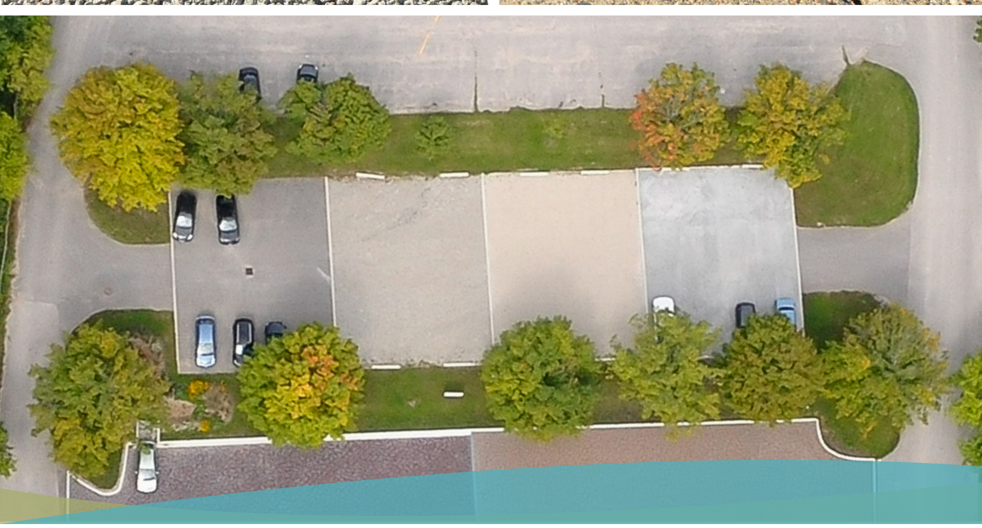
FIVE YEAR PERFORMANCE EVALUATION OF PERMEABLE PAVEMENTS

FINAL REPORT



Sustainable Technologies Evaluation Program
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Toronto and Region Conservation for The Living City

University of Toronto

FIVE YEAR PERFORMANCE EVALUATION OF PERMEABLE PAVEMENTS – KORTRIGHT, VAUGHAN

Final Report

Prepared by:

Toronto and Region Conservation
and
University of Toronto

under the
Sustainable Technologies Evaluation Program

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NOTICE

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 the University of Toronto, Department of Civil Engineering (project lead: Jennifer Drake, PhD). TRCA field and technical support was provided by Christy Graham, Kristina Delidjakova, Yuestas David, Matt Derro, Paul Greck, Amanda Slaght, Mark Hummel and Jacob Kloeze.

This project is an extension of a previous research project undertaken by the University of Guelph and STEP covering the first 22 months of monitoring at the Kortright permeable pavements research site. See the STEP web site for a copy of the earlier report entitled *Evaluation of Permeable Pavements in Cold Climates*.

Report citation: Van Seters, T, Drake, J. 2015. *Five year performance evaluation of permeable pavements*. Sustainable Technologies Evaluation Program, Toronto and Region Conservation Authority, Toronto, Ontario.

Reports conducted under the Sustainable Technologies Evaluation Program (STEP) are available at www.sustainabletechnologies.ca. For more information about this project or the STEP program, 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 livable communities.

ACKNOWLEDGEMENTS

Financial support for the extended monitoring program, undertaken between July 2012 and December 2014, was generously provided by the Cement Association of Canada, the Interlocking Concrete Paving Institute and STEP program partners – Region of Peel, York Region and the City of Toronto. In-kind services for monitoring and research were provided by the University of Toronto.

The first phase of the project, undertaken between September 2010 and June 2012, was supported financially by the following organizations:

- Great Lakes Sustainability Fund
- 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
- Metrus Development Inc.
- Interlocking Concrete Paving Institute
- 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 (Ultra Pervious concrete)
- Hanson (sampling vault)
- Ontario Ministry of the Environment (laboratory services)
- Armtec (pipes)
- Condrain (construction services)
- Dufferin Aggregates (aggregate base)
- Layfield Plastics (liner)

EXECUTIVE SUMMARY

Permeable pavements treat pollutants from parking areas and low traffic roads by filtering runoff through voids in the pavement and base materials. The pavements may be designed for full, partial or no infiltration depending on the characteristics of the underlying native soils (*e.g.* permeability, soil quality). Poured pavements such as pervious concrete, allow water to infiltrate through the entire pavement matrix, while permeable interlocking concrete pavements (PICP) combine pre-cast pavers with open, gravel filled joints to promote infiltration.

This study of permeable pavements was conducted over a five year period at a custom designed field research facility constructed by Toronto and Region Conservation Authority (TRCA) in 2009 at the Kortright Center visitor's center parking lot in Vaughan, Ontario. The site consists of four 230–233 m^2 pavement cells. Two cells are constructed with permeable interlocking concrete pavers (AquaPave® and Eco-Optiloc®), one cell is constructed with Pervious Concrete (PC) and one cell is constructed with traditional asphalt. Each permeable pavement cell is drained by a perforated pipe. The asphalt cell is surface drained via a catchbasin in the center of the plot. Concrete curbs between cells prevent inter-mixing of flows.

The first phase of this study was conducted as part of a doctoral research study by researchers from the University of Guelph, in collaboration with the TRCA's Sustainable Technologies Evaluation Program. The overall objective of the initial research study, conducted between September 2010 and June 2012, was to evaluate the hydrologic, water quality and functional performance of different types of concrete permeable pavements under Ontario climate and geologic conditions. This initial study also examined the effectiveness of different types of permeable pavement cleaning equipment.

The second phase of the study, initiated in July 2012, extended the original study for another 2.5 years with the intent of documenting the direction and magnitude of changes in performance over time. The monitoring program included measurements of rainfall, outflow, water quality, water levels in the base and temperature. After nearly 5 years of monitoring, this project represents one of the longest continuous field monitoring data sets of permeable pavements in North America.

Study Findings

Results of this study indicate that permeable pavements are an effective practice for maintaining or restoring infiltration functions on parking lots and other low volume traffic areas, even in areas with low permeability soils. Key findings of the extended monitoring program include the following:

- ***Surface infiltration:*** The rate of infiltration through the surface of the three permeable pavements was initially very high but declined rapidly over the first two years as sediment accumulated in surface voids of the pavements. Vacuum cleaning in June 2012 partially restored permeability to the pavements. However, by December 2014, infiltration rates on the AquaPave® (AP) and Eco-Optiloc® (EO) pavements had declined below thresholds established to avoid surface runoff during intense rain events (15 cm/h). The PC had a surface infiltration rate over 30 times that of the AP and EO pavements after 4 years and one maintenance cycle. While this pavement continues to infiltrate well, it is not yet clear how effective vacuum maintenance will be in reversing clogging on this type of pavement.

