings and observations.

- Restricting outflow rates from partial infiltration PP systems through raised pipes or flow control valves is recommended to increase stormwater volume reductions through infiltration.
- Closed outlet valve tests suggested that raising the perforated outflow pipe in the cross section of the PP structure or elevating the discharge pipe downstream of the PP system is feasible on low permeability silty clay soils and may result in substantially larger outflow volume reductions than would occur from restricting outflow rates alone. Further investigation of this type of application on low permeability soils is recommended.
- Pollutant leaching of pavement and aggregate materials was observed, particularly for pervious concrete. Leaching was observed to decline as the pavement aged. For large pervious concrete installations, additional treatment may be required if outflows drain to ecologically sensitive streams. Further testing of the performance and leaching potential of different types of pervious concrete is recommended.
- PPs were observed to reduce the loads and concentrations of several stormwater contaminants. Additional investigations are needed to define the specific conditions (*e.g.* magnitude of load reductions, ecological sensitivity of receiving waters, maintenance guarantees) under which partial infiltration PP systems should be eligible for pollutant removal credits in Ontario jurisdictions.
- Vacuum cleaning of permeable interlocking concrete pavements was found to only partially restore surface permeability after 2 years of operation. Further tests of different techniques for loosening or dislodging compacted material in PP joints or pores prior to cleaning are needed to improve the effectiveness of regenerative air and vacuum sweeping trucks.
- Based on maintenance practices evaluated in this study, annual vacuum cleaning of permeable interlocking concrete pavements is recommended to increase the operational life of these pavements. The PC pavement maintained high surface permeability over the study period, and therefore maintenance is recommended less frequently (i.e. > 2 years).
- Further research on the long-term (*i.e.* > 3years) performance of PP systems is needed to assess how the hydrologic, water quality and functional characteristics of the pavements may change over time.
- In this study, the 2011/2012 winter was unseasonably warm with low amounts of snowfall. Additional monitoring of winter performance and behaviour is recommended.
- In 2011/2012 operational staff found that the PPs did not require salting as frequently as the asphalt pavement. Further research is needed to evaluate how and whether PPs can maintain safe conditions with lower salt use than conventional pavements.

- Elevation surveys of the pavements during this study showed no significant movement across the four pavement cells. Further testing of pavement movement under increased traffic frequencies and loading scenarios are needed to verify the range of functional conditions under which these pavements are suitable alternatives to asphalt.

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1.0 BACKGROUND

Roads and parking lots increase the imperviousness of land surfaces, resulting in increased volumes and rates of stormwater runoff, as well as the accumulation and wash-off of a variety of contaminants. Conventional stormwater management approaches have focused on conveying the runoff, and in some cases, detaining it near the outlet, to receiving waters. These approaches have helped to attenuate peak flows and improve water quality, but have not been successful in achieving the level of management necessary to maintain baseflow characteristics in streams, prevent stream erosion and avoid degradation of water quality and aquatic habitat (ABL, 2006).

In Ontario, provincial guidelines emphasize integrated management (Ministry of the Environment (OMOE), 2003) and prevention practices (OMOE and TRCA, 2001) along with source, conveyance and end-of-pipe controls (OMOE, 2003). Low Impact Development (LID) has emerged as an alternative to sole reliance on conventional urban stormwater management approaches. LID includes both planning techniques such as alternative development layout, narrower roads, impervious area disconnection and engineering techniques such as rainwater harvesting, bioretention and permeable pavement. When distributed, LID measures intercept rainfall and facilitate its use, return it to the atmosphere as evapotranspiration, infiltrate it into the ground, and/or detain and slowly release it in an effort to reproduce the rates and processes of the pre-development hydrologic regime.

Although comprehensive provincial design guidelines for LID techniques do not yet exist, detailed regional guidelines were developed (*e.g.* CVC and TRCA, 2010; GVRD, 2005) and several LID practices have, or are currently being evaluated under southern Ontario climatic and geologic conditions through initiatives such as the Sustainable Technologies Evaluation Program (STEP). In an effort to protect receiving waters, some municipalities and conservation authorities are actively advocating for LID approaches. For example, the Toronto Wet Weather Flow Management Guidelines (2006) and TRCA stormwater criteria (2012) require that a minimum 5 mm of each rainfall event be infiltrated or evapotranspired on site through LID practices.

Pervious concrete, porous asphalt and permeable interlocking concrete pavers (PICP) are specifically identified in several regional guidelines as one possible measure by which infiltration can be increased. Along with the aforementioned design guidelines there are several other technical design aids available for permeable pavements. Most recently, the American Concrete Institute published a report outlining materials, properties and mixture proportioning for Pervious Concrete (PC). The ACI publication is a resource for design and construction methods as well as testing and inspection practices for PC. Similar resources also exist for PICP and porous asphalt (PA) through the Interlocking Concrete Pavement Institute and the National Asphalt Pavement Association, respectively. A textbook on porous pavements written by Ferguson (2005) also provides details on several types of permeable pavements, including case studies and summaries of previous research.

Permeable pavements can be applied on parking lots or roads either alone or with other LID practices such as bioretention swales or islands. Since permeable pavements replace conventional asphalt, they are ideal for older built-up areas that lack stormwater management and have little to no space for conventional stormwater facilities. They can also be cost effective in new development areas where runoff reductions from infiltration can reduce or eliminate the need for sewer infrastructure beneath the pavement.

In 2008, a 36 month monitoring evaluation of PICP was completed on a parking lot at Seneca College's King Campus (TRCA, 2008). The study addressed a variety of common concerns about permeable pavements relating to the hydrologic benefits of the pavements, long term clogging of surface drainage cells, and the potential for groundwater and soil contamination associated with infiltration of contaminated runoff. The results have helped to quantify the benefits and constraints to the use of permeable pavements to satisfy municipal water balance, water quality and erosion control requirements in developments throughout the GTA.

Despite recent research on permeable pavements, a lack of data demonstrating their effectiveness continues to be a barrier for implementation of these technologies in Ontario. Even though many LID technologies are supported by a large body of peer-reviewed literature or independent performance evaluations the field conditions of LID research projects rarely reflect Ontario climate or geology. The long-term effectiveness of permeable pavements, especially on tight soils (*i.e.* hydrologic soil types C and CD), and their ability to function under cold climate conditions have not been extensively evaluated. In particular, there are concerns that underdrain applications of permeable pavements on soils dominated by silt or silt-clay combinations provide only negligible runoff reduction benefits, and that filtration of pavement runoff through coarse granular base media (open graded media) does not significantly improve effluent quality. These concerns are an especially important barrier to wider adoption of permeable pavements in the Greater Toronto Area as most of the remaining buildable areas are characterized by low permeability soils. This project is aimed at addressing some of these questions while also informing the development of GTA specific guidelines for the technology.

2.0 STUDY OBJECTIVES

This research on permeable pavements is being conducted collaboratively between TRCA's Sustainable Technologies Evaluation Program and the University of Guelph's School of Engineering. The overall purpose of the study is to advance knowledge about the performance of permeable pavements under Ontario climatic and geologic conditions. The specific objectives are to:

- Identify key factors affecting design (material type, traffic pattern, maintenance practice, organic inputs) and quantify impacts on long term performance;
- Compare the performance of various permeable pavements (different types of permeable interlocking concrete pavers, Pervious Concrete) and traditional impervious asphalt in terms of functional, hydraulic and water quality effectiveness;
- Assess benefits and limitations of using permeable pavement in areas of native soils with low permeability and determine required type and degree of underdrainage;
- Evaluate seasonal hydraulic and water quality performance over 3 years and identify critical cold climate factors that may influence performance, such as winter maintenance, material durability, freeze/thaw cycles and salt pervasiveness;
- Evaluate and compare effectiveness of alternative cleaning practices;
- Recommend design, and operation and maintenance modifications to enhance overall performance.

The research primarily centres on a new permeable pavement lot at TRCA's Living City Campus at Kortright, in Vaughan, Ontario. The Kortright site provides the unique opportunity to simultaneous study multiple pavements subjected to the same local effects. This is the first research project of this scope to be conducted in Canada and under typical winter conditions. The study investigates the performance of the Kortright lot over 3 years. Drainage controls were designed to enhance infiltration into native soils and measures were put in place to assess the risks of stormwater infiltration on groundwater sources of drinking water.

In order to assess the impact maintenance practices and in-situ conditions have on pavement performance, experiments were conducted on older permeable pavement parking lots within the Greater Toronto Area (GTA). Multiple types of proprietary street cleaners as well as labour intensive vacuuming and pressure washing on different types of permeable pavements were examined. In-situ conditions were characterized according to drainage patterns, traffic use, age, and adjacent vegetation to evaluate impacts to pavement performance.

3.0 STUDY SITE

The parking lot for this project is located at TRCA's Living City Campus at Kortright in Vaughan, roughly 8 km north of Toronto. The Living City Campus is a centre for education and research on sustainable technologies and, as such, generates frequent visitors interested in innovative approaches to building and urban design. The parking lot includes five parking bays. Each bay is separated by a grassed berm with mature trees. Prior to construction, drainage from the parking lot was directed towards vegetated areas and swales around the perimeter, ultimately draining to a tributary of the Humber River.

In 2009, one of the parking bays was replaced with new permeable and impermeable pavements. The new permeable pavement parking lot, shown in Figure 3.1, consists of four 230–233 m^2 pavement cells. Two cells were constructed with permeable interlocking concrete pavers (AquaPave® and Eco-Optiloc®), one cell was constructed with Pervious Concrete and one cell was constructed with traditional asphalt. The clear stone granular base for the permeable pavements provides roughly 49 cm of storage. A schematic of the facility is shown in Figure 3.2 and outlines the location of the 4 pavement cells and general location of the drainage pipes. A description of the construction and photographs of the new parking bay is provided in Appendix A.

Figure 3.1: Kortright permeable pavements

Each permeable pavement cell is drained by a perforated pipe placed 50 cm below the surface at the interface between the open graded granular sub-base layer and the native soil. The asphalt cell is drained via a catchbasin. Infiltrated water collected from each of the 3 cells as well as runoff collected in the catchbasin is conveyed separately in sealed pipes to a downstream sampling vault. A Mirafi Filter Weave® 500 geotextile was placed below the base as a separation layer. Underdrains for each cell are fitted with flow restrictors to control the rate of drawdown after storm events and prolong the period over which infiltration can occur. The pavement cells are hydraulically separated by concrete curbs which extend down to the bottom of the native soil to ensure the separation of runoff and infiltrated stormwater for each pavement type. Concrete pipe collars at cell boundaries prevent water movement along granular trenches surrounding pipes. Beneath the AquaPave cell a second perforated pipe is placed on a 1.0 x 20 m impermeable liner below native material ranging in depth between approximately 0.5 to 1 m. The native material is shallowest beneath the trench in which the central pipes are contained (Figure 3.3).

Geotechnical investigations during the summer of 2008 were conducted at 4 locations to characterize the soil, water table and subsurface geological conditions beneath the parking lot. Selected samples were sent to a laboratory for water content and grain size analyses. Briefly, the borehole data showed native soil conditions below the existing pavement structure to consist primarily of silt to silty clay soils underlain by clayey silt till material at 1.8 to 2.4 m. These glacial till soil types are typical in this area and often interspersed with cobbles and boulders with some gravel inclusions. Clay content in the samples ranged between 7 and 30%. The saturated hydraulic conductivity of silty clay till materials typically ranges between 10^{-6} and 10^{-4} cm/s, which is equivalent to an infiltration rate of 12 to 50 mm/h based on conversion factors provided by Ontario Ministry of Municipal Affairs and Housing (1997). While this seems very low, it should be noted that, even at an infiltration rate of only 1 mm/hr, runoff from a 48 mm event would fully infiltrate over 2 days. The water table beneath the parking lot and across the Kortright property lies several meters below the surface.

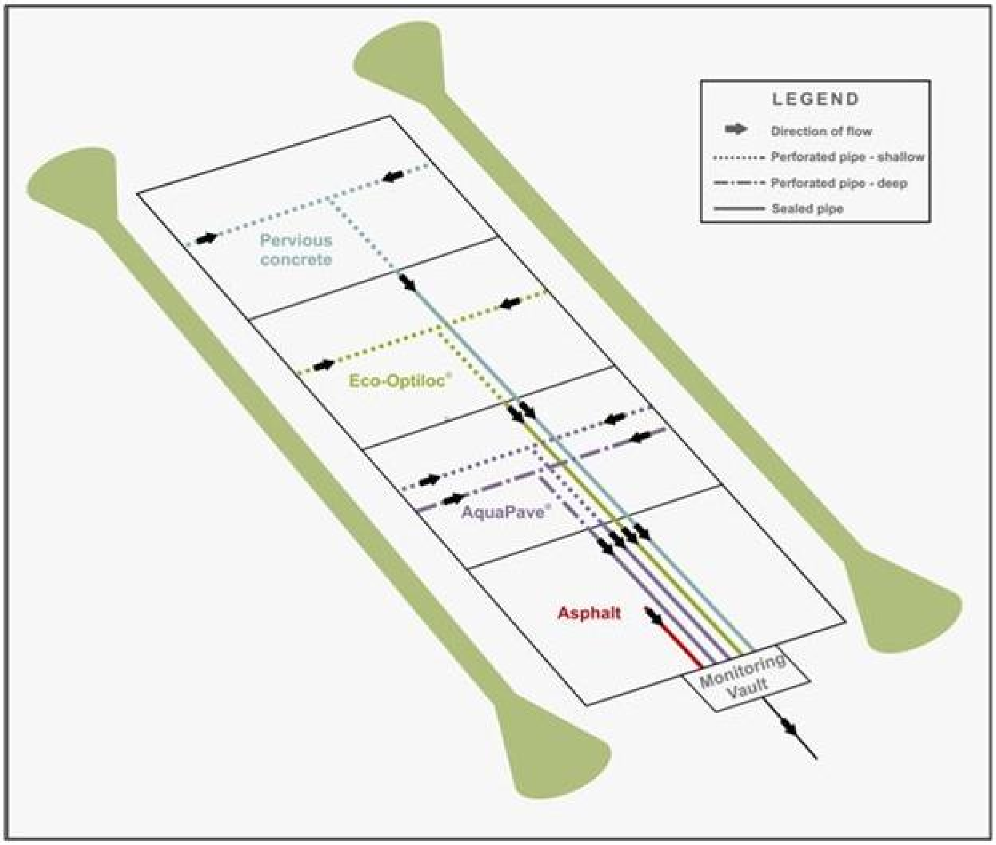


Figure 3.2: Schematic of Kortright permeable pavement

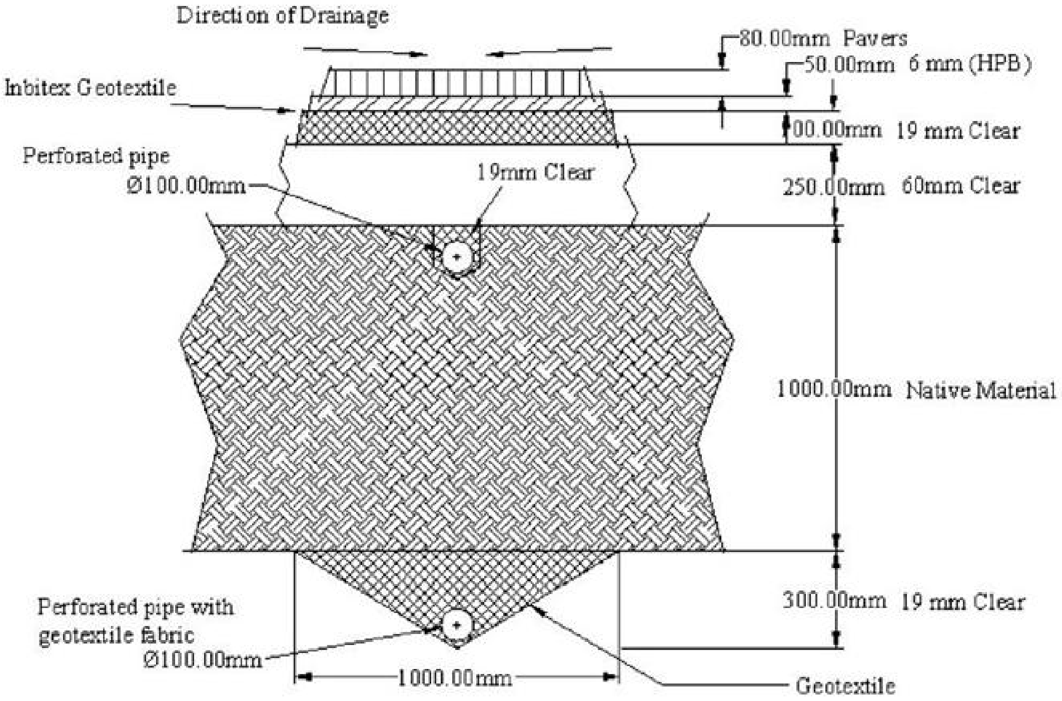


Figure 3.3: Cross sectional view of AquaPave PICP cell

4.0 STUDY APPROACH

4.1 Experimental Set-up and Data Collection

Inside the control vault the quantity and quality of surface and subsurface flows are continuously monitored. Water quantity data is collected with Geneq tipping flow buckets while water quality samples are collected with ISCO automated samplers. Wells in each cell are equipped with Onset Hobo® U20-001-04 or Diver® water level sensors to continuously record water levels within the permeable pavement and granular base. Thermal conditions within the permeable and asphalt pavement structures, and in the effluent from the asphalt and AquaPave plots, are monitored using Onset 12-Bit Temperature Smart Sensors®. The sensors in three of the pavement structures were installed as a vertical profile in the surface course and base materials, as shown in Figure 4.1. A meteorological station located at the Kortright Centre records precipitation and air temperature data at 5 minute intervals.

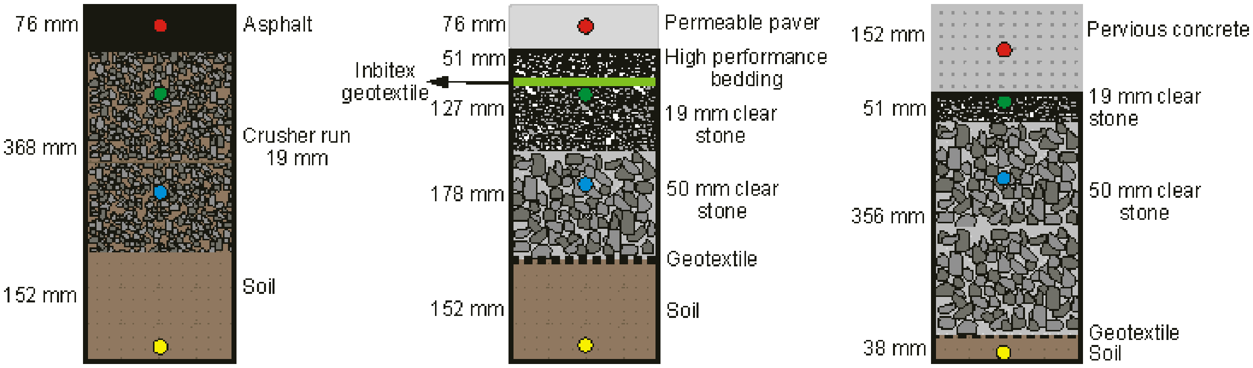


Figure 4.1: Location of temperature sensors in the asphalt, AquaPave and Pervious Concrete structures

The double pipe collection system beneath the AquaPave allows comparisons among water samples collected in the upper and lower pipes representing the underdrain flows and infiltrated water, respectively. Using 2 collection pipes at different depths facilitates study of the effect that infiltration through native soils has on water quality and provides a basis for evaluating potential risks to groundwater in situations where the seasonally high water table is 0.5 m below the base of the permeable pavement.

Ball valves attached to the collection pipes restrict the flow of water out of the parking lot. For the 1st year of data collection valves for the permeable pavements were closed to an opening of approximately 1 mm so that stormwater would draw down slowly after rain events, thereby increasing infiltration into the native soils. The 1 mm orifice was considered the smallest opening that could be achieved without risk of clogging while still allowing stormwater drawdown in less than 48 hours. Flows from the asphalt plot were restricted to ensure that stormflows did not exceed the tipping bucket's upper measurement limit of 60 L per minute. In November 2011 and April/May 2012 the ball valves were closed to assess infiltration rates into the native soils and evaluate the impact that detention time had on outflow volumes.

Water quality samples were proportioned according to flow 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 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 both parking lots and urban centres.

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	**Polycyclic Aromatic Hydrocarbons**
Aluminum	1-methylnaphthalene
Antimony	2-methylnaphthalene
Arsenic	7, 12-dimethylbenz(a)anthracene
Barium	Acenaphthene
Beryllium	Acenaphthylene
Boron	Anthracene
Cadmium	Benzo(a)anthracene
Calcium	Benzo(a)pyrene
Cobalt	Benzo(b)fluoranthene
Chromium	Benzo(k)fluoranthene
Copper	Benzo(e)pyrene
Iron	Benzo(g,h,i)perylene
Magnesium	Chrysene
Manganese	Dibenzo(a,h)anthracene
Molybdenum	Fluoranthene
Nickel	Fluorene
Lead	Indeno(1,2,3-c,d)pyrene
Potassium	Naphthalene
Selenium	Perylene
Silver	Phenanthrene
Sodium	Pyrene
Strontium	
Thallium	
Titanium	
Uranium	
Vanadium	
Zinc	

Inevitably, sections of the pavement cells will be subjected to localized factors, such as traffic patterns, snow removal practices and vegetation, which may affect short and long-term performance. Surface infiltration capacity has been measured throughout the pavement cells following the ASTM Standard test C 1701/C 1701M – 09, *Standard Test Method for Infiltration Rate of in Place Pervious Concrete,* and compared with documented spatial variables. Annual surveys of pavement elevations document any pavement movement due to frost heave, slumping, ravelling, load cycling, etc. A camera installed in the Spring of 2011 was used to monitor traffic patterns at the site.

Although the Kortright parking lot is cleaned regularly it was uncertain if cleaning practices would significantly impact hydrologic performance because of the pavement's young age. Therefore older permeable pavements (minimum of 2 years old) within the GTA were used as field sites to evaluate cleaning practices. Table 4.2 lists GTA parking lots that were used to evaluate cleaning practices.