- ***Runoff volume reduction***. The pavements were found to reduce runoff volumes consistently over the course of the study, despite the presence of fine grained native soils. Annual warm season volume reduction rates relative to asphalt ranged from 40 to 52 percent (45% over the study period). This finding suggests that native soils below the pavements retained their capacity to infiltrate and that the geotextile below the base layer did not inhibit the movement of water into the underlying soils. The first 5 mm of most events was almost completely retained and infiltrated despite location of the perforated pipe at the bottom of the pavement structure.

- ***Surface Water Quality***. The permeable pavement effluents had lower concentrations of most pollutants relative to asphalt runoff. Reductions in median total suspended solids event mean concentrations (EMCs) by the permeable pavements over the study period were between 88 and 89%. Mass load reductions of pollutants would be greater than concentration reductions because, as noted earlier, 45% less stormwater was discharged from the permeable pavement plots than from the asphalt pavement. The quality of outflows from the different permeable pavements was comparable, but the PC pavement showed higher levels of pH, phosphate and potassium than the pre-cast pavers. Concentrations of these constituents in PC outflows stabilized at levels similar to the AP and EO pavements after two to four years. Effluent quality from the AP and EO pavements were very similar despite differences in the size of joints, filler material and the presence of a geotextile below the bedding layer of the AP pavement.

- ***Groundwater Quality:*** Underdrains were placed in the base and below a 0.5 to 1.0 m layer of native soil to evaluate potential effects on groundwater in areas with high water tables. Results showed that effluent from the upper and lower underdrains had similar concentrations of pollutants and exhibited little change over time. With the exception of salt (NaCl), pollutant concentrations in the lower underdrain were rarely at concentrations that would pose a health threat to the use of groundwater for drinking water. Lead exceeded the guideline in 2% of samples from the lower underdrain, suggesting that a separation distance between the base and seasonally high water table would need to be greater than 0.5 m to prevent contamination from lead. Iron and total dissolved solids were also above the aesthetic objective for drinking water in up to 40% of samples.

- ***Thermal loads***. Paved surfaces and some types of stormwater best practices can pose a threat to aquatic life in receiving waters by increasing the temperature of runoff. Results of this study showed that permeable pavement generated considerably lower thermal loads to receiving waters than the asphalt pavement during hot summer days, primarily due to lower outflow volumes. While the permeable pavement had lower maximum temperatures than asphalt, event mean temperatures (EMT) were higher than asphalt during two of the four events analyzed. During these two events, runoff from the asphalt occurred during the cool night hours, while the permeable pavement drained more gradually (up to 36 hours) and was therefore subject to greater daytime solar heating.

- ***Surface movement***. Elevation surveys conducted annually over the course of the study showed that the permeable pavement surfaces have been relatively stable over time with no obvious signs of heaving or slumping.

Recommendations for further monitoring and research are provided on maintenance of permeable pavements, winter snow and ice management, and the fate and transport of sediment particles within permeable pavement systems.

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1.0 BACKGROUND AND OBJECTIVES

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. Various stormwater best management practices have been devised to mitigate these impacts utilizing one, or a combination of different treatment processes, such as sedimentation, filtration, infiltration, and bio-degradation. Permeable pavements are unique in that they replace existing hard surfaces, and therefore do not require additional space that is either not available (*e.g.* in older developments) or can be alternatively used for greenspace or buildings.

Permeable pavements treat pollutants from parking areas and low traffic roads by filtering runoff through voids in the pavement and base materials. The pavements may be designed for full, partial or no infiltration depending on the characteristics of the underlying native soils (*e.g.* permeability, soil quality). Poured pavements such as pervious concrete, allow water to infiltrate through the entire pavement matrix, while permeable interlocking concrete pavements (PICP) combine pre-cast pavers with open, gravel filled joints to promote infiltration.

Despite an abundance of research on permeable pavements, there is a continued need for performance evaluations under field conditions reflecting Ontario climate or geology. The long-term effectiveness of permeable pavements, especially on fine textured soils, and their ability to hold up under cold climate conditions have not been extensively evaluated. To help better understand the performance of permeable pavements, the Toronto and Region Conservation Authority (TRCA) constructed a research facility in 2009 on the visitor's center parking lot at the Kortright Centre for Conservation in Vaughan, Ontario. In addition to being a showcase for public viewing of permeable pavements, the site was also host to a 22 month doctoral research study conducted by researchers from the University of Guelph, in collaboration with the TRCA's Sustainable Technologies Evaluation Program (Drake et al., 2012).

The overall objective of the initial research study, conducted between September 2010 and June 2012, was to evaluate the hydrologic, water quality and functional performance of different types of concrete permeable pavements under Ontario climate and geologic conditions. This initial study also examined the effectiveness of different types of permeable pavement cleaning equipment. Results of the research have been widely disseminated through white papers, journal articles and presentations (Drake et al., 2012; Drake et al, 2014a,b).

In 2012, the Cement Association of Canada (CAC) and the Interlocking Concrete Paving Institute (ICPI) expressed an interest in extending the monitoring until the end of 2014 to better understand how performance of the different pavement types change over time. This extended monitoring program, initiated in July, 2012, and conducted by two of the same researchers involved in the original project, was focused on evaluating the long term performance of the pavements and documenting the direction and magnitude of changes in performance over time. After nearly 5 years of monitoring, this project represents one of the longest continuous field monitoring data sets of permeable pavements in North America.

2.0 STUDY SITE

The research facility consists of four 230–233 m^2 pavement cells (Figure 2.1). Two cells are constructed with permeable interlocking concrete pavers (AquaPave® and Eco-Optiloc®), one cell is constructed with Pervious Concrete and one cell is constructed with traditional asphalt. The open graded aggregate base for the permeable pavements (Figure 2.3) provides storage that is roughly equivalent to a 100 mm rain event. Each permeable pavement cell is drained by a perforated pipe placed 500 mm below the surface at the interface between the open graded aggregate subbase layer and the native soil. The asphalt cell is surface drained via a catchbasin in the center of the plot (Figure 2.1).

Infiltrated water collected from the 3 cells as well as runoff collected in the catchbasin is conveyed separately in sealed pipes to a downstream monitoring vault where automated samplers, flow meters and temperature sensors are housed (Figure 2.2). A Mirafi Filter Weave® 500 geotextile was placed below the base as a separation layer. An Inbitex® geotextile with an apparent opening size of 0.145 mm and a flow rate of 4500 L/min/m^2 was placed between the bedding and base aggregate layers of the AquaPave pavement (Drake et al., 2014b). 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. Full drawdown of runoff for large events occurred within 48 hours or less. The pavement cells are hydraulically separated by concrete curbs and seepage collars to prevent cross flow among cells. Beneath the AquaPave cell a second perforated pipe is placed on a 1.0 x 20 m impermeable liner below 0.5 to 1.0 meters of native soil (Figure 2.3).[1] The lower drain was installed to evaluate the potential impact of stormwater infiltrated through native soils on groundwater quality.

A more detailed description of the site and results from the first phase of the study are available on Toronto and Region Conservation's Sustainable Technologies Evaluation Program web site (www.sustainabletechnologies.ca).

[1] The depth of native soil below the upper and lower underdrains varies from approximately 0.5 m below the center where pipes convey water to the sampling vault to 1.0 m below the rest of the permeable pavement plot.

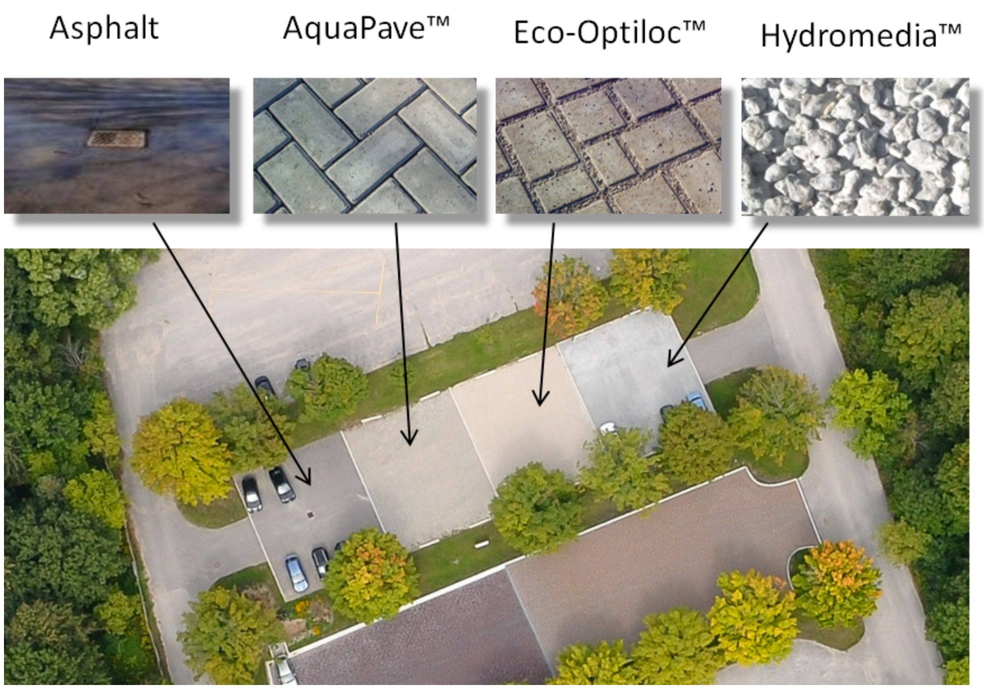

Figure 2.1: *Photo of the research facility showing the conventional asphalt and three types of permeable pavement.*

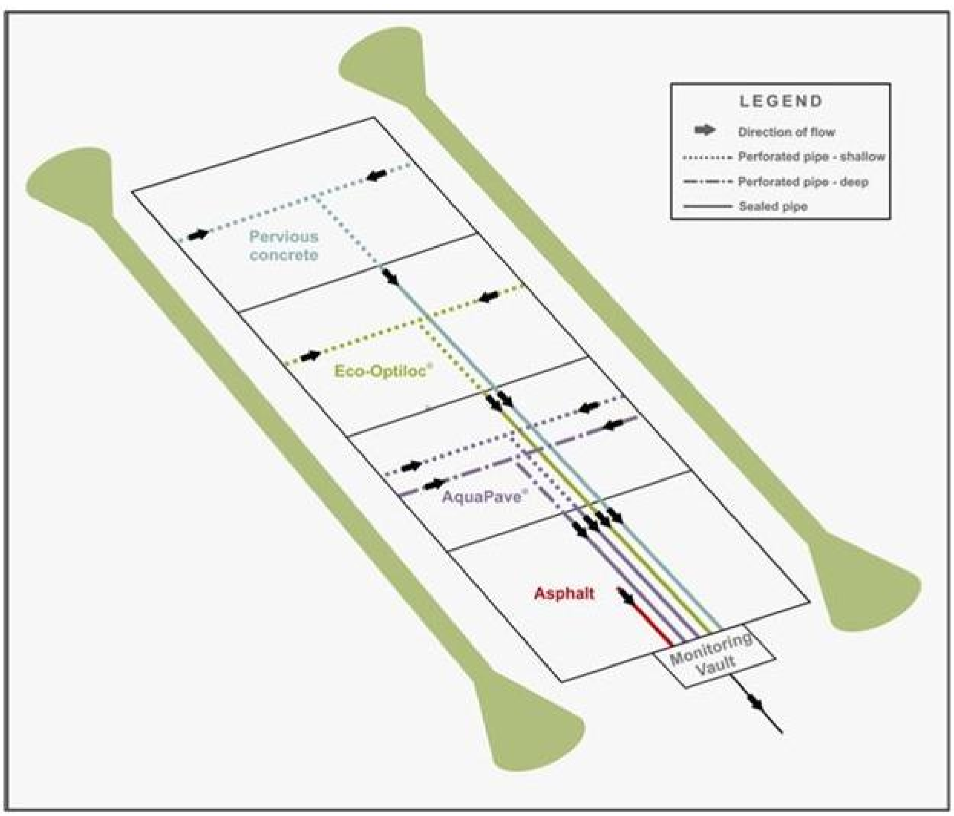

Figure 2.2: *Schematic of Kortright permeable pavement showing the monitoring vault and location of perforated underdrains and sealed pipes.*