Table 4.2: Permeable pavement parking lots

Location	Age	Uses	Underdrain	Reservoir details
Earth Rangers Foundation, Woodbridge	2004	Drop off and parking	unconfirmed	55 cm Granular A base, 10 cm high performance bedding
MTO Guelph Line Commuter parking lot	2007	Parking	unconfirmed	unconfirmed
Exhibition Place's BMO Field, Toronto	2007	Parking	Yes	unconfirmed
Sunset Beach, Richmond Hill	1998	Drop off round about & handicap parking	No	2.5 cm sand bedding, 15 cm compacted Granular A, 15 cm well compacted Granular B
Seneca College King's Campus	2004	Parking	No	45 cm Granular A base and 15 cm high performance bedding
East Gwillimbury GO Station	2004	Commuter Drop off and Pick up	Yes	15 cm Granular A, 45 cm Granular B, geotextile at the base
St. Andrew's Church, Niagara-on-the-Lake	-	Parking	unconfirmed	unconfirmed

Cleaning experiments have tested multiple types of proprietary street cleaners as well as labour intensive vacuuming and pressure washing practices. Hydrologic performance before and after pavement cleaning was measured and analyzed for statistically significant improvements. Samples of accumulated dirt and debris were collected and categorized. Confounding variables such as antecedent conditions and machine performance were minimized as much as possible. Experiments were organized on dry days and demonstration street cleaners were operated by manufacturer or supplier representatives to ensure it was operated correctly. Cleaning experiments were conducted during or immediately after the spring thaw and during the summer. Debris and clogging material is most abundant during the spring but antecedent conditions are more variable. Repeating the experiment during the summer provided more controlled experimental conditions.

4.2 Data Analysis

At the Kortright parking lot the pavement cells were subjected to the same conditions and loadings. Comparisons and analysis of pavement performance were made for both inter and intra annual time scales. Analysis focused on four research topics: pavement type performance, spatial performance, risks to groundwater and impacts of maintenance. Time-dependent relationships and interaction of variables were determined through statistical and regression analysis. Table 4.3 summarizes the variables associated with each research topic.

Table 4.3: Performance variables

Pavement Type Performance	Spatial Performance	Risk to Groundwater	Impacts of Maintenance
1. Rainfall hyetograph 2. Air temperature 3. Exfiltrated water hydrograph 4. Pavement type 5. Exfiltrated water quality 6. Pavement temperature 7. Drawdown time 8. Pavement deterioration and movement 9. Season and pavement age	1. Pavement type 2. Infiltration capacity 3. Surface clogging material 4. Traffic patterns 5. Maintenance patterns 6. Adjacent vegetative material 7. Pavement deterioration and movement 8. Season and pavement age	1. Rainfall hyetograph 2. Air temperature 3. Exfiltrated water hydrograph for upper drains 4. Exfiltrated water quality at upper and lower drains 5. Drawdown time 6. Season and pavement age	1. Maintenance practice 2. Infiltration capacity 3. Surface clogging material 4. Antecedent conditions 5. Pavement age

Once the relationships between performance variables is understood modifications to design as well as operation and maintenance procedures can be made to achieve specific performance objectives such as maximizing infiltration, minimizing risks to groundwater or minimizing maintenance costs.

For each precipitation or melt event, hydrologic characteristics including peak flow (Q_P), duration, total volume (V_T), total unit volume (V_{Tunit}), and hydrograph centroid (t_C) were calculated and used to estimate total volume and peak flow reductions, lag times and lag coefficients.

Total Unit Volume: $$V_{Tunit} = \frac{V_T}{Area}$$

Percent volume reduction (*VR*): $$VR = \frac{V_{Tunit}^{control} - V_{Tunit}^{PP}}{V_{Tunit}^{control}} \times 100$$

Percent peak flow reduction (*QR*): $$QR = \frac{Q_{Pcontrol} - Q_{Ppp}}{Q_{Pcontrol}} \times 100$$

Lag time (t_l): $$t_l = t_{Cpp} - t_{Ccontrol}$$

Lag coefficient (k_l): $$k_l = \frac{t_{Coutflow}}{t_{Cinflow}}$$

Water quality data were analyzed for pollutant removal in terms of concentration and mass reductions. Reduction efficiencies were calculated using the median event mean concentration (EMC) for control and PP data. Mass reductions were calculated to determine the total mass of pollutants captured by the PPs. Negative reduction efficiencies or mass loading reductions signify an increasing pollutant concentration or mass.

Reduction efficiency (ER): $RE = \frac{EMC_{control} - EMC_{PP}}{EMC_{control}} \times 100$

Event loading (L): $L = EMC \times V_T$

Mass loading reduction (MLR): $MLR = \sum_{i=1}^{n} L_{control}^{i} - L_{PP}^{i}$

Descriptive statistics including maximum, minimum, mean and median were calculated for EMC water quality data. Some of the water quality data were censored by minimum detection limits (MDL). If the censored EMC data for a given water quality variable were <10% of the total for the same variable, censored results were assumed to be $\frac{MDL}{2}$. If the censored data were between 10 and 50% of the total for the water quality variable, censored results were estimated using regression on order statistics (ROS) with the statistical software program ProUCL.

5.0 PREVIOUS LITERATURE

The following sections provide a brief summary of previous literature and an overview of the research in the major areas that are being addressed by the study. For the purposes of the literature review the content has been structured under the headings of runoff reduction, pollutant removal, groundwater contamination potential, comparison of different types of permeable pavements, and effectiveness of maintenance practices.

5.1 Runoff Reduction

Permeable pavements help preserve natural hydrologic functions by infiltrating stormwater runoff and promoting groundwater recharge. Several field studies have demonstrated that permeable pavements can result in significant reductions in runoff when installed on sandy soils (e.g. Brattebo and Booth, 2003; Collins et al., 2008). Although there are only a few studies that have examined permeable pavements installed on fine textured soils (hydrologic group C), the available evidence indicates that these soils can infiltrate a substantial proportion of annual rainfall volumes (Tyner et al. 2009, TRCA, 2008; Dreelin et al., 2006, Fassman and Blackbourn, 2010). Permeable pavements have also been shown to be capable of infiltrating water during the winter. Roseen *et al*. (2009b) observed that over two winter seasons porous asphalt and pervious concrete pavements were often clear of ice and snow faster than traditional pavements.

Native soils at the site for this study consist of silty clay till (hydrologic group C), and are characteristic of soils in many other parts of the GTA. The potential for permeable pavements to reduce runoff on these soils were assessed by comparing event and seasonal unit area flow volumes from the impermeable asphalt with unit area flow volumes from the underdrains below the three types of permeable pavements. Seasonal differences in flow volumes are attributed to infiltration and evaporation from the granular base. These volumetric differences provide the basis for evaluating reductions in runoff relative to the conventional asphalt.

5.2 Pollutant Removal

Permeable pavements help improve the quality of urban stormwater by allowing water to percolate through the subsurface media and trapping or breaking down contaminants through filtration, adsorption, microbial decomposition and other chemical and biological reactions within the soil or granular media (Pitt *et al.*, 1996). The capacity of permeable pavements to improve the quality of water infiltrated through the base and native soils depends on several factors, particularly the chemical characteristics of the water entering the pavement and the texture, permeability and organic content of the underlying soils. All else remaining the same, dirtier water infiltrated through very porous soils with low fractions of organic content and low sorption capacities will tend to pose a higher risk to groundwater (Pitt *et al.*, 1996).

Several studies have indicated that soils and granular media can retain heavy metals in urban runoff, thereby preventing transport to lower soil horizons and groundwater. In Calgary, a pilot-scale installation of PICP and pervious concrete was shown to reduce Total Suspended Solids (TSS) by 90 to 96%

(Brown *et al.*, 2009). The field observations were also supported by similar TSS removal results in lab-based experiments and both pavements were reported to meet the current TSS removal guidelines for the City of Calgary. In Washington, stormwater concentrations of copper, zinc and motor oil were significantly improved through infiltration via a PICP installation that received constant traffic over a period of 6 years (Brattebo and Booth, 2003). The researchers reported that 88 and 100% of asphalt runoff samples exceeded Washington receiving water standards for zinc and copper, respectively. By contrast, only 6 and 17% of PICP infiltrate samples (n=18) exceeded the standards for copper and zinc, and motor oil was consistently below analytical detection limits, even though the soil through which water infiltrated was only 10 cm deep. A study conducted at Guelph University in Ontario reported similar water quality improvements, especially for zinc and iron, after infiltration of stormwater through PICP and a shallow base course (Shahin, 1994).

On porous asphalts, pollutants accumulate mainly within the surface pores and, to a lesser extent, on the geotextile layer separating the base course layer from the underlying native soil (Legret *et al*., 1996). Copper, lead, zinc, and cadmium are retained near the surface in association with clogging particles (Legret *et al*., 1999). Sampling of water percolating through a porous asphalt pavement in Rhode Island, New York also showed good removal of PAHs within the base course (Boving *et al*., 2008). In the Rhode Island study, dissolved nutrients (PO4, NO3) from wind blown dust and atmospheric deposition were less effectively attenuated. In North Carolina, Bean *et al.* (2007) compared water that had filtered through a 275 mm open graded PICP base with conventional asphalt runoff. They reported significantly lower PICP infiltrate concentrations of zinc, total phosphorus, ammonia and TKN, but no significant differences in total nitrogen, nitrates, dissolved phosphorus, TSS and copper.

Although there are very few studies addressing pollutant removal during winter months there have been some promising published results. A study in New Hampshire monitored the performance of porous asphalt over two winter seasons (Roseen *et al.* 2009a). The study found that the pavement removed SS, total petroleum hydrocarbon-diesel, dissolve inorganic nitrogen, total phosphorus and total zinc during the winters. It has also been shown that winter salting or de-icing practices require substantially less salt on permeable pavements because snow melt is able to infiltrate which prevents ice forming on the pavement surface (Roseen *et al*. 2009b).

While previous studies have generally reported improvements in runoff quality after filtration through granular base course layers, it is still unclear whether or not, in field applications, these improvements are sufficient to meet local site water quality criteria for stormwater management, particularly in areas with low permeability native soils. Only a few of the earlier studies were conducted in cold climates over the winter and none have explicitly examined the effect that road salts may have on contaminant removal processes. Further, many of the pavement designs in the literature were not designed to detain runoff for significant periods of time, as occurs at this study site, and there are no studies that have specifically examined the effect that runoff detention time has on effluent quality.

In this study, the effect of permeable pavements on surface water quality has been evaluated by comparing the quality of subsurface runoff (i.e. underdrain runoff) from the permeable pavements to one another and to the quality of surface runoff from the asphalt pavement (concentrations and loads). Effluent quality has also been compared to applicable receiving water objectives in order to assess whether or not permeable pavements meet receiving water objectives. The groups of water quality variables analyzed for this purpose include general chemistry (e.g. pH, alkalinity, TSS, chloride), nutrients, metals, *E.coli* and PAHs.

5.3 Groundwater Contamination Potential

Contaminants that pose the greatest risk to groundwater via surface percolation include nitrate, a few pesticides, some polycyclic aromatic hydrocarbons (PAHs), enteroviruses, and salts such as chloride (Pitt *et al*., 1996). Pavements are not a significant source of nitrogen, pesticides or enteroviruses, hence there is a low risk of groundwater contamination from infiltration of these contaminants through pavements. Chloride is applied extensively to pavements during the winter as a de-icing agent and is of particular concern because it is extremely mobile in soil, and has been shown to increase the mobility of metals (Norrstrom, 2005; Backstrom et al, 2004). Oils and hydrocarbons are relatively insoluble in water and tend to be adsorbed readily by sediment and granular media. A growing body of research has demonstrated that naturally occurring microbial communities on pavement building materials (particularly the geotextile separation layer) helps to retain and degrade hydrocarbons within the base course layer, even in cold climates (*e.g.* Newman *et al*., 2006).

Most of the evidence demonstrating the capacity of soils to mechanically filter, biodegrade and retain urban runoff contaminants through physicochemical processes is documented in studies of infiltration basins and road side ditches or trenches. Runoff entering these systems originates from large drainage areas, often with multiple land uses. Hence, infiltrated water contains both a larger mass and more diverse range of contaminants than is characteristic of infiltrated water on permeable pavements. Despite high loading rates, however, studies of these systems show that attenuation of contaminants occurs predominantly within the upper soil layer beneath the base of the systems. In France, for instance, Barraud et al. (2005) reported that soil contamination (metals, PAHs, hydrocarbons, nutrients) in 4 infiltration basins ranging in age between 2 and 21 years was limited to less than 50 cm below the surface. Investigations of lead, zinc and copper in 12 urban runoff retention basins in California showed soil contamination to a depth of only 15 cm (Nightingale, 1975). In the same county, Salo et al. (1986) reported sharp declines in soil concentrations of lead, arsenic, nickel, and copper in the first meter below five groundwater recharge basins, two of which had been in operation for more than 20 years at the time of the study. Several organic compounds were monitored in this study both in the soil and groundwater, but analysis of these samples revealed no adverse effects on groundwater as a result of infiltrating stormwater.

During winter conditions in cold climates the situation is somewhat different than indicated above as road salts can have significant effects both on the soil structure and its ability to retain contaminants. Norrstrom (2005) identified colloid assisted transport as the primary mechanism for increased lead release from soils in a roadside ditch in Sweden. The formation of chloride complexes and potentially ion exchange were thought to be important in the release of zinc and cadmium. In an examination of pore water chemistry of roadside soils in Sweden, Backstrom et al. (2004) identified the primary mechanisms for metal mobilization as ion exchange, lowered pH, the formation of chloride complexes and potentially colloid dispersion. The presence of high concentrations of exchangeable calcium was thought to be an important factor in the enhanced release of cadmium.

In field studies, Boving et al. (2008) in Rhode Island and TRCA (2008) in the GTA both noted an increase in metal concentrations after infiltration through a permeable pavement structure and native soils. In the TRCA study, the increase occurred only after the second winter and was paralleled by higher loading rates, complicating a clear interpretation of the upward trend. Further monitoring is planned at this site to assess changes in metal concentrations over a longer time period.

In this study, the site was constructed to provide the controlled environment needed to investigate potential effects of stormwater infiltration on groundwater. For this purpose, a perforated pipe placed on a 1 x 15 m impermeable liner and perforated pipe located up to one meter below the native soils collected infiltrated water and conveyed it to the sampling vault for collection and analysis. A depth of one meter of soil was selected because existing guidelines for permeable pavements recommend that the seasonally high water table be no less than one metre below the base of the installation. Groundwater contamination potential is assessed by comparing permeable pavement infiltrate (from the PICP section) to Ontario drinking water objectives. Exceedances of drinking water objectives are regarded as a threat to groundwater. A statistical comparison of the quality of permeable pavement infiltrate with the quality of underdrain runoff provides the basis for determining changes in the chemistry of infiltrated water.

5.4 Comparison of Different Types of Permeable Pavements

While several studies have examined the effectiveness of specific types of permeable pavements, few have directly compared their effectiveness side-by-side at the same site. This study presents a unique opportunity to evaluate both their individual performance relative to conventional asphalt as well as their performance relative to one another. Water quality performance is of particular interest as the very different surface pore structure of PICPs and pervious concrete may have important influences on the trapping of soil particles and associated contaminants. The three types of pavements were compared and evaluated relative to one another through comparisons of runoff volumes, effluent concentrations and effluent loads.

5.5 Effectiveness of Maintenance Practices

Permeable pavements will clog over time as dust and dirt accumulate in the pavement matrix. Rain and traffic further exacerbate the problem by breaking up soil aggregates into finer particles that block the pores and allow for further accumulation of fines. Eventually a hard crust forms upon drying, creating a seal that can drastically reduce infiltration through the surface openings (Balades *et al*., 1995, Pratt *et al*, 1995).

Clogging has been a serious problem in some of the early permeable pavement installations. Lindsey *et al.* (1992) surveyed several infiltration facilities in Maryland, including 13 ‘porous pavement’ installations, most of which were between 5 and 6 years old. They found that only 2 of the 13 pavements surveyed were operating according to design, mostly due to sediment clogging. Although the authors did not provide details on the type of porous pavements or materials used in construction, more recent evaluations have shown that clogging in older permeable pavements is often due to the presence of sand, either in the bedding layer or applied on the surface to improve wheel traction during the winter (TRCA, 2008).

Newer installations use washed stone in the pavement openings (e.g. PICPs) and base because these resist breakdown into smaller particles with age, and the pore spaces are large enough to transmit fine particulate matter deeper into the coarser base layers, thereby reducing the potential for surface sealing. Experiments conducted on PICPs in Guelph showed considerably better infiltration on 8 year old permeable pavers constructed with a bedding layer of 7.5 cm of clear washed stone than those with a 10 cm mixture of clear washed stone and sand (Gerrits, 2001). These results are consistent with laboratory tests of various interlocking pavement surface drainage materials that have shown uniform sized washed gravel (2–5 mm) to provide the best infiltration capacities (Shackel, 1995).

In Maryland and North Carolina, Bean *et al.* (2007) simulated maintenance of permeable pavements using an approach similar to Gerrits (2001). Of the 14 concrete grid paver sites tested, 13 exhibited notably higher infiltration rates than the sites that had not undergone maintenance. The mean infiltration rate increased by 66%. The surface infiltration rate also increased substantially on the one PICP site subjected to maintenance. Similar results were found in maintenance tests of three PICP sites in the Greater Toronto Area, ranging in age between 2 and 18 years (TRCA, 2008).

Other studies that have evaluated pavement maintenance practices have not reached similar conclusions. Lab-based experiments by Pezzaniti *et al.* (2009) observed that simulated maintenance using a stiff brush and vacuum produced only a small improvement in hydraulic conductivity. Pezzaniti et al. (2009) simulated 35 years of synthetic stormwater through permeable pavement samples. Simulated runoff targeted a TSS concentration of 200 mg/L, and runoff rates were simulated based on the assumption that the permeable paved area received runoff from an equally sized upstream impervious area. Cleaning of the permeable interlocking concrete pavement surface after each year of simulated stormwater improved the outflow suspended solids concentration by only 12.4% compared to a test of the same pavement type without annual cleaning. After the 35 year simulation, 94% of the sediment had been retained within the permeable interlocking concrete pavement structure and the hydraulic conductivity of the pavement had been reduced by 59% from 1.7×10^5 to 6.5×10^4 mm/h.

Although surface cleaning may restore infiltration rates there are still several remaining questions regarding the type and frequency of maintenance needed to optimize long term performance. Chopra et al. (2010) investigated three types of maintenance; vacuuming, pressure washing and a combination of both. Lab based tests indicated that a combination of vacuuming and pressure washing provide the highest surface rejuvenation and pressure washing alone was more effective than vacuuming. Field tests conducted by Henderson and Tighe (2011) on pervious concrete pavements noted that small-scaled vacuuming and pressure washing did not rejuvenate surface permeability but some benefits were observed by washing the pavement with a large diameter hose.

While several studies suggest that maintenance can substantially restore permeability to clogged pavements, there are few if any studies demonstrating the actual effect of maintenance using standard pavement cleaning equipment. The present study examines two of the most common pavement cleaning methods - vacuum assisted sweeping and power washing - on older pavements that show signs of clogging either as a result of age or as a consequence of winter sanding practices. Research has been conducted on the various types of cleaning equipment available and a selection has been made based on standard criteria such as affordability, applicability, and ease of access by landowners. Costs and operational parameters (*e.g.* wash rate, vacuum rate) of the selected equipment has been documented and different treatments were tested to arrive at a ‘preferred’ method that can be subsequently developed into a maintenance guideline for permeable pavements.

6.0 MONITORING RESULTS AND ANALYSIS

6.1 Field Testing of the Experimental Design

The asphalt, AquaPave™ (AP), Eco-Optiloc™ (EO) and monitoring vault were installed in November 2009, followed by the Hydromedia™ pervious concrete (PC) in April, 2010. The entire parking lot was open to public traffic after the concrete had cured in early May. Field testing and adjustments to the experimental set-up were initiated shortly thereafter. After several rainfall events, it became apparent that there was unintended cross flow from one cell to the next. Water tests were employed to identify the sources of leakage and attempts were made to repair and seal the concrete collars and pipes in July and August, 2010.

Controlled water tests performed in fall 2010 indicated that complete hydraulic separation between permeable pavements had not been achieved. The water test involved pouring approximately 1000 L onto the EO pavement while its underdrain valve was closed. Over the following hours 123 L (12%) escaped through the PC underdrain and 23 L (2%) escaped through the AP underdrain. A similar test with the EO valve open had only 3 L escape from the PC underdrain. Applying water to one cell with the underdrain valve closed creates an artificial difference in water levels among cells. Therefore water movement between permeable pavement (PP) plots is anticipated to be much lower during natural precipitation events.

Winter conditions appeared to worsen the situation between the three permeable plots and by spring 2011 flows from the AP pavement were considerably smaller compared to flows observed from the EO and PC underdrains. Discrepancies in underdrain flow volumes among cells may have been caused by a number of factors, such as differences in as-built cell designs or native soil infiltration rates among three plots, but the lack of complete hydraulic separation was thought to be a contributing factor. Consequently, a second round of repairs was performed in May 2011. Although these repairs improved the situation, hydraulic separation among the PICP cells was not achieved. This was confirmed in September 2012, when red dye (rhodamine WT) was injected into four locations within the AP cell prior to a rain event. After more than 40 hours from the event start, very dilute dye was evident in the EO outflows. The PC outflows, however, remained visibly clear, even after dye had entered the EO cell during subsequent rain events, which suggests that mixing between the PICP and PC cells was negligible. This was confirmed by clear differences in the quality of outflows from the two types of pavements (see section 6.3 below).

6.2 Infiltration and Runoff

6.2.1 Infiltration

Surface infiltration rates, measured in June 2010, May 2011 and May 2012; showed spatial variability throughout the PP plots (Table 6.1). As of May 2012, the PC had the highest median surface infiltration (1265 cm/hr), followed by EO (94 cm/hr) and AP (20 cm/hr). An ANOVA test determined that statistically significant differences were present between mean log-transformed surface infiltration rates for the three PP types in 2010 ($p = 1.772e-10$). Each permeable material has a different initial surface infiltration capacity due to different amounts of open spaces at the pavement surface. Throughout the study, mean and median infiltration rates (PC > EO > AP) have reflected these differences and the PC pavement has displayed measured infiltration rates which are an order of magnitude larger than rates measured on the PICP pavements. Even though the infiltration capacity of the AP and EO pavement is smaller there has been sufficient capacity to infiltrate water from all of the monitored events in this study and prolonged surface ponding has not been observed.