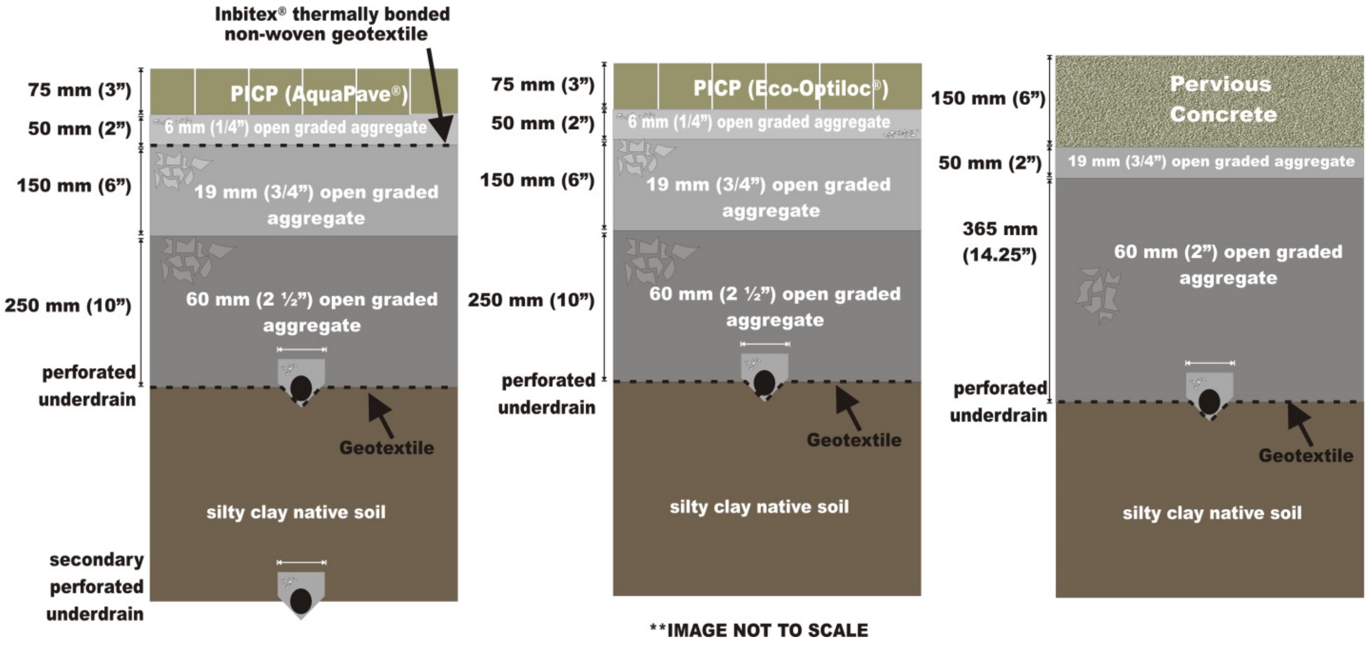

Figure 2.3: *From left to right, cross sections of the AquaPave (AP) Eco – Optiloc (EO) and pervious concrete (PC) pavements.*

3.0 METHODS

3.1 Monitoring Program

The initial and ongoing long term monitoring program includes coordinated measurements of precipitation, surface and subsurface infiltration, flow rates, and water quality. Precipitation is measured with a tipping bucket rain gauge located approximately 200 meters south of the facility. A second precipitation gauge located 500 meters north of the facility served as a back-up. Flow volumes and rates were determined using four tipping bucket flow gauges for low flows and a clamp-on ultrasonic flow meter for asphalt pavement flows that exceeded the maximum flow rate (60 L/min) of the flow gauge. Two pressure transducers inserted in wells within the pavement base provide measurements of water levels below the pavements.

Surface infiltration rates of the three permeable pavements (18 measurements per pavement) were conducted annually and before and after maintenance using ASTM C1701, *Standard Test Method for Surface Infiltration Rate for Pervious Concrete*. The first infiltration measurement on the AquaPave® and Eco-Optiloc® plots was conducted after a winter of operation. Infiltration measurements on the pervious concrete were conducted soon after installation.

The quality of water discharged from the underdrains of the three permeable pavements, and the asphalt surface were monitored during rain and snow events throughout the year. 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 volume proportioned composite samples for each event were subsequently prepared and delivered to the Ontario Ministry of the Environment (OMOE) Laboratory in Etobicoke for analysis following OMOE lab preparation and submission protocols. The full suite of parameters included in the original research study (*e.g.* solids, nutrients, metals, oil and grease, salts) were analyzed as part of the long term monitoring program. Water temperatures were also recorded to assess the effectiveness of permeable pavements in mitigating thermal impacts of runoff on stream eco-systems.

The elevation of the permeable pavements and asphalt surfaces were surveyed once a year to assess how well the pavements held up to freeze-thaw conditions and traffic loading. These measurements were discontinued after the first two years of the extended monitoring program.

3.2 Data Analysis

The hydrologic data were analyzed on an event basis to assess volume reductions, such that,

$$VR = \frac{V_{Tunit}^{control} - V_{Tunit}^{PP}}{V_{Tunit}^{control}} \times 100$$

where, *VR* = percent volume reduction

$V_{Tunit}^{control}$ = unit area runoff volume from the asphalt pavement (control), and

V_{Tunit}^{PP} = unit area outflow volume from the permeable pavements

An event was defined as the period between the beginning and end of outflow from the permeable pavements. Since this could occur over several days, the 'event' may include one or more discrete runoff events from the asphalt pavement. Only events during the warm season from April to November were analyzed for volume reduction because snow plowed to and from the control to permeable pavements introduced errors into the analysis that could not be quantified.

Water quality data were analyzed for differences in effluent quality among the different pavement types. Statistical analysis was generated using SigmaPlot 12.5 (SYSTAT Software Inc.). Data distributions were tested for normality using the Shapiro-Wilk test, which indicated that all datasets were non-normally distributed. To address non-normality, a Kruskal-Wallis One Way Analysis of Variance (ANOVA) on the Ranks was generated for each parameter and for six possible pairs. Dunn's (Bonferoni t) post hoc method was applied to address Type I errors of false statistical significance. Descriptive summary statistics of water quality data are provided in Appendix A.

The receiving water impact of effluent water temperature from the asphalt and permeable pavements (using AquaPave as a representative example), was assessed based on the event mean temperatures and thermal loads. The event mean temperature (EMT) represents the flow weighted mean temperature over the duration of a given runoff event, and is calculated as:

$$EMT = \frac{\sum_{k=1}^{n} T_k * Q_k * \Delta t_k}{\sum_{k=1}^{n} Q_k * \Delta t_k}$$

Where T is the effluent temperature, Q is the flow rate measured over a finite time interval (Δt), and the duration of the event is measured in discrete time intervals from 1 to n.

The thermal load (TL) represents the total heat delivered to the receiving water during a rain event, and is calculated as:

$$TL = \sum_{k=1}^{n} Q_k * \rho * T_k * C * \Delta t_k$$

Where *p* is the density of water (1000 kg/m^3) and C is the heat capacity of water (4187 J/kg/C). Thermal load reductions were determined by calculating the difference between the asphalt and permeable pavement thermal loads.

4.0 STUDY FINDINGS

4.1 Surface Infiltration

The surface infiltration rates of the three permeable pavements were measured every spring between 2010 and 2014, as well as before and after the pavements were cleaned in 2012 by an Elgin Whirlwind™ vacuum truck. Results for all the surface infiltration tests are presented in Figure 4.1.

The initial infiltration rate measurements conducted in 2010 showed median infiltration rates to be highest on the pervious concrete (PC) (2,123 cm/h), followed by Eco Optiloc® (EO) (504 cm/h) and AquaPave® (AP) (155 cm/h).[2] By 2012,after 23 months, infiltration rates declined to median values of 20 cm/h on the AP, 94 cm/h on EO, and 1,072 cm/h on PC. These represent declines of 87, 81 and 49%, respectively. Cleaning is recommended when surface infiltration rates fall below 25 cm/h.

The vacuum maintenance was able to produce a statistically significant improvement in infiltration rates on the Permeable Interlocking Concrete Pavements (PICP: EO and AP). By contrast, the PC pavement, which had high surface infiltration capacity prior to maintenance, did not show a statistically significant change. Median infiltration rates before/after maintenance were 7/26, 79/187 and 1390/1120 cm/h on the AP, EO and PC pavements, respectively.

After the pavements had been cleaned, surface infiltration rates continued to decline. The latest set of measurements showed median infiltration rates for AP, EO and PC to have fallen to 6, 15 and 556 cm/h, representing decreases since 2012 of 76, 92 and 51%, respectively. Even at these low rates, prolonged surface ponding were not observed because the majority of rain events do not have intensities greater than 5 cm/h for longer than 15 minutes. The maximum rainfall intensity observed over the five year monitoring period was 13 cm over 5 minutes. After the winter of 2014, and the conclusion of the study, surface infiltration continued to decline and several larger events in 2015 showed ponding on the two AP and EO pavements. This would not normally have occurred because permeable pavements are designed to drain overland to a surface outlet. At this site, however, the permeable pavements were graded to the center to help ensure full hydrologic separation of the three plots.

Surface infiltration rates of PICPs are largely controlled by the percent open space, which is in turn related to the size of the jointing material. Pervious concrete is estimated to have up to 30% void space. The EO pavement had wide joints (13-14 mm) between the pavers with roughly 12% open space and 1-9 mm jointing material (high performance bedding, also known as ASTM #9 aggregate).

[2] As noted earlier, surface infiltration measurements of the PC pavement were conducted soon after installation, while measurements on the EO and AP pavements were conducted after a winter of operation. Hence, the installed or initial surface infiltration of EO and AP would have been higher than measured in this study.

The AP had narrow joints (3-4 mm) and the lowest surface infiltration capacity, with only 2-4% open space, and joint stabilizing material ranging from 1 to 3 mm in size.

It should be noted that traffic enters the parking area primarily from the east entrance. Therefore, dirt and sediment on tires from outside areas is more likely to be deposited on PC and the neighbouring EO pavement because these are closer to this entrance. Sand was not used for winter maintenance on the permeable pavement plots and asphalt control; only salt (NaCl).

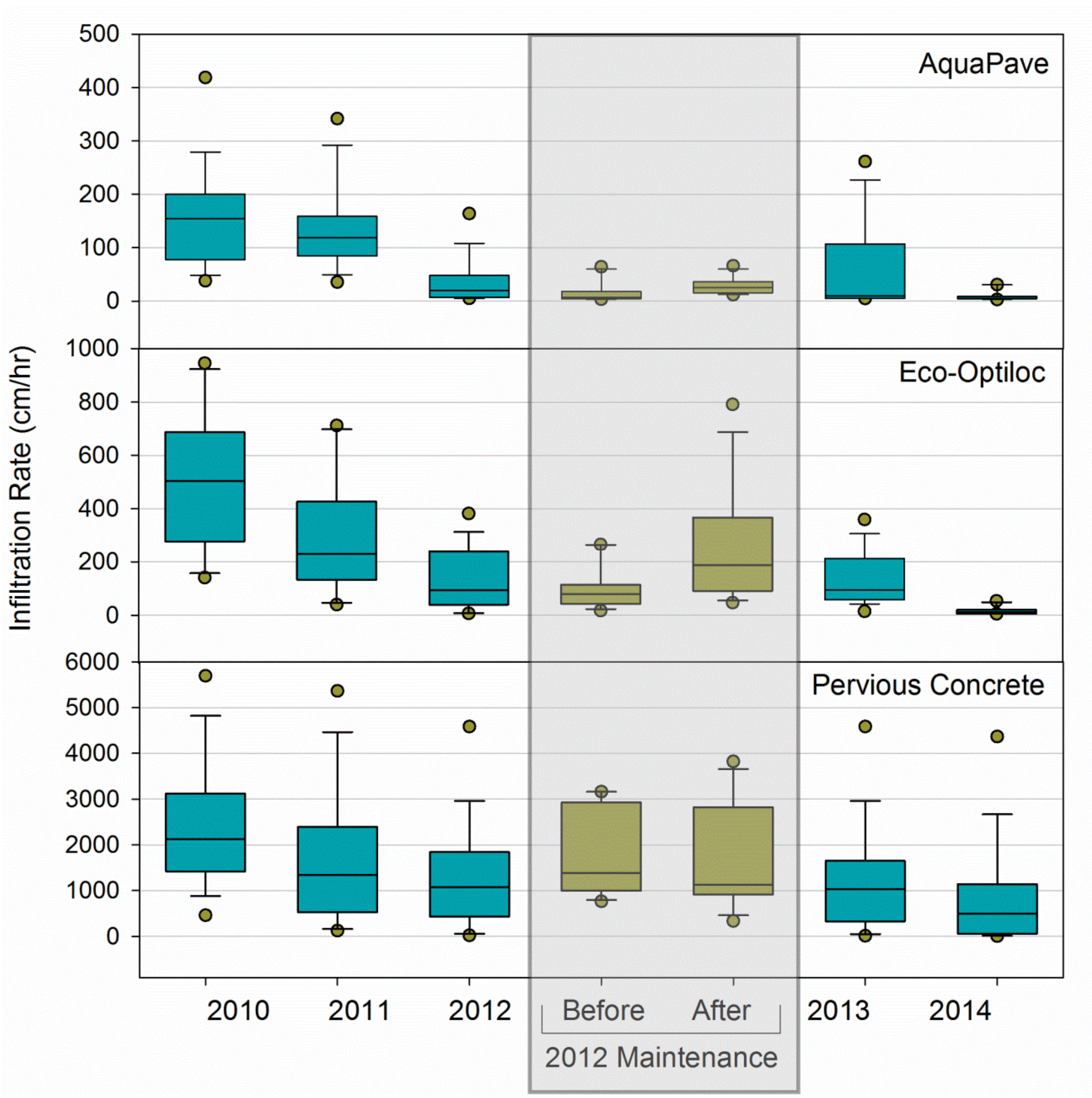

Figure 4.1: *Surface infiltration rates for AP, EO and PC from 2010 to 2014 (n = 18), and before and after pavement cleaning in 2012 (n = 12). Note difference in vertical scales.*

4.2 Volume Reduction

A key objective of the long term monitoring program was to evaluate temporal changes in the volume of stormwater reduced through infiltration and evaporation. Reductions in infiltration over time may occur if fines clogged the geotextile or native soils below the granular base. Further compaction of the subgrade soils may also occur as the pavement ages, which may also affect infiltration. Alternatively, infiltration may increase if preferential pathways for infiltration through the native soil increased in number or became larger over time.