In 2010, all three pavements had similar distributions about the mean infiltration rate reflected by the coefficients of variation ($cov = \sigma/\mu$) which were 0.57, 0.51 and 0.62 for PC, EO and AP respectively. After two years, the *cov* has increased reflecting an overall increase in variability of surface permeability. Measured infiltration rates data has tended to follow a lognormal distribution.

Figure 6.1 illustrates the change in infiltration rates measured throughout the 3 pavement cells from 2010 through to 2012. As shown in Table 6.2, permeability losses were observed on all three pavements. The rate of permeability losses may be dependent on initial surface permeability, which is in turn affected by the amount of open space or voids at the surface. AP, with the lowest initial permeability and open joint space has experienced the largest losses (median = 87%), whereas PC, with the highest initial permeability, and void space across the surface, experienced the smallest losses (median = 43%). The magnitude and timing of permeability losses varied within each of the pavement plots. The largest losses in surface permeability tended to occur along the entrance thru lanes, which is the low point of the two interlocking pavements and received the highest amount of traffic. Although the PP parking lots were not sanded during the winter, sand was applied to the surrounding areas, which may have enhanced the amount of sediment tracked onto the pavements.

Table 6.1: Surface infiltration statistics

Pavement	Mean (cm/hr)	Median (cm/hr)	Standard Deviation (cm/hr)	Skew	COV
2010					
AquaPave	151	155	93	1.35	0.62
Eco-Optiloc	520	503	266	0.06	0.51
Pervious Concrete	2336	2122	1325	1.15	0.57
2011					
AquaPave	136	118	85	1.34	0.63
Eco Optiloc	294	230	221	0.85	0.75
Pervious Concrete	1790	1337	1462	1.11	0.82
2012					
AquaPave	34	20	41	2.3	1.2
Eco-Optiloc	140	94	117	0.66	0.84
Pervious Concrete	1356	1072	1146	1.4	0.85

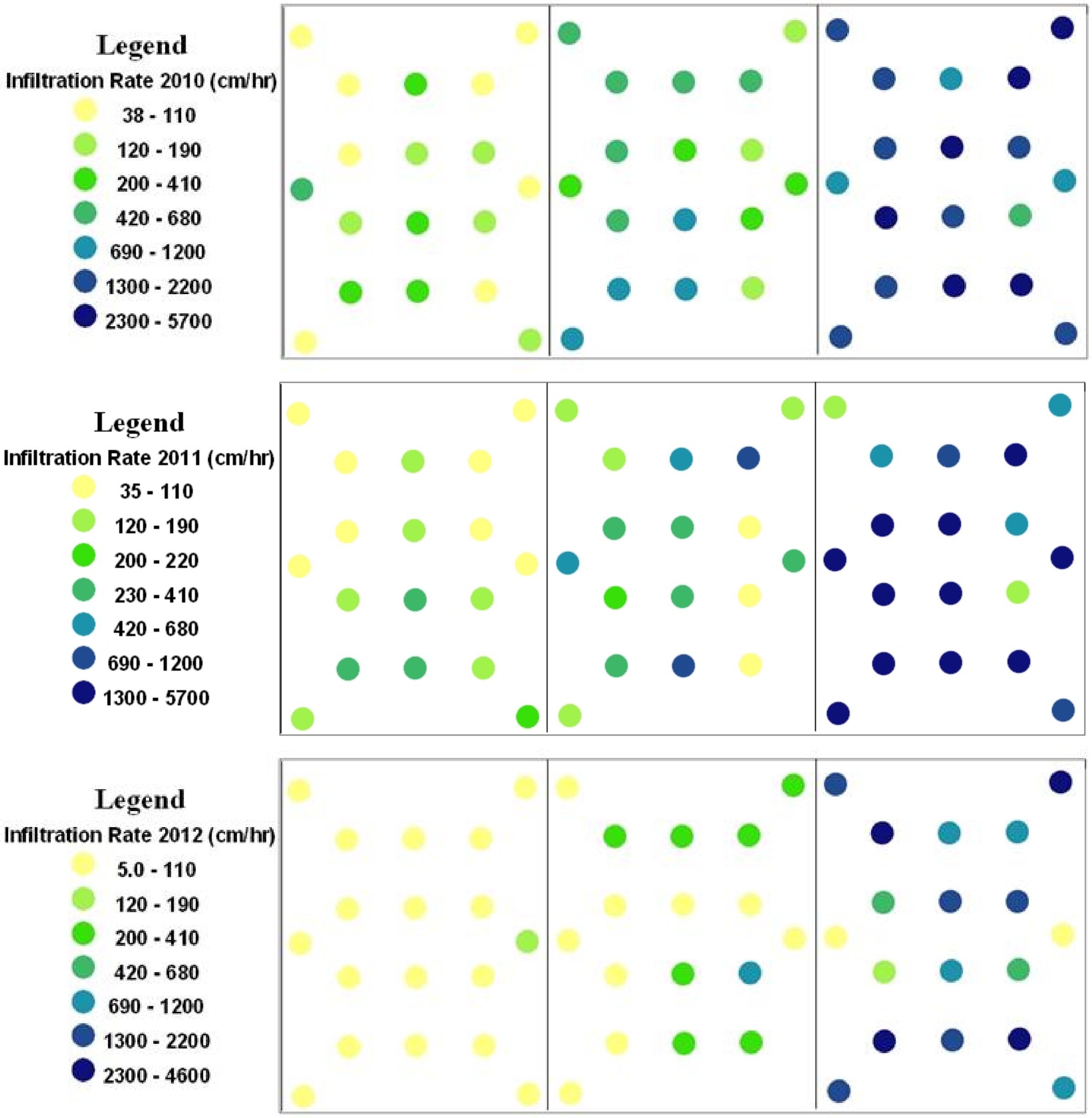


Figure 6.1: Surface infiltration rates from June 2010 to May 2012 (from left-to-right: AquaPave, Eco-Optiloc and Pervious Concrete)

Table 6.2: Changes in surface infiltration rates between June 2010 and May 2012

Pavement	Mean (%)	Median (%)	Standard Deviation (%)	Skew	cov
AquaPave	-86	-87	26	1.9	-.03
Eco-Optiloc	-84	-70	26	0.8	-.02
Pervious Concrete	-44	-43	35	-0.3	-.006

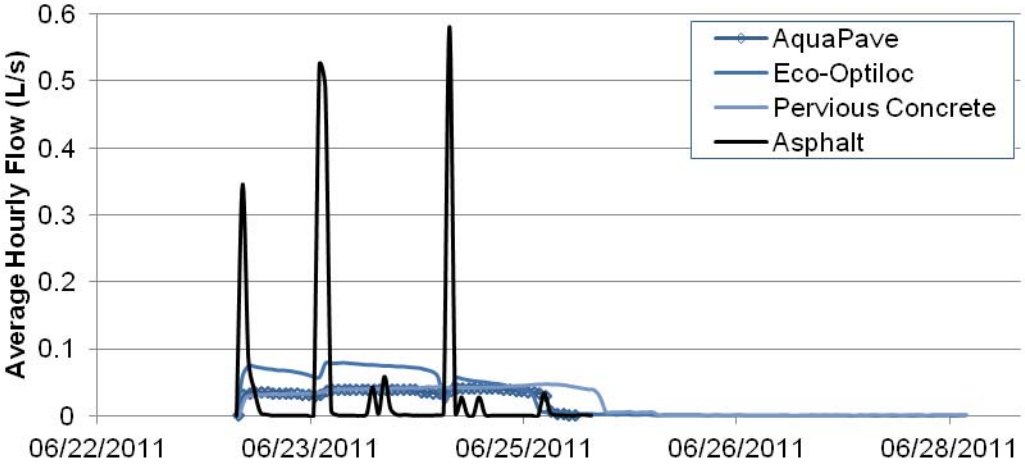
The largest precipitation intensity recorded in the summer of 2011 was 7.6 mm over a 5 min interval (9.12 cm/hr); therefore, even for the most intense storms, surface ponding is not anticipated. However, a surveillance camera monitoring the parking lot documented surface ponding on the AP surface during at least one high intensity rain event on June 23rd, 2011. The rain occurred during the day while all available parking spaces were filled which reduced the total area available to infiltrate the stormwater. In the video it appears that ponding occurred for less than one hour over AP and may have occurred briefly over EO. However, the video footage also indicated that the AP lot may have received run-on water from the adjacent asphalt pavement. Unlike the flat PC, both AP and EO are graded toward the centre, allowing rainwater to pond more readily.

During winter, slush ponding has been observed over the AP pavement on multiple occasions during winter melt events. The narrow joints of the AP pavement appear to be susceptible to icing when the parking lot is not plowed or salted regularly. Winter maintenance at Kortright is sporadic and therefore not typical of most parking lots. Beyond these isolated events no ponding has been observed from any of the PPs and all rainwater has been infiltrated into the PP.

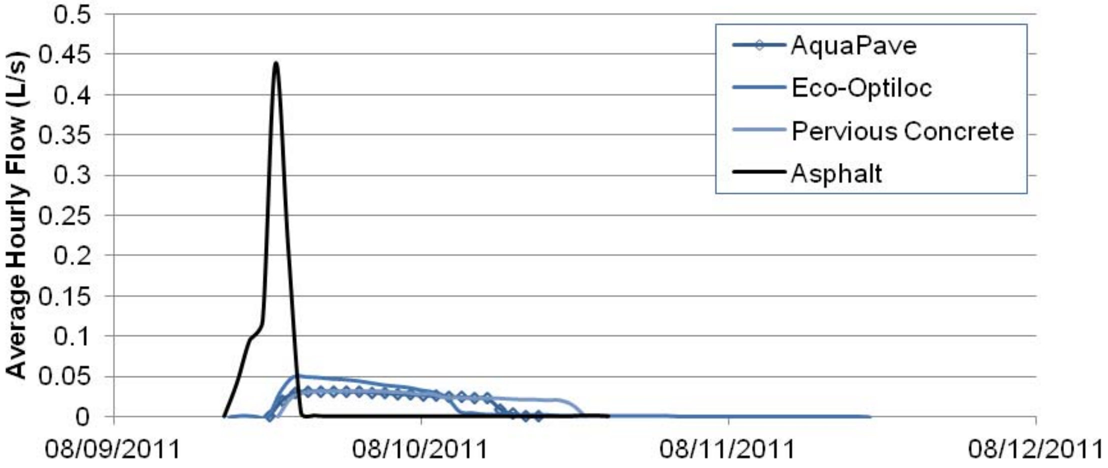
6.2.2 Runoff

A total of 127 rain and melt events were monitored between September 2010 and June 2012. A runoff event is defined as the period from the start of surface runoff to the end of surface or subsurface flow. Outflows from the PPs at rates less than 0.001 L/s were neglected. The response time of the PPs is often several days, therefore ‘events’ can include multiple discrete precipitation and runoff events. Small precipitation events do not always generate outflow from the PPs. At Kortright, when precipitation was less than 7 mm, outflow from the PPs was not always observed but runoff from the asphalt plot was recorded. In total 29 small storms representing 4.5% of the total asphalt runoff did not initiate a hydrologic response from the PP plots. During the winter, daytime conditions can create melt water generating runoff without precipitation. Throughout the winter 30 melt events were recorded from the asphalt plot which accounts for 1.7% of the total observed asphalt runoff. The runoff produced during each of these melt events was less than would have been generated from a 2 mm rain event; hence flow from the PP underdrains would not be expected.

Sample hydrographs of the PP and asphalt for small, medium and large rain events are shown in Figure 6.2. Table 6.3 summarizes outflow and runoff volumes and peak flow rates. More detailed tables are presented in Appendix B including total volumes (V_T), peak flows (Q_p) and associated reductions (VR and QR) for storm and melt events that initiated outflow from the PP underdrains, as well as runoff V_T and Q_p for events that did not produce PP outflow. Four summer events (June 11th, 23rd, August 14th, 2011; June 21, 2012) had negative volume reductions (*i.e.* the volume of stormwater exiting the PPs was larger than the volume of runoff). These results are attributed to malfunctioning equipment which underestimated the volume of runoff. Overall, the PPs reduced the total volume of stormwater outflow by 42%. Throughout the study, the PPs reduced peak flows by between 50 and 100%. The PPs continued to provide peak flow reductions throughout the winter and overall the median QR was 91%. Even larger QR values would have been observed if the asphalt outlet had not been restricted by the gate valve.



(a)



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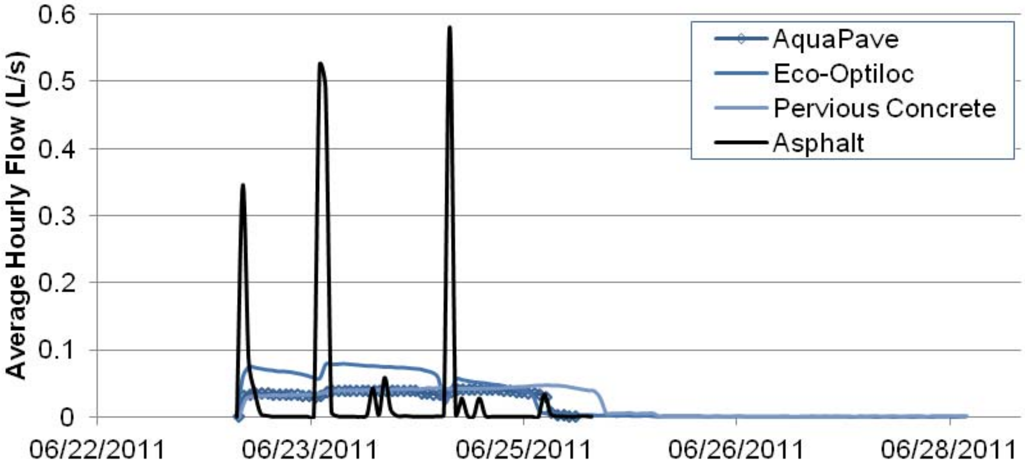


(c)

Figure 6.2: Event hydrographs: (a) October 2, 2011 (7.4 mm), (b) August 9, 2011 (15 mm) and (c) June 23, 2011 (49 mm)

Table 6.3: Summary of outflow and runoff volumes and peak flow rates from September 2010 to June 2012

Hydrologic Parameter	Range	Average	Median
Events with outflow from PPs			
Rainfall (mm)	4 – 49.4	17.3	15.6
V_T Asphalt (L)	102 - 16038	3617	3168
V_T PP (L)	28 - 20855	2419	1734
V_{Tunit} Asphalt (L/m^2)	0.4 - 69	15.5	13.6
V_{Tunit} (L/m^2) PP	0.2 -90.3	10.5	7.5
VR (%)	-145 – 91	37	43
QP Asphalt (L/min)	3 - 258	71	51
QP PP (L/min)	0.04 - 10	2.7	2.5
QR (%)	67 - 100	93	96
Events with asphalt runoff only			
Rainfall[1]	0.2 -6.6	2.2	1.7
V_T Asphalt (L)	12 - 1449	312	132
V_{Tunit} Asphalt (L/m^2)	0.1 – 6.2	1.4	0.6
QP Asphalt (L/min)	3 - 75	12.2	3

Notes: [1]Melted snow also generated runoff

A consistent pattern has emerged since the last round of repairs on the underdrains. Figure 6.3 shows that the EO underdrain regularly collects the largest volume of stormwater during an event while the AP underdrain collects the smallest volume of stormwater. All three pavements are exposed to the same precipitation inputs, are nearly identical in size and drain to the same soil types. Therefore it would be expected that for a given event the underdrains would collect the same volume of stormwater and that the total volume of water collected in the underdrains would be split evenly. Analyzing the total volume of stormwater collected in the underdrains revealed that 34% was collected in PC, 42% was collected in EO and 24% was collected in AP. One possible explanation for the low AP outflow volumes is that stormwater infiltrated from the AP pavement is draining through the EO underdrain. Heterogeneity within the native soils caused by boulders, rocks, cracks or lenses, may also account for observed variations in stormwater volumes by creating localized areas of high infiltration capacity. Additional factors contributing to the observed variability in hydrologic responses may include differences in flow rates through the control valves due to partial or temporary clogging of the orifice (which was set at approximately 1 mm), differences in the products or as-built cell designs, and/or natural variability associated with antecedent dry periods or other factors. Investigations are currently underway to assess potential causes of observed variability.

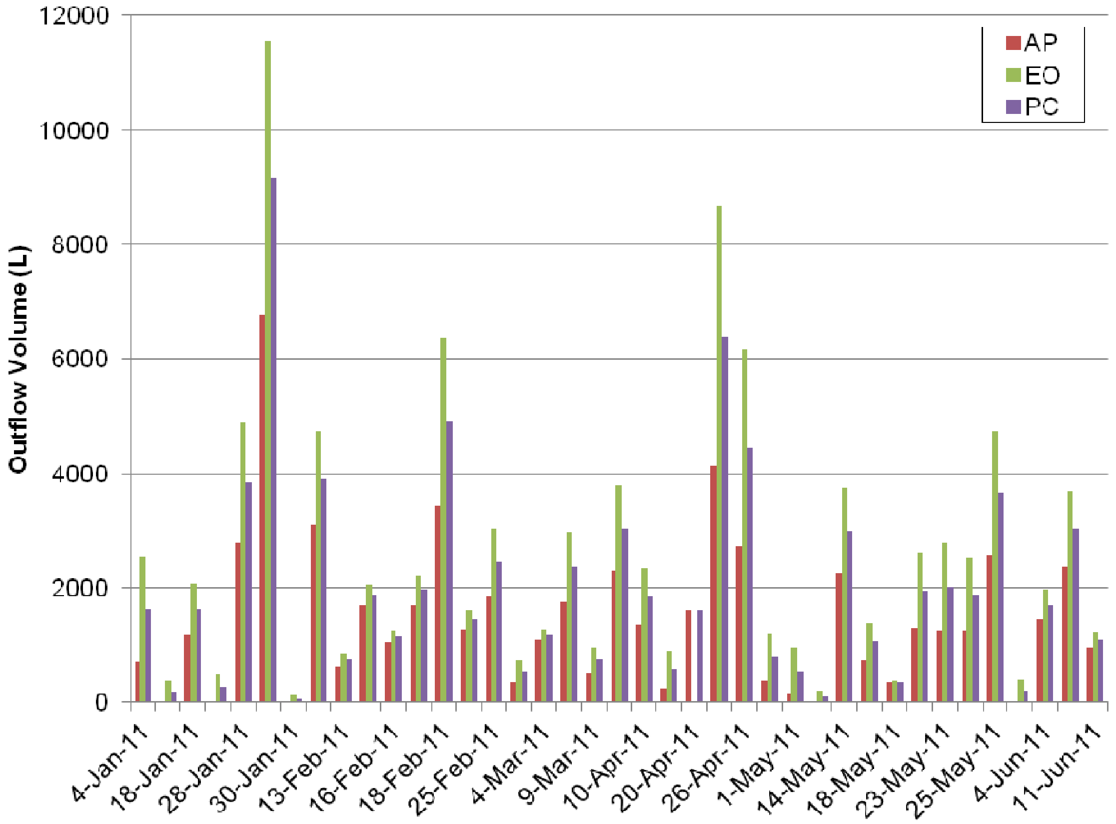


Figure 6.3: Stormwater volumes collected in permeable pavement underdrains

The three PPs, which each have a ball valve restricting flows through a 1 mm opening increased the detention time of stormwater. Lag times between the conventional asphalt and the PP (t_{lc}) ranged between 45 and 3447 minutes (57.5 hours) and lag coefficients (k_l) for PPs ranged between 1.1 and 78.2. Large lag coefficients (>10) are associated with short intense storms where the centroid for the asphalt runoff occurs within one hour or less. In this study, the AP, EO and PC pavements had a median k_l of 2.4, 2.9, 3.3, respectively and a collective median k_l of 2.9 relative to the asphalt runoff. There was essentially no detention of stormwater on the asphalt pavement. For some events, flows exiting the asphalt preceded rainfall recorded at the rain gauges indicating minor discrepancies between rainfall at the site and rainfall measurements at the nearby meteorological station.

For the majority of events two distinct draining phases are visible within the underdrain flows; a *primary* and *tail* response, which were distinguished by a clear and rapid decrease in flow rate followed by sustained low flows less than 0.0025 L/s. Tail flows most commonly occur through the EO underdrain although the PC underdrain also occasionally conveys tail flows. The volume of infiltrated stormwater contained within the tail of an event represented 5% and 3% of the EO and PC outflow. Tail flows occurred throughout all seasons but the largest tail flows were observed during the winter. Tail flow volumes ranged between only 18 and 912 L regardless of the precipitation event characteristics.

Several hydrologic performance variables were identified as seasonally-dependent. During thaw events throughout the winter of 2010/2011 lower volume reductions were observed. For the major thaw event (March 9th to 28th) the volume of stormwater exiting from the PP underdrains was 31% larger than the asphalt runoff. The increase in total volume is attributed to a couple of factors. First, water from two smaller thaw events on February 28th and March 4th did not fully drain or infiltrate prior to the major thaw event starting on March 9th. Hence, some of the water detained within the aggregate reservoir during these events was released later during the March 9th event (Figure 6.5). When all three events are considered, the stormwater volume exiting the PP underdrains was 7% less than the asphalt runoff. Second, snow was piled in the far corners of the PC cell which was a source of additional inflow that was not equally shared with the asphalt pavement. As illustrated in Figure 6.4 even though the PP had large spring thaw volumes, the infiltrated stormwater was well attenuated and the centroid of the spring thaw was delayed by approximately 3 days. Peak flow from the PP system was also reduced by 85% during this thaw.

Comparing hydrologic variables between a warm (May-September) and cool (October-April) season reveal some differences in performance. Peak flow reductions are slightly larger and less variable during the warm season (Figure 6.6), although the PPs continued to provide large reductions, QR >60%, throughout the cool season. Slow release of water during winter melt events contributed to higher cool season peak flow variability. The relative delay of stormwater, represented by k_l, also tended to be longer during the warm season compared to the cool season but the summer months also displayed higher variability overall.

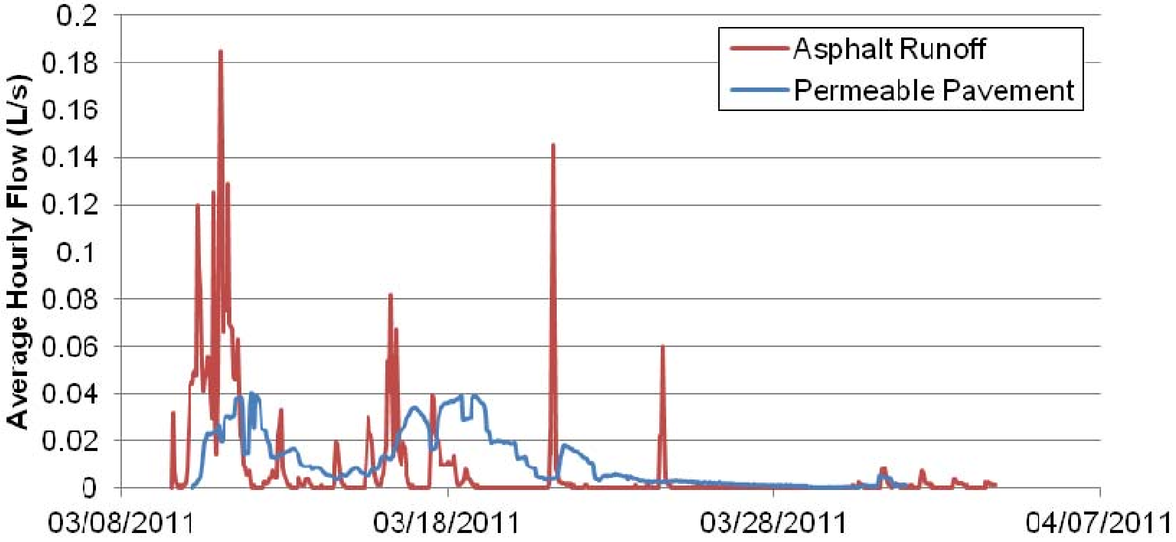


Figure 6.4: Spring thaw hydrographs of asphalt surface runoff and permeable pavement underdrain flows

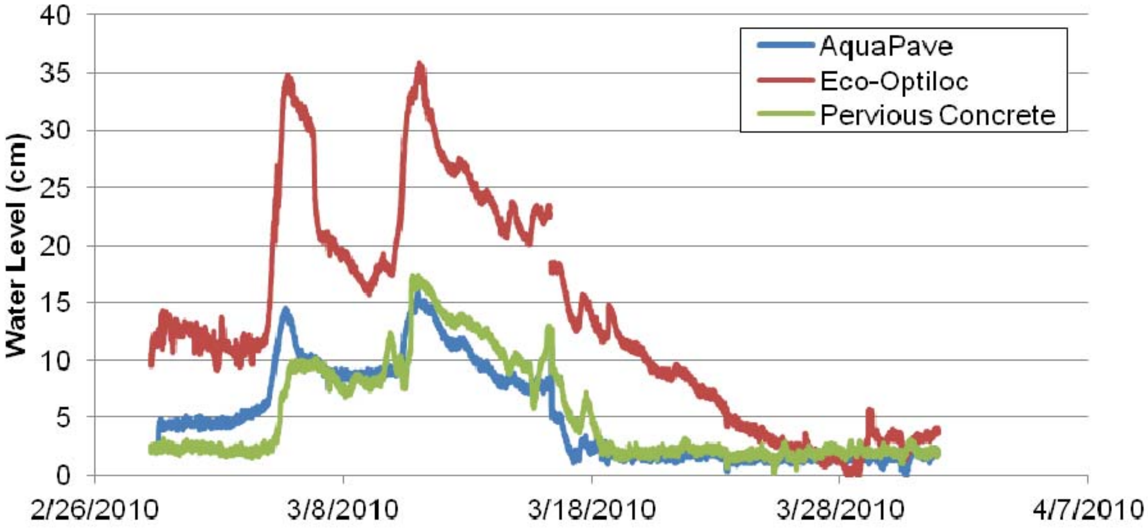


Figure 6.5: Spring thaw water levels

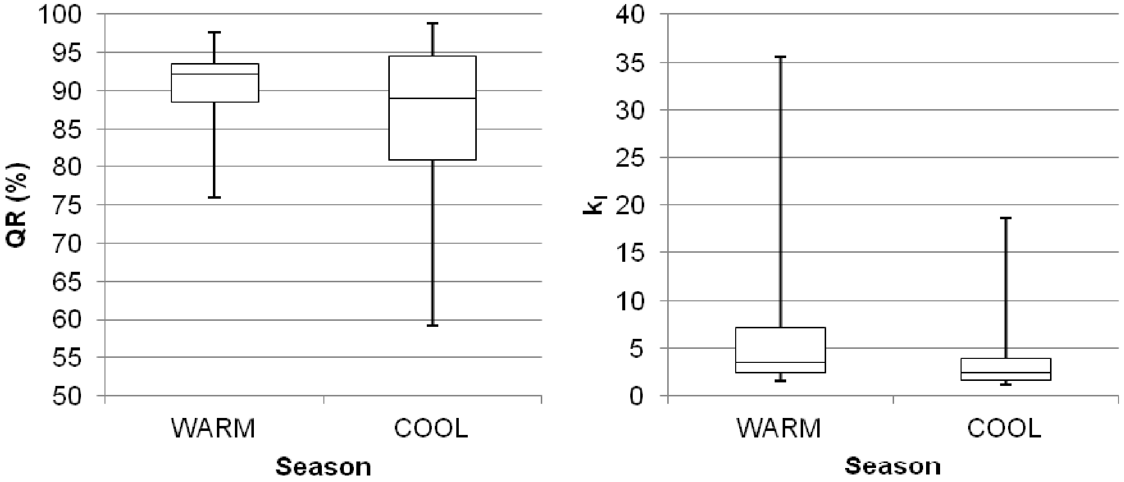


Figure 6.6: Seasonal peak flow reduction and lag coefficient boxplots

The three wells located on the south side of the PP parking have only shown elevated water levels during the spring thaw. Throughout the rest of the year water drains sufficiently rapidly to prevent accumulation of water along the outer edges of the parking lot. Rising water levels were regularly observed along the AP and EO centre underdrains during precipitation events. Water level fluctuations were consistently more frequent in the AP well most likely because this well is located next to the downstream edge of the pavement plot, whereas the EO well is positioned at a higher elevation near the upstream edge of the plot. Since the pavement systems drain rapidly, water does not accumulate in the underdrain trenches over the full length of the parking lot (Figure 6.7). The maximum water depth observed at AP was 533 mm / 195.858 m EASL (May 15th, 2011) and at EO was 291 mm / 195.915 m EASL (March 11th, 2011). At no time during the monitoring period did water levels rise above closer than 35 cm from the surface, suggesting that the pavement aggregate reservoirs had ample storage, even during very large events. Figure 6.7 shows the water level data for August 2011, which had 7 precipitation events that caused trench water levels to rise.

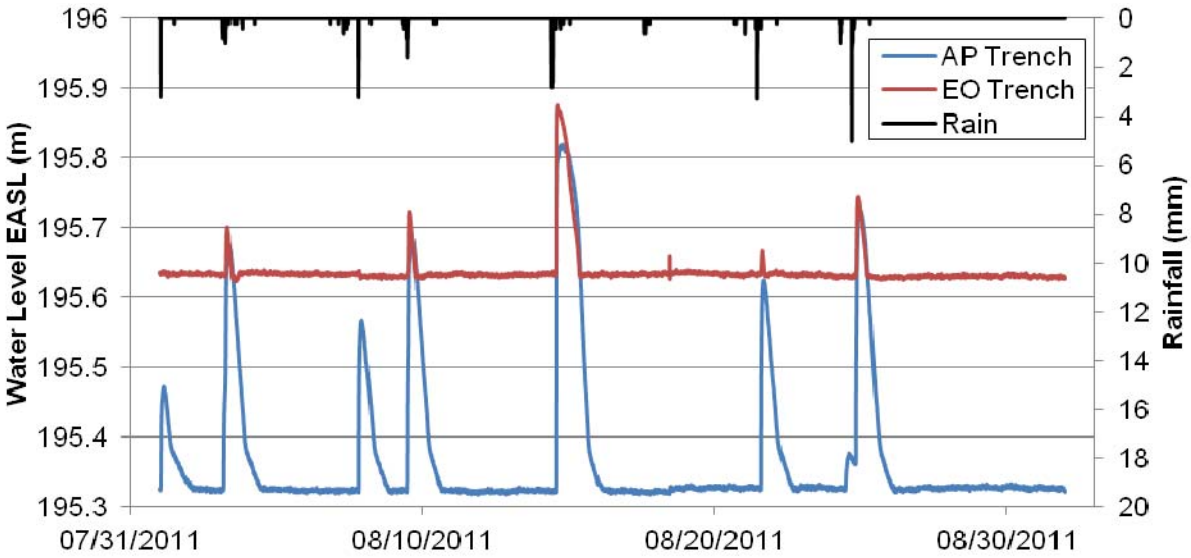


Figure 6.7: August 2011 water level data

In the fall of 2011 and spring of 2012, several tests were performed to assess the capacity of the system to infiltrate water in the absence of drainage for specified periods of time, thereby simulating the effect of a drainage pipe raised in the cross section of the base reservoir. These tests involved closing ball valves on the drainage pipes prior to a precipitation events and opening them after 32 hours or more. Figure 6.8 illustrates the water levels inside the wells during tests conducted in 2011. Table 6.4 summarizes the precipitation, closed valve time, stormwater volumes and well drawdown.

During all closed valve tests infiltration into the native soils was evident by sustained and steady drawdown of water levels after a precipitation event. Detaining the stormwater produced high volume reduction (VR) as more stormwater infiltrated to the underlying native soils. Volume reduction averaged 82% during these tests, which was close to double the VR achieved with free flowing restricted valves. For many of the monitored events infiltrated stormwater water did not accumulate in the other four monitoring wells because the sensors in these wells were either located outside of the trench or at a higher elevation near the upstream edge of the pavement plot. Precipitation events that were 15 mm or smaller caused water levels to rise in the AP trench well only. Moderate sized events ranging from 15 to 25 mm, had water levels increase in both the AP and EO trench. Valves were closed for two weeks in November/December 2011 during a series of moderate and large-sized precipitation events. This allowed for the observation of infiltration processes during very wet conditions. Elevated water levels were noted in all five wells indicating stormwater was stored temporarily throughout the entire pavement system. Even though high well water levels were present when the valves were opened the majority of stormwater had infiltrated into the soils resulting in a 91% reduction in the total event volume.

The calculated well drawdown rates do not appear to provide a good representation of the physical infiltration rates of the soil. Stormwater losses, primarily due to infiltration (i) over the course of the event were estimated using the missing stormwater volume (V_T) and detention time (t).

$$i = \frac{V_{Tc} - V_{Tpp}}{t}$$

Based on the closed valve tests the stormwater volume was reduced by a minimum rate of 1.9 mm/day. The losses are attributed primarily to infiltration into the native soil, which occurs mostly in the trench surrounding the outflow pipes. High rates of losses are likely dependent on antecedent conditions and storm characteristics.

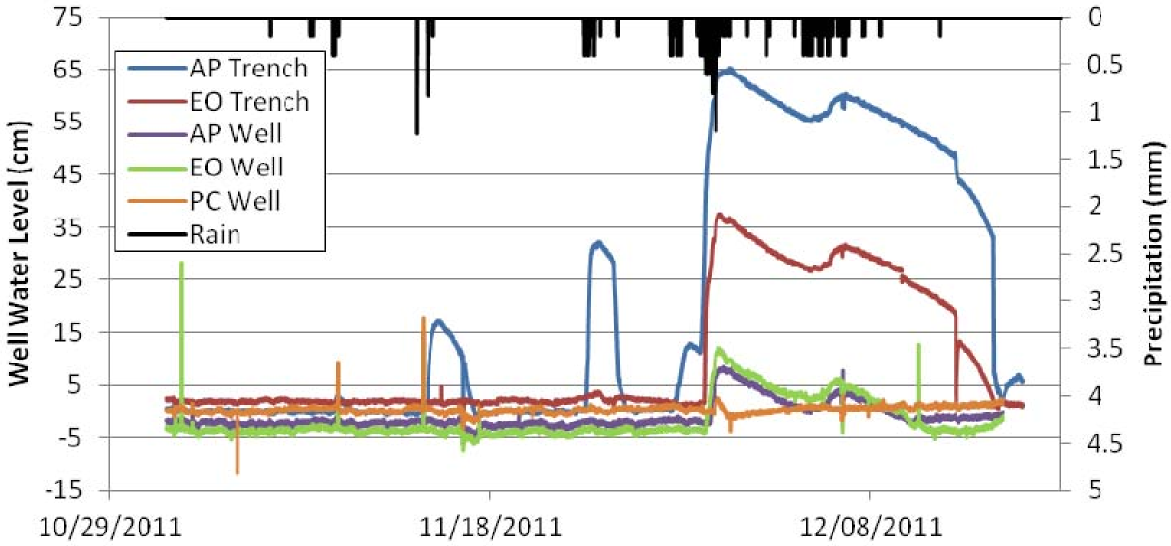


Figure 6.8: Well water levels during closed valve events during the fall

Table 6.4: Test results from closed valve events

Event Date	Rain (mm)	Closed Valve Time	V_T (L/m^2)		VR (%)	Max AP Well depth (mm)	Well drawdown (mm/day)	Estimated VR (mm/day)
			Asphalt	PP				
15/11/11	5.2	46 hr	4.8	1.1	77	171	47.5	1.9
23/11/11	15.4	32 hr	13.2	3.7	72	321	44.6	7.1
28/11/11	82.8	15 days	84.7	7.55	91	130	24.5	2.1
30/11/11						652	23.0	
6/12/11						597	16.6	
12/12/11[1]						458	61.9	
21/4/12	9.0	58 hr	8.3	0.06	99	42	40.3	5.7
23/4/12	17.0	75 hr	14.3	2.4	83	375	100.8	3.8
30/4/12	10.7	43 hr	10.2	1.9	81	211	54.7	4.6
3/5/12	25.4	94 hr	24.1	6.4	73	519	38.9	4.5
8/5/12	6.2	32 hr	6.1	1.1	82	65	56.2	3.8

Notes: [1] Valves were temporarily opened and reclosed.

6.3 Water Quality

6.3.1 Water quality concentrations

In total, 64 events were analysed for water quality between June 2010 and 2012. As shown in Table 6.5, significant changes in EMC were observed for several metals, nutrients and solids. Descriptive statistics for pollutant concentrations observed in stormwater are presented in Appendix C. Overall, compared to asphalt runoff, stormwater which infiltrated through the PP had, for all permeable surfaces, significantly lower mean/median concentrations of suspended solids, extractable solvents (oil & grease), ammonia-ammonium nitrogen ($NH_3^-NH_4^+$), nitrite, total kjeldahl nitrogen (TKN), total phosphorus, chloride, calcium, copper, iron, manganese and zinc.

At the same time, infiltration through the pavements increased the median/mean concentration of variables such as dissolved solids, barium, strontium, magnesium and potassium, although not to levels exceeding receiving water guidelines. Water chemistry parameters like pH, alkalinity, conductivity and temperature also change as a result of infiltration.

The PP stormwater had a higher pH (Figure 6.9) compared to the asphalt runoff, and thus also higher alkalinity. Effluent from the PC has consistently shown higher pH levels (averaging 9.2) than the effluent from the PICP plots (averaging 8.3), although these levels decreased over time. The Provincial Water Quality Objectives (PWQO) recommends that pH be maintained within a range of 6.5 to 8.5 for the protection of aquatic life.

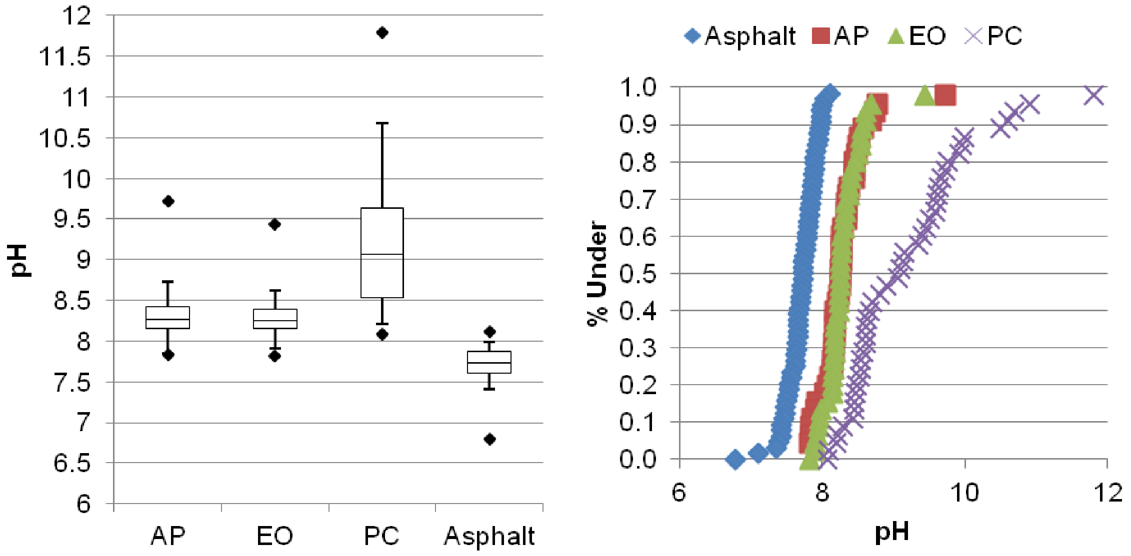


Figure 6.9: pH; box plot (left), probability plot (right)

Table 6.5: p-values from hypothesis tests

Pollutant	ASH-AP		ASH-EO		ASH-PC		AP-EO		AP-PC		EO-PC	
	p		p		p		p		p		p	
Alkalinity	1.54E-11	(<)	4.72E-13	(<)	<2.2E-16	(<)	4.67E-06	(<)	1.01E-15	(<)	2.72E-11	(<)
Conductivity	2.15E-04*	(<)	4.48E-06*	(<)	8.18E-07*	(<)	1.69E-03*	(<)	1.27E-05*	(<)	9.57E-04*	(<)
Hardness	2.88E-02*	(=)	5.97E-04*	(<)	7.36E-01*	(=)	6.46E-06*	(<)	1.05E-09*	(>)	7.27E-12*	(>)
pH	4.55E-13*	(<)	1.14E-13*	(<)	1.14E-13*	(<)	5.00E-01*	NO	4.55E-13*	(<)	1.14E-13*	(<)
Solids; dissolved	1.66E-03*	(<)	1.05E-03*	(<)	2.68E-04*	(<)	1.47E-04*	(<)	1.27E-05*	(<)	9.57E-04*	(<)
Solids; suspended	2.68E-15	(>)	<2.2E-16	(>)	3.25E-16	(>)	3.45E-02	(>)	1.88E-01	(=)	8.49E-03	(<)
Solids; total	5.75E-03*	(<)	3.03E-04*	(<)	4.48E-06*	(<)	6.61E-05*	(<)	1.27E-05*	(<)	9.57E-0*4	(<)
Aluminum	4.28E-04	(>)	7.66E-06	(>)	3.47E-05	(=)	3.60E-01	(>)	2.44E-06	(<)	1.51E-09	(<)
Antimony	7.19E-01	(=)	6.21E-01	(=)	7.89E-01	(=)	6.35E-01	NO	6.35E-01	(=)	8.04E-02	(=)
Arsenic	-	-	-	-	-	-	1.01E-04	(>)	1.55E-04*	(<)	1.52E-06*	(<)
Barium	3.92E-10*	(<)	1.08E-10*	(<)	1.58E-02*	(<)	3.49E-01*	NO	4.55E-13*	(>)	1.14E-13*	(>)
Boron	-	-	-	-		-	3.78E-09	(<)	5.24E-01*	(=)	4.68E-03*	(>)
Calcium	2.43E-01*	(=)	1.88E-01*	(=)	1.97E-03*	(>)	6.46E-06*	(<)	1.46E-11*	(>)	7.28E-12*	(>)
Chloride	8.30E-03*	(<)	3.96E-03*	(<)	1.58E-02*	(<)	7.55E-01*	NO	5.33E-01*	(=)	8.78E-01*	(=)
Copper	2.72E-12	(>)	4.04E-12	(>)	2.52E-06*	(>)	7.64E-01	NO	7.45E-05*	(<)	1.08E-04*	(<)
Iron	2.98E-09	(>)	3.74E-11	(>)	3.03E-04	(>)	9.39E-06	(>)	9.11E-05	(<)	2.44E-06	(<)
Lead	3.43E-01	(=)	4.81E-02	(>)	9.41E-01	(=)	1.23E-08	(>)	3.20E-01	(=)	9.25E-04	(<)
Magnesium	9.71E-09*	(<)	2.77E-10*	(<)	9.71E-07*	(<)	1.56E-04*	(<)	6.46E-06*	(>)	5.12E-09*	(>)
Manganese	2.02E-14	(>)	3.10E-15	(>)	1.40E-13	(>)	8.71E-04	(>)	4.15E-03	(<)	4.93E-05	(<)
Molybdenum	-	-	-	-	-	-	6.63E-03	(<)	1.09E-04	(>)	9.77E-04	(.)
Potassium	5.38E-10*	(<)	5.38E-10*	(<)	2.91E-11*	(<)	7.98E-15	(>)	<2.2e-16	(<)	<2.2e-16	(<)
Sodium	1.56E-04*	(<)	3.76E-04*	(<)	3.48E-05*	(<)	2.43E-01*	NO	1.56E-04*	(<)	2.35E-02*	(<)
Strontium	4.57E-13*	(<)	1.14E-13*	(<)	1.14E-13*	(<)	3.92E-07*	(<)	1.91E-11*	(>)	1.14E-13*	(>)
Uranium	-	-	-	-	-	-	2.39E-03	(>)	7.75E-07*	(>)	2.82E-06*	(>)
Vanadium	3.35E-04	(>)	2.66E-05	(>)	6.36E-01*	(=)	6.58E-03	(>)	3.02E-07*	(<)	2.82E-09*	(<)
Zinc	3.05E-08	(>)	5.18E-15*	(>)	1.08E-10	(>)	5.13E-08*	(>)	2.78E-09	(>)	2.80E-01*	(=)
Ammonia+ Ammonium	3.32E-12	(>)	4.02E-12	(>)	8.96E-11	(>)	9.94E-03	(>)	4.89E-01	(=)	9.33E-03	(>)
Nitrate+ Nitrite	7.85E-05	(<)	6.86E-03*	(<)	1.00E+00*	(=)	2.44E-06*	(>)	3.92E-10*	(>)	1.14E-13*	(>)
Nitrite	1.64E-10	(>)	5.72E-11	(>)	8.20E-06	(>)	1.37E-02	(>)	4.97E-05	(<)	5.84E-08	(<)
TKN	<2.2E-16	(>)	<2.2E-16	(>)	2.33E-13	(>)	5.76E-02	NO	1.08E-06	(<)	6.16E-09	(<)
Phosphate	6.36E-03	(>)	3.32E-04	(>)	9.23E-05	(<)	2.88E-02	(>)	6.22E-09	(>)	5.45E-12	(<)
Total Phosphorus	4.30E-14	(>)	1.00E-13	(>)	1.06E-03	(>)	2.97E-01	NO	4.20E-14	(<)	5.30E-13	(<)
Fecal streptococcus	1.03E-01	(=)	5.71E-01	(=)	8.44E-03	(>)	1.17E-02	(>)	1.20E-05	(>)	2.70E-03	(>)
Pseudomonas aeruginosa	2.16E-02*	(<)	8.39E-01*	(=)	-	-	1.69E-01*	NO	-	-	-	-

Notes: *sign test performed

(<) = EMC mean/median pavement 1 < EMC mean/median pavement 2

(>) = EMC mean/median pavement 1 > EMC mean/median pavement 2

(=) = mean/median pavement 1 = mean/median pavement 2

To highlight the water quality improvements provided by the PPs, boxplots and effluent probability plots were created for zinc concentrations (Figure 6.10). As with most of the water quality data, zinc concentrations tended to be log-normally distributed. Paired t-tests between the PPs and asphalt zinc data found statistically-significant reductions ($\alpha = 0.05$) of the log-transformed mean for AP (p = 1.2 E-8), EO (p = 4.2 E-12) and PC (p = 3 E-15). The median removal efficiency for zinc was 69% (AP), 75% (EO) and 80% (PC) which is comparable to other PP studies (Rushton, 2001; Sansalone and Teng, 2004; TRCA 2008). The interim PWQO for the protection of aquatic life in receiving waters is 20 µg/L for zinc, the PP outflow was more likely to meet this objective than runoff from the asphalt plot. Eighty six percent (n=55) of asphalt runoff samples exceeded the PWQO, whereas only 40% of samples (n=17) from AP, 18% of samples (n=8) from EO, and 18% of samples (n=8) from PC exceeded this objective.