To assess the extent of changes, the volume of stormwater reduced by the permeable pavements was calculated during the warm season (April to November) from 2010 to 2014 (Table 4.1). Cold season outflow volumes were also available but flow reductions calculated from comparison to the asphalt reference could not be verified to be accurate because, as mentioned earlier, some of the snow that fell on the asphalt pavement may have been plowed to the permeable pavement plots, or vice versa. It should be noted that the permeable pavement underdrains are equipped with control valves to help detain the water for up to 48 hours after a rain event. All efforts were made to ensure these control valves were maintained at the same settings throughout the monitoring period to minimize influences on volume reduction rates.

Table 4.1 shows warm season (April to November) outflow volumes and runoff reduction rates from 2010 to 2014. Figure 4.2 shows reduction rates by event size. Runoff reduction results for all warm season events are presented in Appendix B. On an annual basis, warm season volume reduction rates ranged between 40% and 52%. Year to year differences may be attributed to variations in the size and durations of events. Most rain events less than approximately 5 mm generated almost no outflow from the permeable pavements (Figure 4.2); hence a larger proportion of rainfall occurring as small, low intensity rain events during any given year can boost overall volume reduction values. Despite fine textured native soils that were intentionally compacted to accommodate traffic loads, permeable pavement outflows were 45% less than asphalt runoff over the five year monitoring period. These data indicate that infiltration into the native soils beneath the pavements has remained relatively constant over the first five years of operation, suggesting that infiltration into the native soils may not be strongly influenced by pavement age, and that the geotextile between the base and native soils is not inhibiting the transfer of water to the soils below.

Infiltration of nearly all of the first 5 mm of each event largely explains the relationship shown in Figure 4.2 between event size and runoff reduction. This initial volume of runoff is stored within the base and fills the shallow sump between the native soils and perforated pipe. During the inter-event period, water in this sump partially or fully infiltrates, creating new storage for the next event. As event size increases, the water in the sump forms a declining proportion of total rainfall, resulting in the leveling off of runoff volume reduction rates shown in in Figure 4.2.

Table 4.1: *Annual Volume Reduction from April to November*

Year	Asphalt Runoff Volume (mm)	Permeable Pavement Outflow Volume (mm)	Volume Reduction (%)
2010	220	105	52
2011	575	334	42
2012	350	171	51
2013	496	277	44
2014	462	277	40
Total	2103	1164	45

Note: 2010 started in September, 2012 started in June after closed valve tests, 2013 ended in late September due to electrical outages and a very dry November.

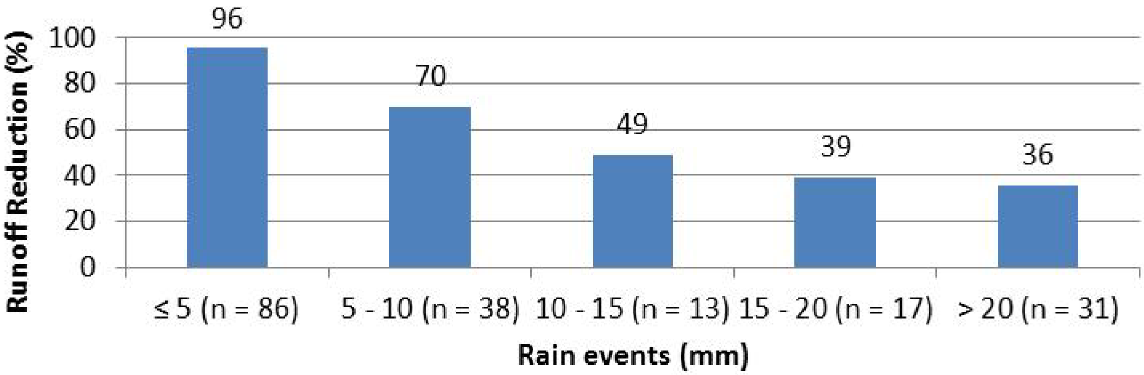

Figure 4.2: *Runoff reduction by event size*

Peak flows, lag times and lag coefficients calculated in the initial study (Drake et al, 2012) were not repeated during the extended monitoring study because the original values were not expected to change given similarities in runoff reduction rates and flow control valve settings. In the previous study, which covers the first 22 months of monitoring, peak flows were reduced by an average of 91% relative to the asphalt pavement, and stormwater was released over a longer time period. A typical hydrograph for a summer event is shown in Figure 4.3. It should be noted that flow rate reductions achieved by the permeable pavements are controlled by the valves used to enhance infiltration into the native soils. Flow rates from the asphalt pavement were also restricted to allow for more accurate measurement of asphalt control volumes. Since asphalt control flow rates would not normally be restricted, the peak flow reduction rates are a conservative estimate of the rates expected in real world installations.