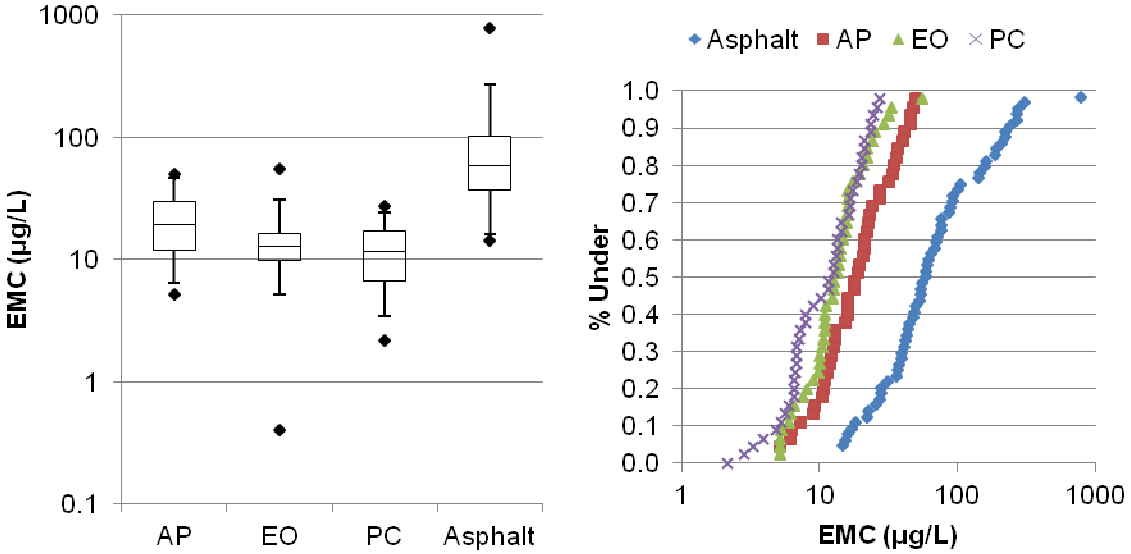


Figure 6.10: Zinc EMC; box plot (left), probability plot (right)

During the winter the parking lot was salted using Windsor Safe-T-Salt®. Road salting activities during the winter introduce additional pollutants into winter stormwater. In addition to sodium and chloride, lab analyses of a dissolved solution of the road salt found that the product contained measureable concentrations of metals (aluminum, arsenic, barium, boron, calcium, lead, magnesium, manganese, nickel, potassium, strontium and zinc), nutrients (nitrogen and phosphorus) and PAHs (naphthalene). The degree of seasonality in pollutant concentrations was more pronounced in the runoff than the PP outflow. The parking lot was salted during the winter and samples were classified as “winter stormwater” once elevated levels of chloride were observed. Throughout the spring-to-fall seasons runoff had only minimal levels of chloride (EMC < 15 mg/L) but, winter concentrations averaged 5,330 mg/L and spiked up to 43,100 mg/L. Seasonal chloride concentrations from PP outflow were muted; winter concentrations only averaged 462 mg/L and spring-to-fall concentrations averaged 18 mg/L.

Effluent from AP and EO pavements often had similar water quality characteristics while the PC water quality was notably different. The results suggest that different pollutants are captured or mobilized in these two pavement types. For example strontium concentrations were shown to be significantly greater in PICP effluent (medians were 3750 µg/L and 4370 µg/L for AP and EO, respectively) compared to concentrations in the PC effluent (median was 1430 µg/L). As an example of the opposite trend, potassium concentrations were much higher in PC effluent (median was 109.5 mg/L) compared with PICP effluent (medians were 27.5 mg/L and 20.1 mg/L for AP and EO, respectively). Median phosphate concentrations in PC effluent were also over 4 times greater than PICP effluents. The large and significant differences in water quality parameters between the PICP and PC pavements suggests that any mixing of stormwater which may still exist at Kortright has only a negligible impact on water quality results.

Water samples were analysed for a variety of PAHs. Frequently, detected concentrations are very near the lab detection limits so precise concentration estimates are not possible. Table 6.6 lists the number of events which have contained trace concentrations of PAHs. The PPs demonstrated removal of several PAHs including 1-methylnapthalene, 2-methylnaphthalene, benzo(e)pyrene, fluoranthene, naphthalene, phenanthrene, and pyrene. PPs provide opportunities to remove PAHs from stormwater outflow through volatilization, photolysis, hydrolysis, microbial degradation, adsorption and sedimentation. PAHs tend to adsorb to particulates because they are hydrophobic and have low solubilities (CEQG, 1999). Infiltrating stormwater through the PP filters suspended solids removing the PAHs that adhered to these particles. The temporary storage of infiltrated stormwater creates opportunities for volatilization which is the dominant removal mechanism for some PAHs such as naphthalene (CEQG, 1999). The PPs reduced the frequency that PAH concentrations exceeded water quality guidelines. For example, 33% of the sampled runoff exceeded the PWQO of 30 ng/L for phenanthrene whereas less than 5% of the sampled PP outflow exceeded this objective.

Table 6.6: Frequency of detectable Polycyclic Aromatic Hydrocarbon concentrations

PAH	Water Quality Objectives	Events with detectable concentrations			
		Asphalt	AP	EO	PC
1-methylnaphthalene		15	0	0	0
2-methylnphthalene		19	0	0	2
7,12-dimethylbenz(a)anthracene		0	0	0	0
Acenaphthene	5800 ng/L	3	0	0	1
Acenaphthylene		0	0	0	0
Anthracene	0.8 ng/L	0	0	0	1
Benzo(a)anthracene	18 ng/L	1	0	0	1
Benzo(a)pyrene	15 ng/L	2	0	0	1
Benzo(b)fluoranthene		3	0	0	1
Benzo(e)pyrene	0.2 ng/L	9	0	0	1
Benzo(g,h,i)perylene		5	0	0	1
Benzo(k)fluoranthene	0.02 ng/L	1	0	0	1
Chrysene	0.1 ng/L	5	0	0	1
Dibenzo(a.h)anthracene	2 ng/L	1	0	1	0
Fluoranthene	0.8 ng/L	41	1	0	3
Fluorene	200 ng/L	6	0	1	0
Indeno(1,2,3-c,d)pyrene		2	0	0	1
Napthalene	7000 ng/L	19	0	0	1
Perylene	0.07 ng/L	0	0	0	1
Phenanthrene	30 ng/L	43	7	5	10
Pyrene	25 ng/L	33	2	2	4

Samples from 30 events were analysed for *escherichia-coli* (*e-coli*), *fecal streptococcus* and *pseudomonas aeruginosa* populations. Descriptive statistics are included in Appendix C. *Fecal streptococcus* was more regularly observed in stormwater samples than *pseudomonas aeruginosa* and *e-coli*. *E-coli* was observed in half of tested AP samples but in only a third of tested EO, PC and asphalt samples. The PWQO recommend that for recreational water uses *e-coli* populations should not exceed 100/100mL and *pseudomonas aeruginosa* populations should not exceeded 10/100mL. Stormwater samples for PP and runoff have only exceeded *e-coli* guidelines on a few occasions (events with *e-coli* 100/100mL: Asphalt = 3, AP = 5, EO = 0, PC = 2). Levels for *pseudomonas aeruginosa* have exceeded guidelines more regularly (events with *pseudomonas aeruginosa* >10/100mL: Asphalt = 25, AP = 24, EO = 17, PC = 7). Even though population levels for infiltrated stormwater were generally low the three PPs appear to provide varying conditions for growth. AP, which includes a geotextile below the bedding layer, appeared to support more favorable conditions for growth than the other two PPs as measurable populations were observed more frequently and in higher concentrations relative to effluent collected from the EO and PC cells. PC, which had high pH, appeared to have less favorable conditions than the PICPs as measureable populations were observed less frequently and in lower concentrations relative to effluent collected from AP and EO cells.

6.3.2 Temporal changes in water quality concentrations

As noted previously, evidence of pollutant leaching from the PC and aggregate layers as well as a long-term stabilization trend was observed throughout the study period. This trend was reflected by a decreasing concentration for some pollutants over the course of the twenty-two monitored months. Figure 6.11 and 6.12 shows declining potassium levels in PC outflow and declining strontium levels in PICP outflow. Larger concentration declines were observed from the PC pavement, which is 6 months younger than the PICP pavements. The data suggest that mobile pollutants, including metals, dissolved solids and phosphate are leached from the PP system. PC outflow initially had pH levels which exceeded recommended provincial guidelines (>9). However, these levels did not persist and since July 2011 PC stormwater has had pH levels comparable to PICP stormwater, ranging from 8-9. Similar stabilization processes may have occurred in the PICPs but were not observed in the monitoring data because water quality sampling began 6 months after the pavers were installed.

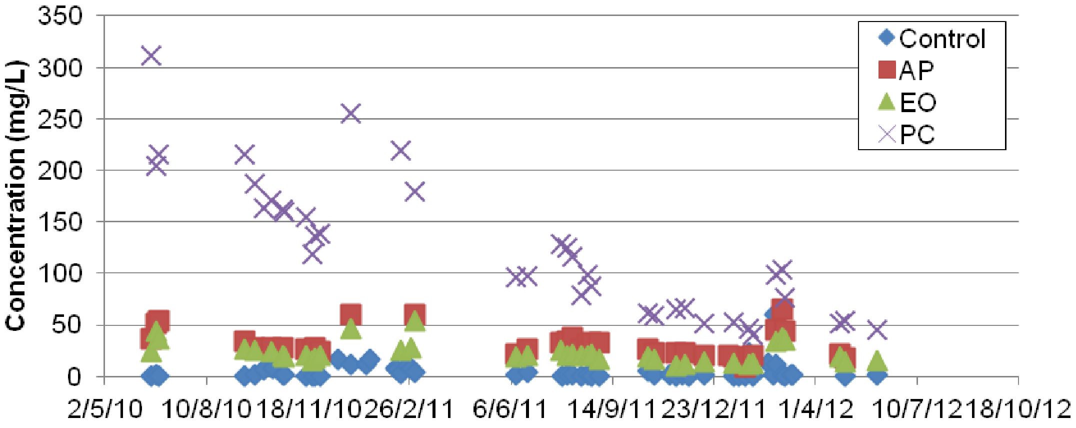


Figure 6.11: Changes in potassium concentrations over the study period

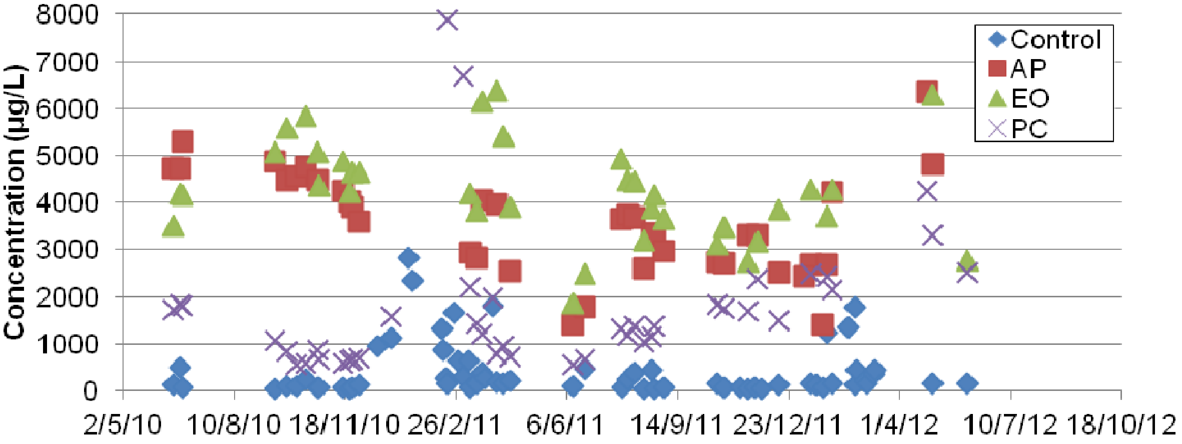


Figure 6.12: Changes in strontium concentrations over time (winter concentrations > 8000 ug/L has been excluded)

6.3.3 *Intra-event changes in water quality concentrations*

Six events were sampled to investigate intra-event patterns in water quality to determine how concentrations from the different pavements change over the course of the event. Twenty-four water samples were collected with the automated samplers during each event. Discrete samples were analyzed for turbidity and TSS. The duration of sampled events is 48 hours for PPs but only 2 hours for the runoff. As shown in Figure 6.13, runoff from the control plot exhibits a strong first flush pattern and TSS rapidly declines after the first few bottles. A small 'first flush' is observed in the AP and PC stormwater but it is considerable muted when compared with the asphalt runoff. The smaller first flush from the PPs is attributed to filtration through the pavements and the delay of runoff initiation caused by storage and infiltration of the first 5 to 7 mm of rain events.

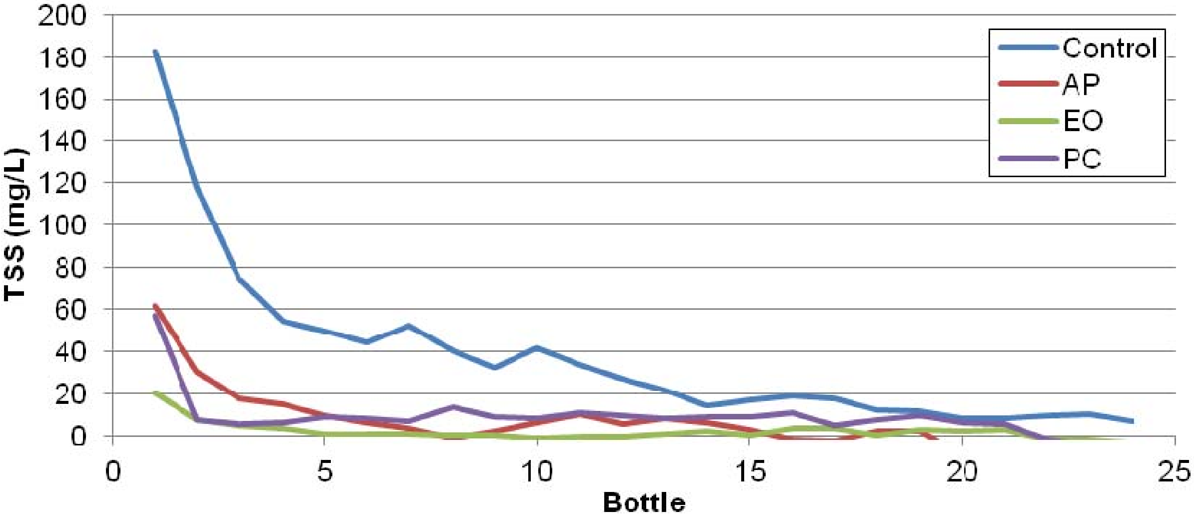


Figure 6.13: Intra-event TSS averaged from six monitored events

6.3.4 Effects of infiltration on the relationship between turbidity and TSS

The relationship between TSS and turbidity is different for runoff and infiltrated stormwater (Figure 6.14). Infiltrated stormwater has a higher turbidity at a lower concentration of TSS than runoff. As a result of filtration through the pavement, the suspended solids within infiltrated stormwater are finer and less dense, which can create turbid conditions at relatively low TSS concentrations.

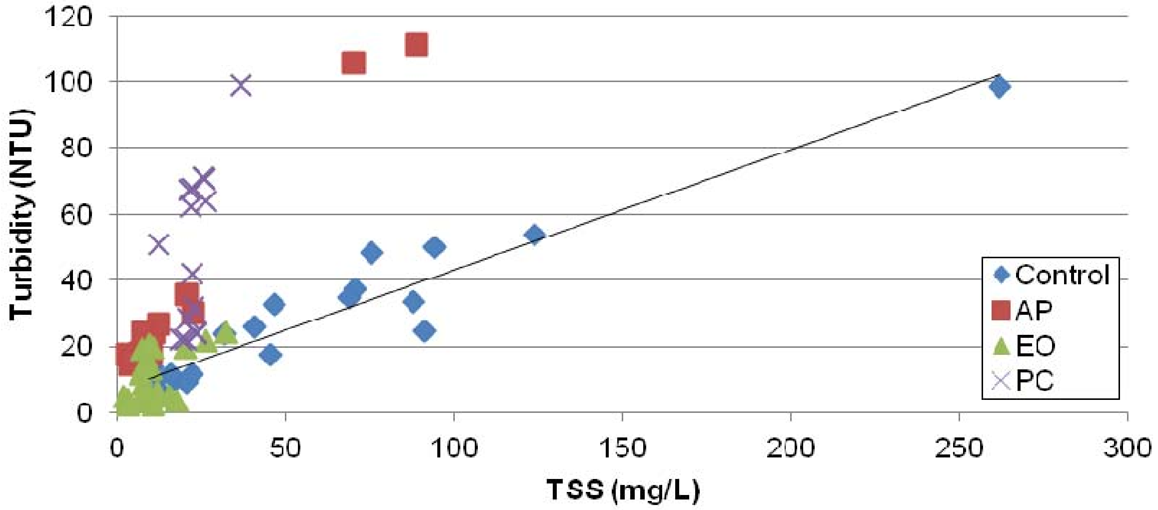


Figure 6.14: Turbidity vs. TSS for August 29, 2011 event

6.3.5 Efficiency ratios

Overall and seasonal efficiency ratios (ER) are presented in Table 6.7. A positive ratio indicates that pollutant concentrations within the PP outflow were lower than those in the asphalt runoff (i.e. the PPs decreased pollutant concentrations), and *vice versa*. For pollutants and parameters associated with road salt, winter concentrations distort the overall impact of the PPs on water quality. Infiltrated stormwater had higher conductivity and concentrations of dissolved solids, total solids, chloride and sodium relative to runoff throughout the majority of the year. However, during the winter, the concentration of these pollutants increased so drastically within the runoff that a net reduction, as represented by a positive ER, in concentration was observed overall. Seasonal changes were also observed in nitrogen concentrations. The PPs reduced nitrite concentrations throughout the year but reductions in nitrate concentrations were only observed during the winter. This result suggests that winter conditions may provide conditions which allow for the denitrification of nitrate.

Table 6.7: Average ER of permeable pavements relative to the asphalt control

Pollutant	Overall ER			Seasonal ER					
				Winter			Spring to Fall		
	AP	EO	PC	AP	EO	PC	AP	EO	PC
Alkalinity; total fixed endpt	-0.91	-1.09	-2.36	-0.72	-0.92	-2.53	-1.12	-1.31	-2.33
Conductivity	0.86	0.84	0.83	0.85	0.84	0.85	-2.00	-2.20	-4.21
Hardness	0.10	-0.16	0.54	0.03	-0.34	0.53	-0.29	-0.50	0.32
Solids; dissolved	0.90	0.88	0.87	0.86	0.84	0.87	-1.21	-1.35	-3.05
Solids; suspended	0.87	0.89	0.79	0.89	0.89	0.75	0.80	0.87	0.80
Solid; total	0.87	0.85	0.84	0.86	0.84	0.87	-0.83	-0.92	-2.29
Solvent extractable	0.68	0.59	0.67	-	-	-	-	-	-
NH_3-NH_4^+	0.90	0.92	0.90	0.88	0.92	0.89	0.90	0.90	0.89
NO_3^-,NO_2^-	-0.19	-0.05	0.21	0.11	0.23	0.39	-0.84	-0.65	-0.21
NO_2^-	0.73	0.83	0.59	0.56	0.79	0.68	0.85	0.85	0.50
TKN	0.88	0.88	0.79	0.87	0.89	0.78	0.88	0.87	0.79
PO_4^{3-}	0.80	0.83	0.26	0.27	0.48	-0.53	0.91	0.90	0.50
TP	0.88	0.87	0.51	0.79	0.80	0.26	0.92	0.91	0.65
Aluminum	0.46	0.53	-0.05	0.48	0.54	0.15	0.35	0.47	-0.40
Antimony	-0.03	0.03	-0.01	0.16	0.22	0.23	-0.19	-0.13	-0.28
Barium	-0.36	-0.52	0.43	-0.40	-0.61	0.49	-1.85	-1.79	-0.43
Calcium	0.33	0.10	0.70	0.28	-0.02	0.71	0.02	-0.18	0.51
Chloride	0.93	0.92	0.95	0.91	0.90	0.93	-1.01	-1.91	-1.41
Chromium	-0.43	-0.06	-1.98	-0.50	-0.05	-1.87	-0.16	0.00	-1.49
Copper	0.74	0.75	0.49	-	-	-	-	-	-
Iron	0.73	0.78	0.58	0.74	0.77	0.65	0.66	0.73	0.42
Lead	-0.20	0.27	-0.05	-0.08	0.43	0.22	-0.64	-0.18	-0.80
Magnesium	-2.04	-2.68	-0.91	-2.45	-3.49	-1.31	-2.91	-3.13	-1.28
Manganese	0.88	0.90	0.84	0.89	0.90	0.88	0.85	0.88	0.75
Molybdenum	0.34	0.31	-0.08	0.76	0.76	0.58	-2.45	-2.78	-4.70
Nickel	0.64	0.29	0.49	0.52	0.22	0.39	0.71	0.45	0.54
Potassium	-5.30	-3.66	-24.12	-2.98	-2.17	-11.31	-16.06	-11.04	-74.78
Sodium	0.94	0.93	0.94	0.92	0.92	0.93	-12.12	-14.56	-18.25
Strontium	-12.45	-16.62	-5.04	-12.94	-18.15	-5.91	-23.81	-26.38	-7.24
Vanadium	0.50	0.56	-0.11	0.62	0.67	0.17	0.36	0.42	-0.47
Zinc	0.78	0.85	0.87	0.76	0.85	0.89	0.78	0.84	0.85

6.3.6 Water quality loads

In addition to altering the concentration of pollutants during individual events the PPs alter the total pollutant loading on downstream receiving systems. Pollutants with cumulative loads larger than 1 g and their associated mass loading reductions (MLR) are presented in Table 6.8. The PPs reduced the net mass of chloride, iron, manganese, sodium, zinc, copper, nutrients, solids and extractable solvents available to receiving systems. The infiltration process was shown to slightly increase the net mass of boron and, more notably, to increase the net mass of potassium and strontium, although not to levels that would be of concern to aquatic life. Concentrations of nutrients within infiltrated stormwater were frequently larger than concentrations within runoff; however, the reduction in stormwater volume produced a net reduction in total nutrient loads. This effect of reduced stormwater volumes on pollutant loading to receiving waters represents one of the most important environmental benefits of PPs, and highlights the importance of configuring drainage in PP systems to maximize infiltration (*e.g.* through flow restrictors, or raised pipes).

Table 6.8: Total Event Loading (L_{Total}) and MLR

Pollutant	L_{Total} (g)				MLR (%)		
	Control	**AP**	**EO**	**PC**	**AP**	**EO**	**PC**
General							
Solids, dissolved	104332	23777	78026	71560	77	25	31
Solids, suspended	8952	635	1260	3126	93	86	65
Solids, total	115178	24415	79297	74717	79	31	35
Solvent extractable	459	0	3	2	100	99	100
Metals							
Aluminum	61	20	41	79	67	33	-30
Barium	4	4	11	3	10	-165	31
Boron	0	1	4	4	-303	-1014	-1062
Calcium	3161	1382	3728	730	56	-18	77
Chloride	59061	7440	30582	16937	87	48	71
Copper	2	0	1	2	79	64	4
Iron	99	18	34	57	82	66	42
Magnesium	246	428	1043	245	-74	-324	0
Manganese	14	1	2	3	92	84	77
Potassium	311	1471	1999	8824	-373	-542	-2735
Sodium	25301	3012	11171	6336	88	56	75
Strontium	31	272	865	158	-766	-2654	-403
Zinc	10	1	2	2	89	82	85
Nutrients							
Nitrogen, ammonia + ammonium	27	3	5	7	91	83	75
Nitrogen, nitrate+nitrite	82	47	75	52	43	8	37
Nitrogen, nitrite	7	1	2	3	88	76	61
Phosphorus, phosphate	34	1	3	10	96	92	72
Phosphorus, total	59	2	6	18	96	90	70

6.3.7 Effects of soil infiltration

Water samples for 39 events were collected to compare the quality of infiltrated stormwater at the base of the AP pavement, referred to as AquaPave High (APH), to the quality of stormwater that had infiltrated through a section of native material (approx. 0.5 to 0.7 m below the upper pipe), referred to as AquaPave Low (APL). Pollutant concentrations in APH and APL samples are strongly correlated. Some pollutants, such as chloride, move freely through the native soil with minimal retention (Figure 6.15). The native soil also appears to be experiencing stabilization and concentrations of aluminum and iron have consistently declined over the course of the monitoring period (Figure 6.15). Seasonal trends are visible for some nutrients and metals with concentrations in APL matching concentrations in APH (Figure 6.16). Normally, pollutant concentrations that adsorb to soil particles, such as lead and phosphorus, would be expected to decrease as the water is infiltrated through soil media. The similarity of pollutant concentrations in APH and APL samples suggests that the soil depth between the APH and APL may not have been sufficient to adsorb or trap pollutants and/or short circuiting through cracks in the soil media may have been present. Further investigation of this aspect of the study will be addressed in a future phase of the study.

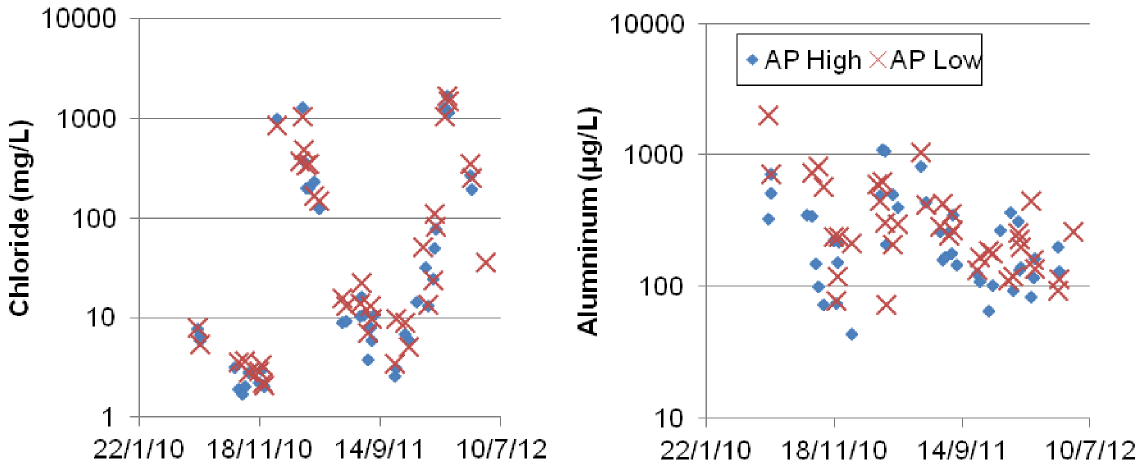


Figure 6.15: Sample concentrations for AquaPave High and AquaPave Low: Chloride (left), Aluminum (right)

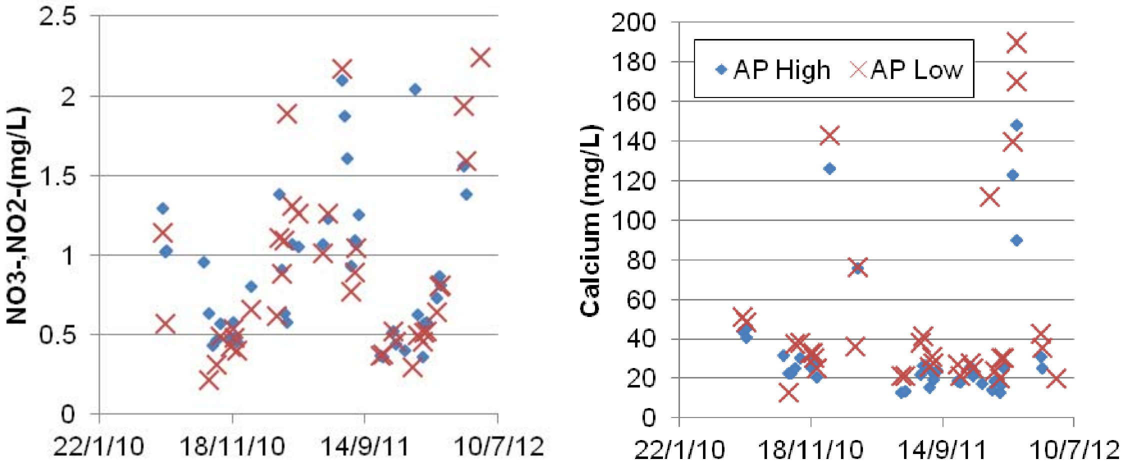


Figure 6.16: Examples of Seasonal Patterns: NO_3^-,NO_2^- (left), Calcium (right)

6.3.8 Water temperature

Outflow pipes for the asphalt and AP pavement are equipped with temperature loggers. Figure 6.17 displays the recorded temperature of water inside drainage pipes for the asphalt and AP pavement. During a precipitation or thaw event the water temperature inside the drain pipe rapidly spikes as the new runoff or infiltrated water has a different temperature compared to the standing water inside the drain. Figure 6.17 shows the effect of infiltrating stormwater through PP. During warm months the infiltrated water is cooler than the asphalt temperature and during cool months the opposite occurs. Days when water temperatures inside the asphalt or AP drain changed by 1 °C or more are classified as flow event days. For flow events in 2011, during the warm months (May-August) the asphalt had daily maximum temperatures which were on average 1.1 °C warmer than the AP. For flow events during the cool months (October-February 2010/2011 and 2011/2012), the asphalt had daily minimum temperature for flow events which were on average 1.7 °C cooler than the AP pavement. Table 6.9 presents cool-season daily minimum and warm-season daily maximum water temperatures. In addition to cooling the water during the summer, the PPs also helped buffer extreme temperatures associated with individual events, as shown in Figure 6.17 by the lower variability during events. Even more importantly, the PPs significantly reduced thermal loads to receiving waters by substantially decreasing outflow volumes.

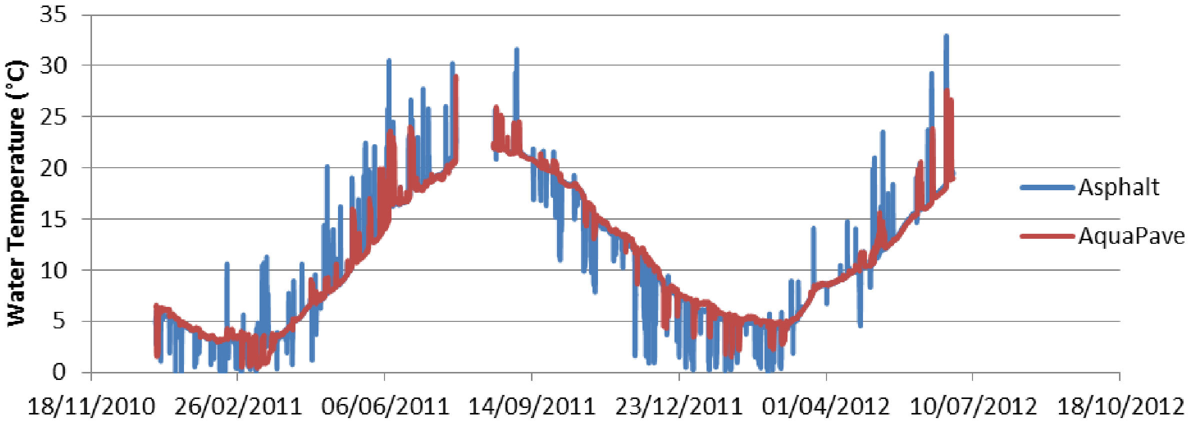


Figure 6.17: 2011 water temperatures in asphalt and AquaPave drain pipes

Table 6.9: Outflow event temperatures

Warm Season (May – August)			Cool Season (October – February)		
Daily Maximum during events	**Total asphalt**	**AP**	**Daily Minimum during events**	**Asphalt**	**AP**
n	46	31	n	57	29
range	10.4 – 30.2	10.5 – 29	range	0 – 18.6	0.5 – 19
mean	20.7	19.6	mean	7.4	9.1
median	21	19.8	median	5.5	7.9

6.4 Functional Performance

In addition to hydrological and water quality performance, various functional attributes of the pavement were monitored. These included surface and subsurface temperatures, elevation changes over time, physical condition, and vegetation colonization.

6.4.1 Temperature profiles

The surface and subsurface temperatures of the asphalt, AP and PC pavements were influenced by varying shading conditions. In 2011 a Solar Pathfinder was used to evaluate the shading conditions over the temperature sensors. These investigations revealed that the PC temperature sensors were subjected to extended periods of shading while AP and asphalt temperature sensors were less shaded. Based on Solar Pathfinder images it is estimated that all three locations received different solar inputs, measured as daily peak sun hours, throughout the year. On average each location received 0.62 (PC), 2.09 (AP) and 1.96 (asphalt) peak sun hours a day and, consequently, warm season temperature results among pavement plots could not be compared statistically.

Despite receiving more shade, the mean surface asphalt temperatures during the warm season were 1.7 and 0.5°C warmer than the AP temperatures in 2010 and 2011, respectively (Table 6.10). This may be attributed largely to the darker colour of the asphalt, which absorbs and retains solar radiation more effectively. Thus, while the AP had a higher maximum (Figure 6.18), the lighter coloured pavers more effectively released this heat during the overnight periods. This is evident in the higher AP variability (caused in part by less shading), and the larger diurnal variations. Further investigations are required to determine the extent to which moisture within the pavement structure may have contributed to the variability.

Table 6.10: Warm (June – August) season temperature data (°C)

Temp. Sensor	Asphalt				AquaPave				Pervious Concrete			
	2010		2011		2010		2011		2010		2011	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Red	27.95	5.28	27.35	5.51	26.25	6.63	26.85	6.93	23.74	4.31	23.52	4.49
Green	26.82	2.75	26.20	2.80	24.91	3.26	25.51	3.41	22.02	2.49	22.29	2.48
Blue	26.21	2.39	25.48	2.55	24.31	2.68	24.81	2.84	21.40	2.09	21.65	2.13
Yellow	24.40	1.77	20.62	2.20	23.97	1.08	23.02	2.49	21.38	1.06	20.54	1.92

Note: The sensors were located at the surface, in the bed See Figure 4.1 for temperature sensor locations

Table 6.11: Cool (Dec 2010-Feb 2011) season temperature data (°C)

Temperature Sensor	Asphalt		AquaPave		Pervious Concrete	
	Mean	STD	Mean	STD	Mean	STD
Red	-4.545	2.521	-6.555	3.598	-6.350	3.256
Green	-3.929	2.124	-3.991	2.237	-4.515	2.167
Blue	3.332	2.061	-3.039	1.967	-3.292	1.803
Yellow			-0.827	1.753	-1.449	1.701

Note: See Figure 4.1 for temperature sensor locations

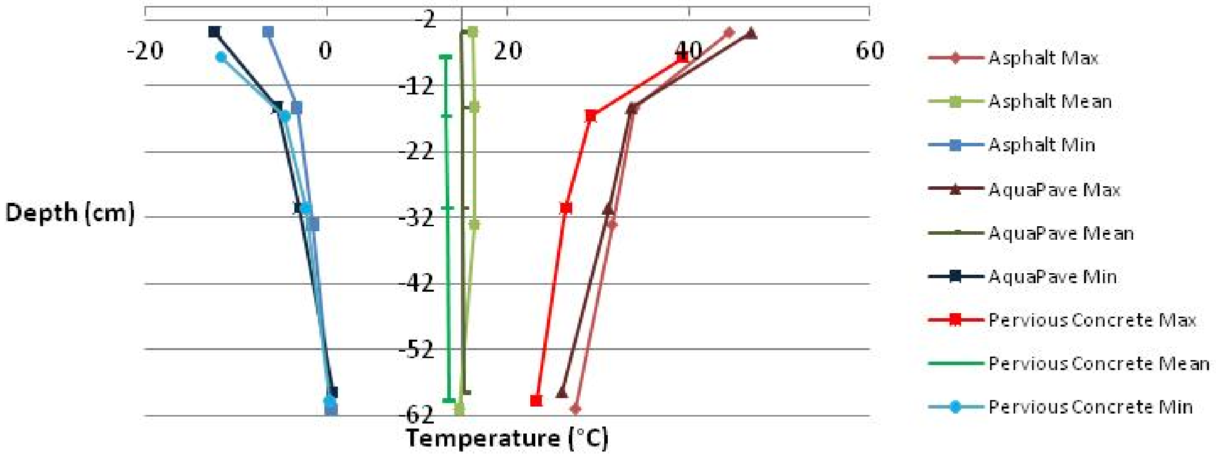


Figure 6.18: Temperature profiles in 2010

6.3.7 Pavement movement

The parking lot was surveyed in the fall and spring of each year of the study. Survey results (Table 6.12) showed no significant movement in any of the four pavement cells. This confirms that the pavement surface elevations are unaffected by winter conditions. No slumping or frost heaving has been observed.

Table 6.12: Survey results: Elevation (m)

Date	Control		AP		EO		PC	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Fall 2009	196.17	0.03	196.15	0.04	196.16	0.02	-	-
Spring 2010	196.14	0.03	196.13	0.04	196.14	0.04	196.17	0.05
Fall 2010	196.0	0.03	196.0	0.04	196.03	0.03	196.08	0.03
Spring 2011	196.3	0.03	196.28	0.04	196.28	0.03	196.32	0.02
Fall 2011	196.26	0.07	196.3	0.04	196.31	0.03	196.35	0.02
Spring 2012	196.33	0.03	196.3	0.04	196.30	0.03	196.35	0.03

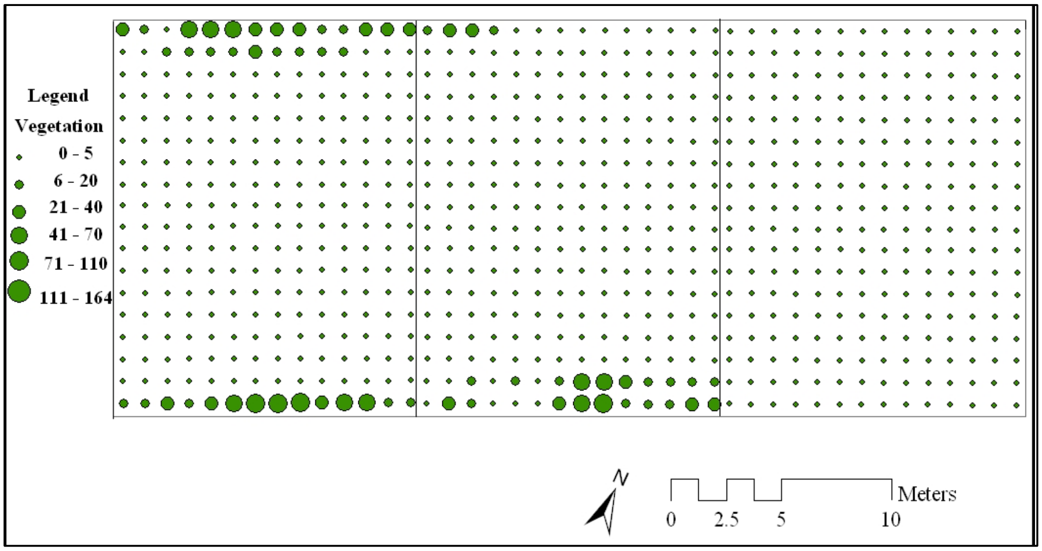
6.3.8 Vegetation colonization

Vegetation colonization of the PPs was assessed in September 2010 and 2011. The north and south sides of the parking lot is bounded by an elevated vegetated berm with overhanging trees that is graded towards the pavement. Small plants were observed along the edges of the AP and EO pavements. These plants are most likely the result of careless reseeding of the grass medians after construction in 2009 as rapid colonization of grass on new interlocking pavements is not common.

Table 6.13 summarizes the amount of colonization that has occurred in each pavement cell and Figure 6.19 illustrates the location and density of vegetation. After a second growing season, vegetation has been more widely established within the PPs. Observed plants increased by more than threefold in AP and more than twofold in EO. The first establishment of plants growing along the edges of the PC pavement was observed in September 2011. The rate of plant colonization may be influenced by the open space area of the pavements. AP, which has narrower joints than EO, may provide more suitable environment for germination, rooting and plant growth. The PC was installed 6 months after the PICPs and was not exposed to reseeding activities; however, after two growing seasons, only limited colonization has taken place. It is possible that the large void areas of the PC surface, as well as, a high pH from the concrete may limit opportunities for plant establishment.