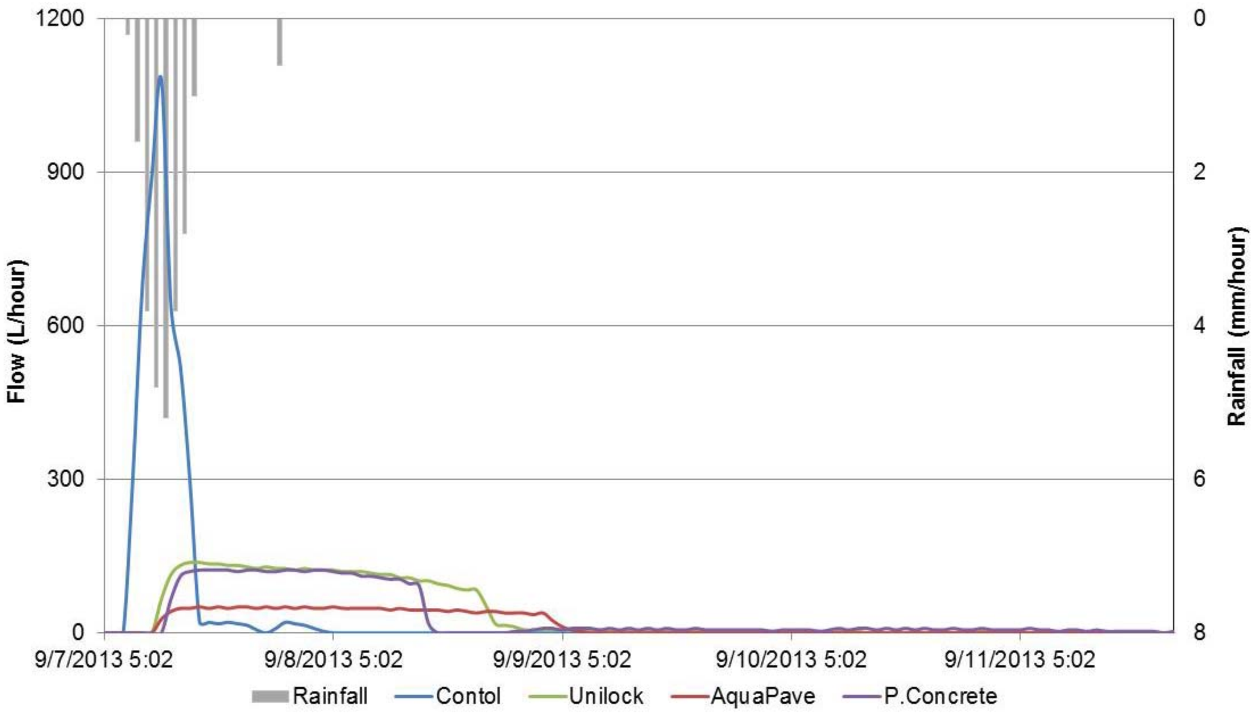

Figure 4.3: *Event hydrograph from the September 7, 2013 event. Total Rainfall: 23.8 mm*

4.3 Water Quality

By 2014, over 250 samples had been collected for water quality analysis. Samples were analyzed for solids, nutrients, metals, road salt constituents, and general chemistry. Descriptive statistics are presented in Appendix A. Box plots for selected variables are presented in Figures 4.4 and Figure 4.5. Table 4.2 shows statistical differences between plots for selected variables.

4.3.1 Concentrations

Asphalt runoff concentrations for several variables were statistically higher than those in the effluent of the three permeable pavements at the 95% level of confidence. These included total suspended solids (TSS), total phosphorus, total nitrogen, total kjeldahl nitrogen (TKN), ammonia nitrogen, iron and zinc. Oil and grease (solvent extractable) was detected above the method detection limit (MDL) in over 83% of asphalt samples, but in less than 6% of permeable pavement samples. Copper also had lower median concentrations and lower detection frequencies in permeable pavement samples (Appendix A). Relative to the asphalt pavement, the permeable pavements had statistically higher concentrations of nitrate, potassium, strontium, pH and alkalinity. Potassium and strontium in runoff are of little concern because these do not pose a threat to receiving waters at observed concentrations. The pH and alkalinity of effluent from the PC was elevated during the first two years, but otherwise all permeable pavement effluents had pH and alkalinity values within acceptable ranges for the protection of aquatic life.

The only difference between the EO and AP was the size of joints between the pavers, the joint stabilizing material and the presence of the Inbitex® geotextile below the open graded bedding of AO. The lack of a significant difference in water quality between the two pavements (Table 4.2) suggests that geotextile, joint size and joint filler may not have a significant influence on water quality performance. This finding agrees with lab scale research by Mullaney et al (2011) in Scotland that showed no significant difference in the removal of metals and oils on permeable pavements with and without geotextile placed below the bedding layer. By contrast, Van Duin *et al* (2008) reported that suspended solids filtering occurred primarily by the geotextile in lab scale studies. The authors note, however, that lab results contradict their own field results and other studies that showed filtration occurring primarily at the surface of the pavement. In earlier research from the UK, Newman et al (2006) found that the geotextile membrane and other pavement building materials help to remove hydrocarbons by supporting the growth of naturally occurring microbial communities that degrade oils and maintain free-draining characteristics of the membrane. In the present study, oil and grease was often present in asphalt runoff but rarely detected in permeable pavement outflows, indicating that all permeable pavements were effective in removing oils regardless of their differences.

In addition to reducing the concentration of pollutants in stormwater runoff, permeable pavements also reduce the mass load of pollutants discharged to receiving waters. Mass load reductions of pollutants would be greater than concentration reductions because, as noted earlier, 45% less stormwater was discharged from the permeable pavement plots than from the asphalt pavement. In the earlier study, loads from the permeable pavement plots were considerably lower than asphalt. This continues to be true. The Ontario Ministry of the Environment stormwater guidelines specify that stormwater BMPs achieving 'enhanced' level treatment must remove a minimum of 80% of TSS (MOE, 2003). In this study, the permeable pavements well exceeded this criterion, removing in excess of 90% of TSS loads.