Table 6.13: Vegetation Counts

Pavement	Total Counted		Max Density per m^2		Total Increase (%)
	2010	2011	2010	2011	
AquaPave	1153	5483	84	164	375
Eco-Optiloc	685	2391	72	91	250
Pervious Concrete	0	32	0	0	-



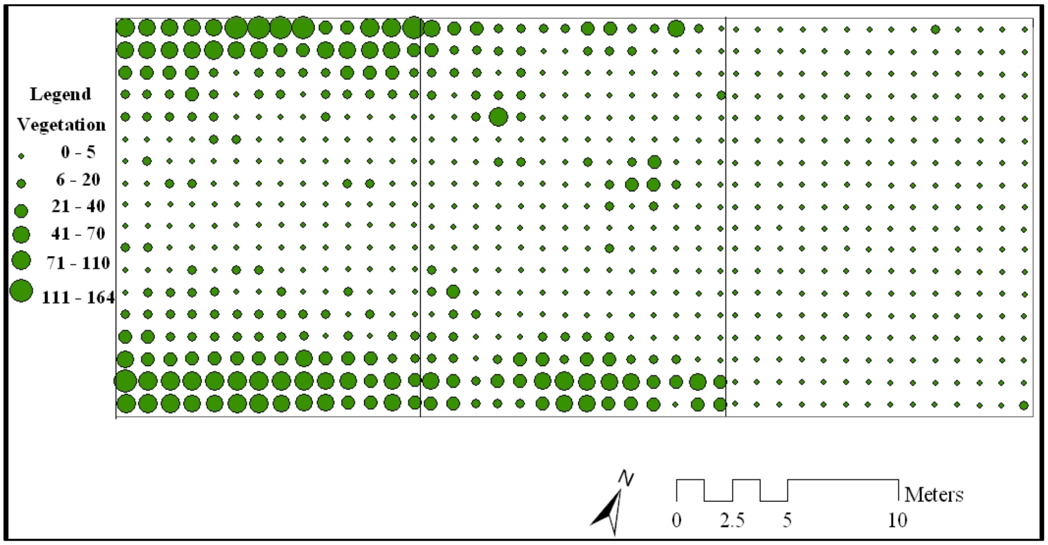


Figure 6.19: Vegetation counts: Fall 2010 (top), Fall 2011 (bottom)

6.5 Maintenance

Infiltration tests were conducted before and after scheduled 2010 spring maintenance at Earth Rangers, BMO Field and the MTO Guelph Line Commuter lot. The Earth Ranges and MTO parking lots were swept with a mechanical sweeper and BMO Field was pre-wetted and cleaned with a regenerative air sweeper. At each location, no significant changes to infiltration rates were observed. Mechanical sweeping is not recommended as a maintenance technique for PPs and thus it is an expected outcome that the sweeper would have little to no impact on the pavement hydrologic performance. Pre-wetting of pavement is also not a recommended practice and may have negatively impacted the effectiveness of the regenerative-air sweeper. Additionally, winter construction activities at Exhibition Place exposed the PP to an excessive amount of fine sediment. These extenuating circumstances meant that the maintenance results from BMO Field do not reflect 'typical' conditions as the degree of sediment accumulation far exceeded amounts that would be expected from regular day-to-day use of the parking lot.

Small scale cleaning treatments were tested at seven GTA parking lots by the University of Guelph. The preliminary results (Table 6.14) indicate that the older pavements continue to infiltrate water, albeit at a reduced rate. Infiltration rates were observed to increase after vacuuming and pressure washing treatments. Preliminary observations suggest that the most effective surface treatment is a two-part practice: dislodging compacted sediment followed by the permanent removal of sediment.

Testing of regenerative-air and vacuum-sweeping trucks as techniques to restore surface permeability was conducted in 2011. A regenerative-air Tymco-DST 6® truck was tested on two parking lots (East Gwillimbury GO Station and Guelph Line) while a Elgin Whirlwind® Vacuum truck was demonstrated on a third parking lot (Earth Rangers). Both systems proved to provide partial rehabilitation of the PPs. Post-treatment surface infiltration rates on all three parking lots displayed large spatial variability highlighting that micro-conditions throughout the pavement have a confounding influence on the overall effectiveness of maintenance.

Table 6.14 presents the measured infiltration rates before and after maintenance. Pre-treatment infiltration measurements revealed that all three PPs had poor surface permeability and, as a result, tests with the sweeper trucks resembled rehabilitation practices not preventative maintenance. Under these conditions it was shown that regenerative-air and vacuum trucks provide partial restoration of surface permeability. Overall, 50% of the cleaned surfaces displayed improved surface permeability after maintenance. The results indicate that suction-based sweeper trucks are well suited to rehabilitative maintenance.

In the summer of 2012 the Kortright pavement was vacuumed with an Elgin Whirlwind® Vacuum truck as an example of preventive, rather than rehabilitative maintenance. Infiltration measurements were performed before and after to assess the impact of the maintenance (Table 6.16). One-sided paired t-tests of the log-transformed data found statistically significant increases of mean infiltration rates for the AP (p = 4.6E-5) and EO (p = 0.011) pavements. Significant changes were not observed in the PC pavement (p = 0.4) although the PC continued to have significantly higher infiltration than the PICPs. Failure to have any impact on the 43% reduction in permeability since 2010 suggests that vacuuming may not be as effective a technique on pervious concrete.

Table 6.14: Infiltration test results

Treatment	Infiltration Rate (cm/hr)		Change (cm/hr)	Depth Exposed (cm)
	Pre-treatment	Post-treatment		
Seneca College King's Campus				
No Treatment	1.1	2.9	1.8	NA
Hand Sweeping	0.7	4.7	4.0	0.1
Low Suction Vacuum	0.7	6.5	5.8	0.5
High Suction Vacuum	0.7	4.0	3.2	0.3
Pressure Wash	0.7	[1]		3.0
Sunset Beach, Richmond Hill				
No Treatment	0.7	1.4	0.7	NA
Hand Sweeping	1.4	1.4	0.0	0.4
Low Suction Vacuum	0.4	1.4	1.1	0.8
High Suction Vacuum	0.7	2.9	2.2	0.4
Pressure Wash	0.7	> 250[2]		2.2
East Gwillimbury GO Station				
No Treatment	3.2	5.8	2.5	NA
Hand Sweeping	2.2	1.1	-1.1	0.2
Low Suction Vacuum	2.2	253.8	251.6	1.0
High Suction Vacuum	2.5	96.5	94.0	0.5
Pressure Wash	3.6	295.9	292.3	2.5
St Andrew's Niagara-on-the-Lake				
No Treatment	32.0	47.5	15.5	NA
Hand Sweeping	10.1	6.5	-3.6	0.1
Low Suction Vacuum	13.7	211.3	197.6	3.5
High Suction Vacuum	10.4	100.4	90.0	1.0
Pressure Wash	17.3	246.2	229.0	4.5
BMO Field				
No Treatment	16.2	5.4	-10.8	NA
Hand Sweeping	10.08	9.72	-0.4	NA
Low Suction Vacuum	5.76	15.48	9.7	NA
High Suction Vacuum	9.36	9.36	0.0	NA
Pressure Wash	6.48	15.48	9.0	NA
Earth Rangers				
No Treatment	5.4	38.88	33.5	NA
Hand Sweeping	3.96	4.32	0.4	0.5
Low Suction Vacuum	11.16	161.64	150.5	2
High Suction Vacuum	2.88	193.68	190.8	3.5
Pressure Wash	5.76	176.04	170.3	3.0
Guelph Line				
No Treatment	3.6	1.44	-2.2	NA
Hand Sweeping	3.6	-	-	NA
Low Suction Vacuum	3.6	5.4	1.8	NA
High Suction Vacuum	1.08	-	-	NA
Pressure Wash	1.08	21.96	20.9	NA

Notes: 1. infiltration rate into the pavement was too fast to measure accurately. 2. A complete seal between the rings and pavement was not achieved, resulting in large losses through the sides.

Table 6.15: Measured infiltration rates (cm/hr) at GTA sites

Test	GO Station		Earth Rangers		Guelph Line	
	Pre	Post	Pre	Post	Pre	Post
1	<5	7	<5	8	<5	30
2	<5	5	<5	8	11	70
3	<5	4	<5	53	<5	6
4	<5	172	<5	154	<5	50
5	11	46	<5	120	<5	15
6	<5	8	<5	282	<5	54
7	<5	6	5	25	<5	59
8	<5	79	<5	25	<5	9
9	<5	128	<5	152	4	16
10	<5	58	9	<5	<5	33
11	<5	76	21	363	<5	5
12	<5	13	<5	100	<5	23
13	<5	21	<5	25	35	137
14	<5	20	<5	47	<5	31
15	<5	11			25	131
16	<5	6			<5	20
17	6.	3				
18	<5	114				
19	<5	88				
20	70	114				
21	<5	222				
22	<5	10				
23	<5	4				
24	78	72				
25	19	40				
26	13	14				

Table 6.16: Infiltration rates (cm/hr) at Kortright

Test	PC		EO		AP	
	Pre	Post	Pre	Post	Pre	Post
1	2 860	2 690	56	274	49	46
2	1 180	1 120	80	101	64	66
3	945	1 080	36	399	9	34
4	3 160	3 270	78	76	12	25
5	1 220	1 130	116	187	10	21
6	2 040	333	38	158	4	22
7	2 960	2 860	17	187	6	26
8	873	1 120	78	47	4	33
9	764	751	87	88	5	14
10	1 550	1 580	110	208	3	13
11	1 150	857	266	447	20	37
12	3 160	3 820	262	790	4	12
Mean	**1 820**	**1 720**	**102**	**247**	**16**	**29**
Median	**1 390**	**1 120**	**79**	**187**	**7**	**26**

Although the maintenance significantly improved the surface permeability of the PICPs it was not able to restore permeability to levels even close to those measured after installation. After maintenance median surface infiltration rates for the AP, EO and PC were still 83%, 63% and 47% lower than the respective median infiltration rate measured in 2010. Despite these losses the PPs continue to provide sufficient capacity to infiltrate precipitation events without prolonged ponding. The experiences at Kortright demonstrated that regular maintenance is an important component of the operation of PICPs that will extend the functional life of these pavements. Further research is needed on more effective maintenance techniques on PICPs, particularly as they apply to restorative or rehabilitative maintenance. The maintenance requirements for PC also require further investigation. The performance of PC at Kortright suggests that the pavement may require less frequent cleaning than the PICPs. It remains to be seen if accumulated fines within the PC can be removed by surface vacuuming.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Results of this study show that PPs offer significant benefits for the treatment and management of stormwater over conventional asphalt-to-catchbasin collection systems. A key advantage of PPs is the capacity of PP systems to reduce outflow volumes even when applied to areas with low permeability soils. The three evaluated PPs, AquaPave, Eco-Optiloc and Pervious Concrete, did not produce direct surface runoff throughout the 22 month monitoring period of this study. Overall, the PPs reduced the volume of stormwater outflow by 43% and were shown to be capable of completely capturing (i.e. infiltrating and evaporating) the stormwater produced from rainfall events up to 7 mm in depth. This reduction of stormwater volume helps mitigate the adverse impact of the urban landscape on receiving surface water systems.

In addition to reducing outflow volumes, the PPs delayed and reduced peak flows. Attenuation was observed throughout all seasons, including the winter, over the duration of the study. On average, PP peak flows were 91% smaller than peak runoff flows from the asphalt pavement. A median 14 hour attenuation (or 2.9 lag ratio) of outflow was observed from the PPs. The slower and more controlled outflow more closely mimics interflow and reduces the risk of flood and erosion in downstream receiving waters.

Winter data show the PP systems function well even during freezing temperatures. Elevation surveys showed that freezing temperatures did not cause significant surface heaving or slumping. A substantial spring thaw was observed in March 2011, during which the PP delayed the outflow of melt water by three days and greatly reduced peak flows. Increases in outflow volume were occasionally observed during the winter and spring due to the delayed release of stormwater stored within the aggregate reservoir.

Surface infiltration measurements revealed substantial reductions in permeability over the course of the study, although even at reduced permeability levels, all of the pavements continued to have sufficient capacity to rapidly infiltrate all rainfall from the observed storms. Between June 2010 and May 2012, permeability reductions of the narrow jointed PICP (AP), wide jointed PICP (EO) and PC were 87%, 70% and 43%, respectively. These results indicate that PPs with larger surface opening may sustain critical infiltration capacity longer without maintenance than PPs with small surface openings.

The PC pavement continued to have extremely high infiltration capacity even after two years, with median infiltrations rates of 1,072 cm/hr at the end of the study in 2012. By contrast, the median surface infiltration rate of the narrow jointed PICP was only 20 cm/hr after 2 years. Vacuum sweeping provided only partial restoration of surface permeability for the PICPs. No benefit was observed from vacuum sweeping for the PC at Kortright, although the pavement retained a high infiltration capacity. Vacuum sweeping on other PP parking lots produced highly variable results and did not provide consistent removal of embedded fines within PICP joints and PC pavements.

Over the monitoring period, median/mean concentrations of several pollutants in PP outflow were significantly lower than median/mean concentrations in asphalt runoff, including suspended solids, extractable solvents (oil & grease), ammonia-ammonium nitrogen (NH_3-NH_4^+), nitrite, total kjeldahl nitrogen (TKN), total phosphorus, copper, iron, manganese and zinc. The PPs also generated a net reduction in total pollutant mass for all of these constituents in addition to dissolved solids, chloride, sodium, phosphate, and nitrates. Seasonality was more pronounced in runoff than in PP outflow. In the winter the concentration of pollutants associated with road salting were considerably higher in runoff than in PP outflow. The reduction in concentration is attributed to the detention and dilution of winter stormwater provided by the PP systems. Water quality data collected below native soils indicated that sodium and chloride will migrate onwards to groundwater systems, although further investigation is needed to determine how the presence of these constituents may affect the mobility of other stormwater contaminants, such as metals.

The PICP and PC pavements introduced different constituents into stormwater outflow as a result of leaching of materials within the pavement system. In the case of the PC this led to a gradual improvement in water quality over the course of the study, as mobile pollutants were ultimately flushed from the pavement. Throughout the first year of monitoring the PC effluent contained elevated levels of phosphate and released highly alkaline stormwater, which are undesirable characteristics for aquatic ecosystems. Further investigation is needed to explore the implications of pollutant leaching on stormwater quality from large newly constructed PP installations. The long term change in water quality of outflows from these PPs is being investigated in a second phase of this project.

7.2 Recommendations

Results of this study indicate that permeable pavements can be effective measures for maintaining or restoring infiltration functions on parking lots and other low volume traffic areas, even in areas with low permeability soils. The following recommendations are based on study findings and observations.

- Restricting outflow rates from partial infiltration PP systems through raised pipes or flow control valves is recommended to increase stormwater volume reductions through infiltration.
- Closed outlet valve tests suggested that raising the perforated outflow pipe in the cross section of the PP structure or elevating the discharge pipe downstream of the PP system is feasible on low permeability silty clay soils and may result in substantially larger outflow reductions than would occur from restricting outflow rates alone. Further investigation of this type of application on low permeability soils is recommended.
- Pollutant leaching of pavement and aggregate materials was observed, particularly for pervious concrete. Leaching was observed to decline as the pavement aged. For large pervious concrete installations, additional treatment may be required if outflows drain to ecologically sensitive streams. Further testing of the performance and leaching potential of different types of pervious concrete is recommended.
- Permeable pavements were observed to reduce the loads and concentrations of several stormwater contaminants. Additional investigations are needed to define the specific conditions (*e.g.* magnitude of load reductions, ecological sensitivity of receiving waters, maintenance

guarantees) under which partial infiltration permeable pavement systems should be eligible for pollutant removal credits in Ontario jurisdictions.

- Vacuum cleaning of permeable interlocking concrete pavements was found to only partially restore surface permeability after 2 years of operation. Further tests of different techniques for loosening or dislodging compacted material in permeable pavement joints or pores prior to cleaning are needed to improve the effectiveness of regenerative air and vacuum sweeping trucks.
- Based on maintenance practices evaluated in this study, annual vacuum cleaning of permeable interlocking concrete pavements is recommended to increase the operational life of these pavements. The PC pavement maintained high surface permeability over the study period, and therefore maintenance is recommended less frequently (i.e. > 2 years).
- Further research on the long-term (i.e. > 3years) performance of permeable pavement systems is needed to assess how the hydrologic, water quality and functional characteristics of the pavements may change over time.
- In this study, the 2011/2012 winter was unseasonably warm with low amounts of snowfall. Additional monitoring of winter performance and behaviour is recommended.
- In 2011/2012 operational staff found that the permeable pavements did not require salting as frequently as the asphalt pavement. Further research is needed to evaluate how and whether permeable pavements can maintain safe conditions with lower salt use than conventional pavements.
- Elevation surveys of the pavements during this study showed no significant movement across the four pavement cells. Further testing of pavement movement under increased traffic frequencies and loading scenarios are needed to verify the range of functional conditions under which these pavements are suitable alternatives to asphalt.

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APPENDIX A

Parking Lot Construction in 2009/10

Parking lot construction

Construction of the new permeable pavement parking lot took place over the fall of 2009. The existing asphalt and fill was removed (1) and excavated (2) in preparation for the construction of the new parking lot. A drainage pipe was installed which allows runoff and water exfiltrating from the permeable pavement to discharge to the adjacent forest (3), where rip rap and a granular soakaway was installed to prevent erosion. A concrete pad (4) and vault (5) was installed which houses the equipment needed to monitor flows and collect water quality samples. The vault is accessed through a manhole and at the same elevation as the pavement so that the entire monitoring systems is gravity fed (6). With the control vault in place four drainage pipes were placed. These pipes collect stormwater from the four pavement cells. In the control cell the pipe connected to a catchbasin and drains surface runoff from the asphalt pavement. In the three permeable pavement cells the pipe is perforated and collected water that has infiltrated through the pavement and granular fill. An additional collection pipe was placed at a lower depth beneath a meter of native material under the Aquapave® PICP cell. The pipe was positioned in a trench of granular material above an impermeable liner so that water could easily drain into the pipe (7).

All four pavement cells were filled and levelled with clear stone granular material (except for the asphalt, which used a dense graded base) (8). In the permeable pavement cells this material provides up to 49 mm of storage during precipitation events. Trenches were dug between each cell (9) and a concrete curb was installed to hierologically separate the cells (10). The paving material was installed for the asphalt, the AquaPave® and the Eco-Optiloc® in early November (11). Temperature sensors were embedded in the pavement and below for the asphalt and Aquapave® PICP (12). A shallow well was dug through each pavement and transducers were installed to monitor water level responses within the pavement. Since pervious concrete required higher overnight temperatures for curing, the pervious concrete plot was installed in the spring of 2010.

Figure A1: 2009/2010 photos

APPENDIX B

Water Quantity

Table B1: Total volumes (V_T), peak flows (Q_p) and associated reductions (VR and QR) for storm and melt events that initiated flow from the PP underdrains

Event	Rainfall	V_T (L)		V_{Tunit} (L/m^2)		VR	Q_p (L/min)		QR
	(mm)	Asphalt	PP	Asphalt	PP	(%)	Asphalt	PP	(%)
16/09/2010	21.9	5115	3042	22.0	13.2	40	57	7	88
27/09/2010	31.4	6696	4445	28.8	19.2	33	72	4.3	94
05/10/2010	23.5	5589	2853	24.0	12.3	49	45	1.5	97
14/10/2010	21.4	5514	2801	23.7	12.1	49	45	1.3	97
23/10/2010	16.8	3759	1634	16.2	7.1	56	24	0.5	98
26/10/2010	7.7	1821	886	7.8	3.8	51	51	1	98
16/11/2010	21.7	5085	2389	21.9	10.3	53	30	2.5	92
22/11/2010	10.6	2622	963	11.3	4.2	63	51	1.8	96
25/11/2010	9.4	2262	952	9.7	4.1	58	45	2.5	94
30/11/2010	26.6	6516	4217	28	18.2	35	30	3	90
12/12/2010	9.2	2136	658	9.2	2.9	69	9	0.9	90
31/12/2010	-	2541	2575	10.9	11.1	-2	45	2.5	94
18/02/2011	-	1554	384	6.7	2.5	63	6	1.1	83
28/02/2011	-	5514	879	23.7	3.8	84	27	1.4	95
04/03/2011	-	5973	3733	25.7	16.2	37	15	3.3	78
09/03/2011	-	16038	20855	69.0	90.3	-31	30	4.5	85
30/03/2011	-	5028	4872	21.6	21.1	2	120	3.3	97
10/04/2011	7.6	1638	859	7	5.6	21	33	1.5	95
16/04/2011	17.6	4257	2088	18.3	9.0	51	39	2.3	94
20/04/2011	15.6	3762	2684	16.2	11.6	28	81	2.3	97
23/04/2011	7.7	1831	1101	7.9	4.8	39	24	1.0	96
26/04/2011	14	3255	1854	14.0	8.0	43	81	2.3	97
27/04/2011	7.7	1617	1330	7.0	5.8	17	108	1.0	99
01/05/2011	10.8	2574	1330	11.1	5.8	48	21	0.9	96
06/05/2011	4	843	616	3.6	4.0	-10	21	0.3	99
14/05/2011	46	10968	7888	47.2	34.0	28	153	5.2	97
18/05/2011	19.6	4530	4082	19.5	17.6	10	117	4.2	96
24/05/2011	7	1839	380	6.9	2.5	64	222	1.1	100
25/05/2011	20	4761	1993	20.5	8.6	58	57	10.0	82
04/06/2011	13.7	3168	1508	13.6	6.5	52	48	4.0	92
07/06/2011	6.1	1251	286	5.4	1.2	77	48	0.2	100
11/06/2011	-	4710	4143	20.3	17.9	12	126	4.0	97
23/06/2011	49.4	8190	9093	35.2	39.3	-12	258	4.0	98
25/07/2011	31.7	6300	3597	27.1	15.6	43	186	4.0	98
01/08/2011	8.2	1152	664	5.0	2.9	42	150	2.2	99
03/08/2011	15.6	3612	1832	15.5	7.9	49	99	4.0	96
07/08/2011	10	1839	1075	7.9	4.6	41	81	2.3	97
09/08/2011	14.9	3231	1993	13.9	8.6	38	90	4.0	96
14/08/2011	20	4151	4801	17.9	20.8	-16	153	4.0	97
21/08/2011	15.2	2026	1317	8.7	5.7	35	147	2.5	98
24/08/2011	18.6	3740	2454	16.1	10.6	35	123	4.0	97
01/09/2011	9.2	1538	491	6.6	2.1	68	78	3.0	96
04/09/2011	9.6	1992	1077	8.6	4.7	46	126	2.3	98
19/09/2011	20.8	4617	2127	19.9	9.2	54	54	4.0	93
21/09/2011	6.8	1629	835	7.0	3.6	48	54	1.8	97
23/09/2011	19.6	4602	3081	19.8	13.3	33	183	4.0	98
28/09/2011	21.8	4182	1914	18.0	8.3	54	51	4.0	92
03/10/2011	7.4	1626	665	7.0	2.9	59	27	1.2	96
12/10/2011	20.4	4842	1734	20.8	7.5	64	123	1.5	99
19/10/2011	35.6	8634	6214	37.1	26.9	28	63	4.0	94
25/10/2011	26.7	6351	4554	27.3	19.7	28	24	4.0	83
14/12/2011		1947	1017	8.4	4.4	47	18	3.0	83
21/12/2011		2439	643	10.5	2.8	73	183	3.0	98
27/12/2011		1038	231	4.5	1.5	66	9	3.0	78
31/12/2011		4662	3066	20.1	13.3	34	15	3.0	78
12/1/2012		2307	1005	9.9	4.3	56	15	1.7	89
23/1/2012		2844	249	12.2	1.1	91	18	0.7	96
26/1/2012		2415	1936	10.4	8.4	19	9	3.0	67
31/1/2012		918	2231	3.9	9.7	-145	6	2.0	67
22/2/2012		1962	1675	8.4	7.2	14	15	2.0	87
29/2/2012		3372	4074	14.5	17.6	-22	75	2.5	97
7/3/2012		291	28	1.3	0.2	88	21	0.04	100
9/3/2012		102	109	0.4	0.5	-8	3	0.1	99
13/3/2012		1125	385	4.8	1.7	66	33	0.3	99
12/6/2012		3357	1699	14.4	7.3	49	48	4.0	92
21/6/2012		2542	2852	10.9	12.3	-13	189	7.0	96
26/6/2012		2029	1056	8.7	4.6	48	135	3.7	97

Table B2: Total volumes (V_T), peak flows (Q_p) for events with surface runoff from the asphalt but no subsurface runoff from the underdrains

Event	Rainfall (mm)	V_T (L)	V_{Tunit} (L/m^2)	Q_p (L/min)
02-Sep-10	6.6	1221	5.3	27
11-Sep-10	6.6	1449	6.2	30
22-Sep-10	6.2	1098	4.7	75
20-Oct-10	2.3	894	3.8	18
03-Nov-10	0.7	129	0.6	6
05-Nov-10	3.7	816	3.5	12
05-Dec-10	melt	135	0.6	3
11-Dec-10	melt	147	0.6	3
17-Dec-10	melt	222	1.0	3
18-Dec-10	melt	126	0.5	3
20-Dec-10	melt	36	0.2	3
29-Dec-10	melt	42	0.2	3
30-Dec-10	melt	294	1.3	3
31-Dec-10	melt	269	1.2	9
04-Jan-11	melt	39	0.2	3
14-Jan-11	melt	42	0.2	3
18-Jan-11	melt	156	0.7	3
27-Jan-11	melt	27	0.1	3
28-Jan-11	melt	28	0.1	3
29-Jan-11	melt	12	0.1	3
30-Jan-11	melt	12	0.1	3
07-Feb-11	melt	18	0.1	3
13-Feb-11	melt	69	0.3	3
14-Feb-11	melt	459	2.0	3
16-Feb-11	melt	81	0.3	3
16-Feb-11	melt	123	0.5	3
24-Feb-11	melt	42	0.2	3
25-Feb-11	melt	93	0.4	3
8-Mar-11	melt	30	0.1	3
17-May-11	1.8	459	2.0	9
22-May-11	0.2	45	0.2	3
23-May-11	0.5	111	0.5	12
29-May-11	4.2	609	2.6	18
22-Jun-11	2.0	666	2.9	54
28-Jun-11	0.2	402	1.7	54
18-Jul-11	4.2	18	0.1	3
22-Jul-11	0.2	807	3.5	48
29-Jul-11	0.6	132	0.6	9
29-Jul-11	1.1	180	1.1	9
31-Jul-11	0.5	87	0.5	6
06-Aug-11	0.3	45	0.2	3
07-Aug-11	1.8	282	1.2	15
17-Aug-11	0.6	207	0.9	18
20-Aug-11	0.4	24	0.1	3
21-Aug-11	0.6	90	0.4	9
03-Sep-11	1.4	240	1.0	33
14-Sep-11	3.2	549	2.4	6
02-Oct-11	2.2	462	2.0	18
24-Oct-11	2.2	528	2.3	30
9/11/11	5.6	1344	5.8	15
14/11/11	3.6	768	3.3	60
6/1/2012	melt	72	0.3	3
16/1/2012	melt	1413	6.1	12
12/2/2012	melt	24	0.1	3
14/2/2012	melt	78	0.3	3
15/2/2012	melt	48	0.2	3
16/2/012	melt	114	0.5	3
20/2/2012	melt	516	2.2	6
21/2/2012	melt	426	1.8	3
12/3/2012	melt	48	0.2	33
23/3/2012	melt	321	1.4	15
1/4/2012	1.6	390	1.7	6
10/4/2012	0.4	24	0.1	3

APPENDIX C

Water Quality Statistics

Table C1: Asphalt

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	% >MDL	% >Guideline
General Chemistry											
Alkalinity; total fixed endpt	mg/L	2.5			64	17.4	138.35	50.23	42.55	100	-
Conductivity	uS/cm	5			64	57	96200	6762.28	295	100	-
Hardness	mg/L	0.01			55	27	790	147.55	65.7	100	-
pH		5	9	CEQG	64	6.79	8.11	7.71	7.73	100	0
Solids; dissolved	mg/L	50	500	CWQG	64	<MDL	68500	5345.38	254	80	33
Solids; suspended	mg/L	2.5			64	12	313	86.40	62.4	100	-
Solids; total	mg/L	50			64	53	68600	4357.10	253.5	100	-
Solvent extractable	mg/L	1			64	<MDL	36	3.7	2.1	84	-
Metals											
Aluminum	ug/L	1	75	PWQO	63	107	2240	522.21	389	100	98
Antimony	ug/L	0.5	20	PWQO	39	<MDL	1.5	0.81	0.75	85	0
Arsenic	ug/L	1	5	PWQO	39	<MDL	8.7	-	-	10	-
Barium	ug/L	0.5			64	7.1	520	63.19	23.9	100	-
Beryllium	ug/L	0.5	11	PWQO	64	<MDL	0.84	-	-	6	0
Boron	ug/L	10	200	PWQO	39	<MDL	60	-	-	31	0
Cadmium	ug/L	0.5	0.5	PWQO	64	<MDL	1.49	-	-	14	14
Calcium	mg/L	0.01			55	10.1	289	53.36	23.3	100	-
Chloride	mg/L	1	120	CWQG	63	<MDL	43100	2877.55	23.6	90	35
Chromium	ug/L	5	8.9	PWQO	64	<MDL	5.4	-	-	14	0
Cobalt	ug/L	1	0.9	PWQO	39	<MDL	2.4	-	-	28	28
Copper[1]	ug/L	5	5	PWQO	57	<MDL	160	22.87	16.7	89	80
Iron	ug/L	30	300	PWQO	64	140	3850	922.28	677.5	100	80
Lead	ug/L	0.5	5	PWQO	42	<MDL	10.6	4.61	4.225	98	43
Magnesium	mg/L	0.01			55	0.549	16.7	3.46	1.97	100	-
Manganese	ug/L	0.5	50	CWQG	64	18.5	485	147.92	92.85	100	73
Molybdenum	ug/L	0.5	40	PWQO	64	<MDL	78.7	-	-	19	2

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	% >MDL	% >Guideline
Nickel	ug/L	2	25	PWQO	64	<MDL	16.2	5.19	3.3	42	0
Potassium	mg/L	0.06			54	0.361	59.8	4.91	1.48025	100	-
Selenium	ug/L	5	100	PWQO	39	ND	ND	ND	ND	ND	-
Silver	ug/L	0.5	0.1	PWQO	39	ND	ND	ND	ND	ND	-
Sodium	mg/L	0.04	200	CWQO	55	0.334	27900	1942.73	9.5555	100	29
Strontium	ug/L	1			64	42.3	2840	431.91	163.5	100	-
Thallium	ug/L	0.5	0.3	PWQO	39	<MDL	16.3	-	-	5	5
Titanium	ug/L	5			64	<MDL	24.7	9.15	6.9	52	-
Uranium	ug/L	0.5	5	PWQO	39	ND	ND	ND	ND	ND	0
Vanadium	ug/L	0.5	6	PWQO	55	1.4	66.8	6.07	3.9	96	18
Zinc	ug/L	2	20	PWQO	64	14.3	789	99.27	58.85	97	86
Nutrients											
Nitrogen; ammonia+ammonium	mg/L	0.01			64	<MDL	3.9	0.42	0.2875	98	-
Nitrogen; nitrate+nitrite	mg/L	0.025			64	<MDL	3.12	0.76	0.493	97	-
Nitrogen; nitrite	mg/L	0.005			64	0.0095	0.275	0.069	0.048	98	-
Nitrogen; total Kjeldahl	mg/L	0.1			64	0.43	5.75	1.67	1.235	100	-
Phosphorus; phosphate	mg/L	0.0025			64	<MDL	2.26	0.11	0.03445	98	-
Phosphorus; total	mg/L	0.01	0.03	PWQO	64	0.04	2.98	0.29	0.178	100	-
Pathogens											
E coli	c/100mL	4			40	<MDL	540000	-	-	33	-
Fecal streptococcus	c/100mL	4			40	<MDL	7000	878	205	98	-
Pseudomonas aeruginosa	c/100mL	4			40	<MDL	8500	4137	410	65	-

Notes: [1]Copper non-detects are due to Lab error and were neglected in the mean and median calculations

Table C2: Aqua Pave

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	% >MDL	% >Guideline
General Chemistry											
Alkalinity; total fixed endpt	mg/L	2.5			43	48.9	164	95.69	92.6	100	-
Conductivity	uS/cm	5			43	203	5460	927.86	410	100	-
Hardness	mg/L	0.01			38	43	560	132.36	90.7	100	-
pH		5	9	CEQG	43	7.83	9.72	8.29	8.26	100	2
Solids; dissolved	mg/L	50	500	CWQG	43	132	3450	561.21	266	100	23
Solids; suspended	mg/L	2.5			43	<MDL	33.6	11.53	9	91	-
Solids; total	mg/L	50			43	166	3460	572.79	276	100	-
Solvent extractable	mg/L	1			43	<MDL	1.2	-	-	2	-
Metals											
Aluminum	ug/L	1	75	PWQO	43	43.7	1100	283.80	201	100	79
Antimony	ug/L	0.5	20	PWQO	29	<MDL	1.3	0.83	0.8	83	0
Arsenic	ug/L	1	5	PWQO	29	<MDL	6.6	2.04	1.6	83	-
Barium	ug/L	0.5			43	25.4	555	86.09	50.8	100	-
Beryllium	ug/L	0.5	11	PWQO	43	<MDL	0.087	0.06	0.06	5	0
Boron	ug/L	10	200	PWQO	29	11	103	39.04	27.5	100	0
Cadmium	ug/L	0.5	0.5	PWQO	43	<MDL	1.72	-	-	19	19
Calcium	mg/L	0.01			38	12.5	148	35.65	25.1	100	-
Chloride	mg/L	1	120	PWQO	43	1.7	1700	195.41	10.4	100	28
Chromium	ug/L	5	8.9	PWQO	43	<MDL	6.66	-	-	35	0
Cobalt	ug/L	1	0.9	PWQO	29	<MDL	1.8	-	-	14	14
Copper	ug/L	5	5	PWQO	43	<MDL	17.7	5.91	5.4	70	44
Iron	ug/L	30	300	PWQO	43	40	950	250.28	150	100	16
Lead	ug/L	0.5	5	PWQO	30	0.9	18	5.52	3.785	100	37
Magnesium	mg/L	0.01			38	2.91	46.1	10.51	7.34	100	-
Manganese	ug/L	0.5	50	CWQG	43	2.7	56.7	17.71	13.9	100	5
Molybdenum	ug/L	0.5	40	PWQO	43	<MDL	19	5.27	4.88	93	0

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	% >MDL	% >Guideline
Nickel	ug/L	2	25	PWQO	43	<MDL	6.8	1.89	1.29	49	0
Potassium	mg/L	0.06			38	9.45	65.6	30.95	27.3	100	-
Selenium	ug/L	5	100	PWQO	29	ND	ND	ND	ND	ND	-
Silver	ug/L	0.5	0.1	PWQO	29	ND	ND	ND	ND	ND	-
Sodium	mg/L	0.04	200	CWQO	38	10.2	972	121.69	27.05	100	13
Strontium	ug/L	1			43	1400	33400	5807.44	3750	100	-
Thallium	ug/L	0.5	0.3	PWQO	29	<MDL	8.4	-	-	7	7
Titanium	ug/L	5			43	<MDL	6.89	-	-	37	-
Uranium	ug/L	0.5	5	PWQO	29	0.25	2.3	1.21	1	100	0
Vanadium	ug/L	0.5	6	PWQO	42	0.25	12.6	3.02	2.4	98	7
Zinc	ug/L	2	20	PWQO	43	5.19	49.7	21.88	19.1	100	40
Nutrients											
Nitrogen; ammonia+ammonium	mg/L	0.01			43	<MDL	0.2	0.04	0.027	98	-
Nitrogen; nitrate+nitrite	mg/L	0.025			43	0.36	2.1	0.90	0.81	100	-
Nitrogen; nitrite	mg/L	0.005			43	<MDL	0.2	0.019	0.011	81	-
Nitrogen; total Kjeldahl	mg/L	0.1			43	<MDL	0.65	0.21	0.81	81	-
Phosphorus; phosphate	mg/L	0.0025			43	<MDL	0.0908	0.02	0.0169	98	-
Phosphorus; total	mg/L	0.01	0.03	PWQO	43	<MDL	0.116	0.04	0.027	98	35
Pathogens											
E coli	c/100mL	4			30	<MDL	560	-	-	50	
Fecal streptococcus	c/100mL	4			30	<MDL	110000	5557	540	100	
Pseudomonas aeruginosa	c/100mL	4			30	<MDL	51000	4137	410	90	

Table C3: Eco-Optiloc

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	%>MDL	% >Guidline
General Chemistry											
Alkalinity; total fixed endpt	mg/L	2.5			45	57.9	151	105.16	102	100	-
Conductivity	uS/cm	5			45	247	4500	1057.11	454	100	-
Hardness	mg/L	0.01			39	53	720	171.84	110	100	-
pH		5	9	CEQG	45	7.82	9.44	8.28	8.255	100	4
Solids; dissolved	mg/L	50	500	CWQG	45	161	3190	649.24	295	100	36
Solids; suspended	mg/L	2.5			45	<MDL	45.1	9.38	5.8	91	-
Solids; total	mg/L	50			45	161	3190	658.61	302	100	-
Solvent extractable	mg/L	1			45	<MDL	2	-	-	4	-
Metals											
Aluminum	ug/L	1	75	PWQO	45	44.2	1460	243.01	159	100	62
Antimony	ug/L	0.5	20	PWQO	29	<MDL	1.3	0.78	0.8	86	3
Arsenic	ug/L	1	5	PWQO	29	<MDL	3.5	1.48	1.3	69	-
Barium	ug/L	0.5			45	37.1	483	96.23	55.3	100	-
Beryllium	ug/L	0.5	11	PWQO	45	0.033	0.051	-	-	4	0
Boron	ug/L	10	200	PWQO	29	14	128	46.66	35	93	3
Cadmium	ug/L	0.5	0.5	PWQO	45	0.951	1.79	-	-	16	16
Calcium	mg/L	0.01			39	15.3	203	47.93	31.5	100	-
Chloride	mg/L	1	120	CWQG	45	0.5	1460	234.99	13.6	100	36
Chromium	ug/L	5	8.9	PWQO	45	<MDL	5.34	-	-	31	2
Cobalt	ug/L	1	0.9	PWQO	29	1.4	2.6	-	-	10	14
Copper	ug/L	5	5	PWQO	45	<MDL	14.8	5.70	5.47	68	47
Iron	ug/L	30	300	PWQO	45	30	1200	207.24	129	98	18
Lead	ug/L	0.5	5	PWQO	31	0.6	14.6	3.38	2	97	23
Magnesium	mg/L	0.01			39	3.6	52.1	12.73	8.26	100	-
Manganese	ug/L	0.5	50	CWQG	45	2.63	84.2	14.71	10.2	100	7
Molybdenum	ug/L	0.5	40	PWQO	45	<MDL	19	5.57	5.34	89	2
Nickel	ug/L	2	25	PWQO	45	1.83	7.9	-	-	27	2

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	%>MDL	% >Guidline
Potassium	mg/L	0.06			39	10.5	53.2	22.88	20.1	100	-
Selenium	ug/L	5	100	PWQO	29	ND	ND	ND	ND	ND	-
Silver	ug/L	0.5	0.1	PWQO	29	ND	ND	ND	ND	ND	-
Sodium	mg/L	0.04	200	CWQO	39	7.76	668	128.05	35.8	100	26
Strontium	ug/L	1			45	1850	40400	7608.98	4370	100	-
Thallium	ug/L	0.5	0.3	PWQO	29	<MDL	4.1	-	-	7	10
Titanium	ug/L	5			45	<MDL	10.3	-	-	40	-
Uranium	ug/L	0.5	5	PWQO	29	0.5	2	1.09	1	97	3
Vanadium	ug/L	0.5	6	PWQO	44	<MDL	9.72	2.70	2.3	93	7
Zinc	ug/L	2	20	PWQO	45	<MDL	55.5	15.06	13.05	98	20
Nutrients											
Nitrogen; ammonia+ammonium	mg/L	0.01			45	<MDL	0.157	0.04	0.025	91	-
Nitrogen; nitrate+nitrite	mg/L	0.025			45	0.31	2.01	0.79	0.655	100	-
Nitrogen; nitrite	mg/L	0.005			45	0.006	0.065	0.012	0.008	73	-
Nitrogen; total Kjeldahl	mg/L	0.1			45	<MDL	0.7	0.19	0.16	82	-
Phosphorus; phosphate	mg/L	0.0025			45	<MDL	0.12	0.02	0.0146	98	-
Phosphorus; total	mg/L	0.01	0.03	PWQO	45	<MDL	0.185	0.04	0.026	96	49
Pathogens											
E coli	c/100mL	4			30	<MDL	100	-	-	33	-
Fecal streptococcus	c/100mL	4			30	<MDL	42000	3069	245	97	-
Pseudomonas aeruginosa	c/100mL	4			30	<MDL	15000	7601	38	70	-

Table C4: Pervious Concrete

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	%>MDL	% >Guideline
General Chemistry											
Alkalinity; total fixed endpt	mg/L	2.5			45	93.2	421	168.73	155	100	-
Conductivity	uS/cm	5			45	316	4360	1116.11	715	100	-
Hardness	mg/L	0.01			38	23	260	67.19	51.3	100	-
pH		5	9	CEQG	45	8.08	11.8	9.18	9.07	100	20
Solids; dissolved	mg/L	50	500	CWQG	45	205	2260	669.71	463	100	33
Solids; suspended	mg/L	2.5			45	<MDL	101	17.75	6.9	96	-
Solids; total	mg/L	50			45	208	2360	687.53	469	100	-
Solvent extractable	mg/L	1			45	<MDL	1.5	-	-	7	-
Metals											
Aluminum	ug/L	1	75	PWQO	45	47.7	1260	546.08	510	100	67
Antimony	ug/L	0.5	20	PWQO	29	0.25	1.5	0.82	0.8	100	0
Arsenic	ug/L	1	5	PWQO	29	1.1	24.4	5.81	3.4	100	-
Barium	ug/L	0.5			45	14.1	158	36.17	26.5	100	-
Beryllium	ug/L	0.5	11	PWQO	45	<MDL	0.126	-	-	9	2
Boron	ug/L	10	200	PWQO	29	12	82	38.38	40	90	0
Cadmium	ug/L	0.5	0.5	PWQO	45	<MDL	1.08	-	-	9	7
Calcium	mg/L	0.01			38	6.06	55.4	16.05	12.85	100	-
Chloride	mg/L	1	120	PWQO	45	1	1150	156.21	15.4	100	31
Chromium	ug/L	5	8.9	PWQO	45	<MDL	19.5	-	-	47	7
Cobalt	ug/L	1	0.9	PWQO	29	<MDL	1.74	-	-	48	41
Copper	ug/L	5	5	PWQO	45	<MDL	56.6	11.72	6.94	78	47
Iron	ug/L	30	300	PWQO	45	30	970	383.36	370	100	36
Lead	ug/L	0.5	5	PWQO	30	0.6	12.4	4.85	4.5	100	47
Magnesium	mg/L	0.01			38	1.93	30.9	6.60	4.655	100	-
Manganese	ug/L	0.5	50	CWQG	45	2.7	72.1	23.98	19.3	100	11
Molybdenum	ug/L	0.5	40	PWQO	45	0.75	48.5	8.69	6.6	98	0
Nickel	ug/L	2	25	PWQO	45	<MDL	8.35	2.67	2.4	67	0

Pollutant	Unit	MDL	Guideline	Source	n	Min	Max	Mean	Median	%>MDL	% >Guideline
Potassium	mg/L	0.06			38	40.5	311	123.36	109.5	100	-
Selenium	ug/L	5	100	PWQO	29	ND	ND	ND	ND	ND	-
Silver	ug/L	0.5	0.1	PWQO	29	ND	ND	ND	ND	ND	-
Sodium	mg/L	0.04	200	CWQO	38	16.4	780	115.10	36.5	100	13
Strontium	ug/L	1			45	550	18600	2606.76	1430	100	-
Thallium	ug/L	0.5	0.3	PWQO	29	<MDL	10.7	-	-	7	7
Titanium	ug/L	5			45	<MDL	10	-	-	44	-
Uranium	ug/L	0.5	5	PWQO	29	<MDL	1.6	0.79	0.6	90	0
Vanadium	ug/L	0.5	6	PWQO	45	0.5	22.6	6.75	5	100	18
Zinc	ug/L	2	20	PWQO	45	2.17	27.5	12.48	11.7	100	18
Nutrients											
Nitrogen; ammonia+ammonium	mg/L	0.01			45	<MDL	0.165	0.04	0.028	93	-
Nitrogen; nitrate+nitrite	mg/L	0.025			45	0.196	1.71	0.60	0.446	100	-
Nitrogen; nitrite	mg/L	0.005			45	<MDL	0.185	0.029	0.015	96	-
Nitrogen; total Kjeldahl	mg/L	0.1			45	<MDL	0.9	0.37	0.26	98	-
Phosphorus; phosphate	mg/L	0.0025			45	0.0113	0.288	0.08	0.072	100	-
Phosphorus; total	mg/L	0.01	0.03	PWQO	45	0.043	0.655	0.14	0.117	100	100
Pathogens											
E coli	c/100mL	4			29	<MDL	2000	-	-	34	-
Fecal streptococcus	c/100mL	4			29	<MDL	2300	337	200	97	-
Pseudomonas aeruginosa	c/100mL	4			29	<MDL	39000	-	-	38	-