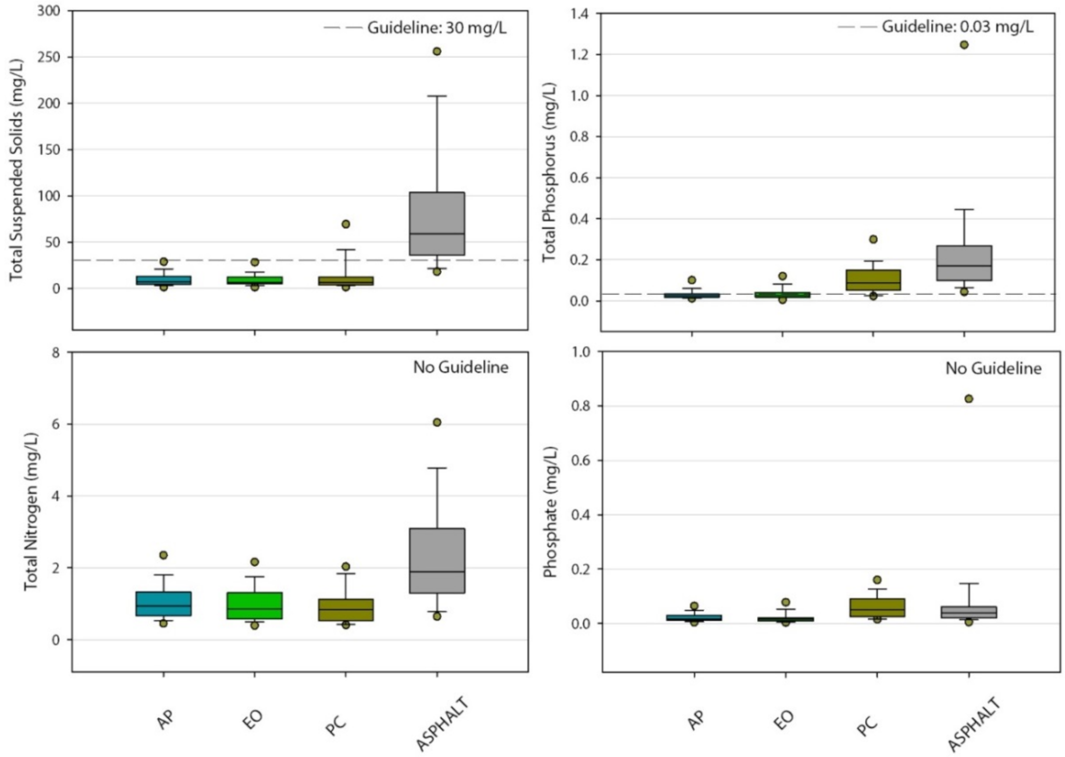

Figure 4.4: *Box plots of TSS and selected nutrient concentrations over the 2010-2014 study period.*

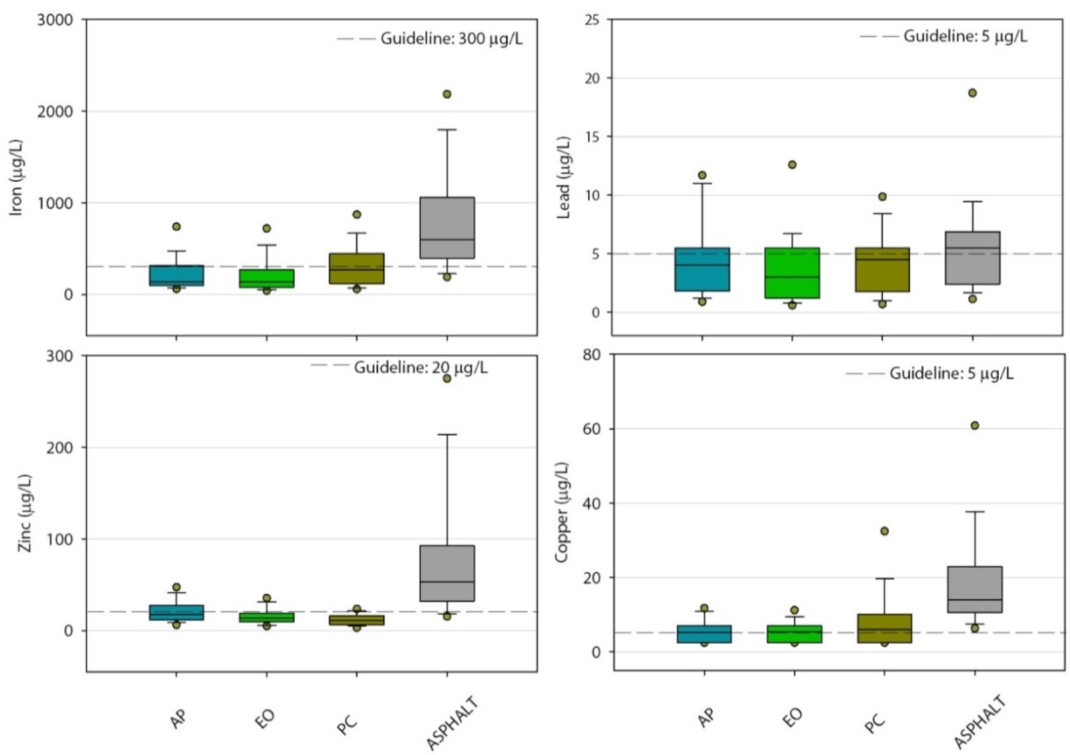

Figure 4.5: *Box plots of selected metal concentrations over the 2010-2014 study period.*

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Table 4.2: *Analysis of Variance for statistical significance between key parameter concentrations of asphalt (AS), AquaPave (AP), Eco-Optiloc (EO) and pervious concrete (PC).*

Legend				
N = no significant difference	AS > EO,AP,PC	PC > AS,EO,AP	EO > AS,PC	AP > AS,PC

Parameters		**AS vs EO**	**AS vs AP**	**AS vs PC**	**PC vs AP**	**PC vs EO**	**AP vs EO**
General Chemistry	TSS	AS>EO	AS>AP	AS>PC	N	N	N
	pH	EO>AS	AP>AS	PC>AS	PC>AP	PC>EO	N
	Alkalinity	EO>AS	AP>AS	PC>AS	PC>AP	PC>EO	N
	Hardness	EO>AS	AP>AS	N	AP>PC	EO>PC	N
Nutrients	Total Phosphorus	AS>EO	AS>AP	AS>PC	PC>AP	PC>EO	N
	Ortho-phosphate	AS>EO	AS>AP	N	PC>AP	PC>EO	N
	Total Nitrogen	AS>EO	AS>AP	AS>PC	N	N	N
	Total Kjeldahl N	AS>EO	AS>AP	AS>PC	N	N	N
	Ammonia	AS>EO	AS>AP	AS>PC	N	N	N
	Nitrate	EO>AS	AP>AS	N	AP>PC	N	N
Metals	Lead	AS>EO	N	N	N	N	N
	Iron	AS>EO	AS>AP	AS>PC	N	PC>EO	N
	Zinc	AS>EO	AS>AP	AS>PC	AP>PC	N	N
	Potassium	EO>AS	AP>AS	PC>AS	PC>AP	PC>EO	N
	Strontium	EO>AS	AP>AS	PC>AS	AP>PC	EO>PC	N

Note: Differences between PC and the other permeable pavements in pH, alkalinity, ortho-phosphate and potassium occurred primarily within the first two years of the study (see section 4.3.2 below).

4.3.2 Water Quality Trends

In the first phase of this study, pH, phosphate and potassium were found to have higher concentrations in PC effluent than in effluent from the EO and AP pavements. Trends in these water quality variables over the five year period from 2010 to 2014 are presented in Figure 4.6 to 4.8. These results show that pH and phosphate (soluble phosphorus) concentrations from PC had largely stabilized after two years, while potassium (K) showed a steady decline over the full five year period. Although initial K concentrations were lower than PC, declines in potassium were also evident in outflows from the EO and AP pavements, suggesting that the source of potassium is not entirely unique to pervious concrete materials. It is hypothesized that high initial pH of the PC effluent may have contributed to high phosphate concentrations since phosphorus availability (i.e. in soluble form as phosphate) is lowest at pH between 7.5 to 8.0 and increases at values above and below this level

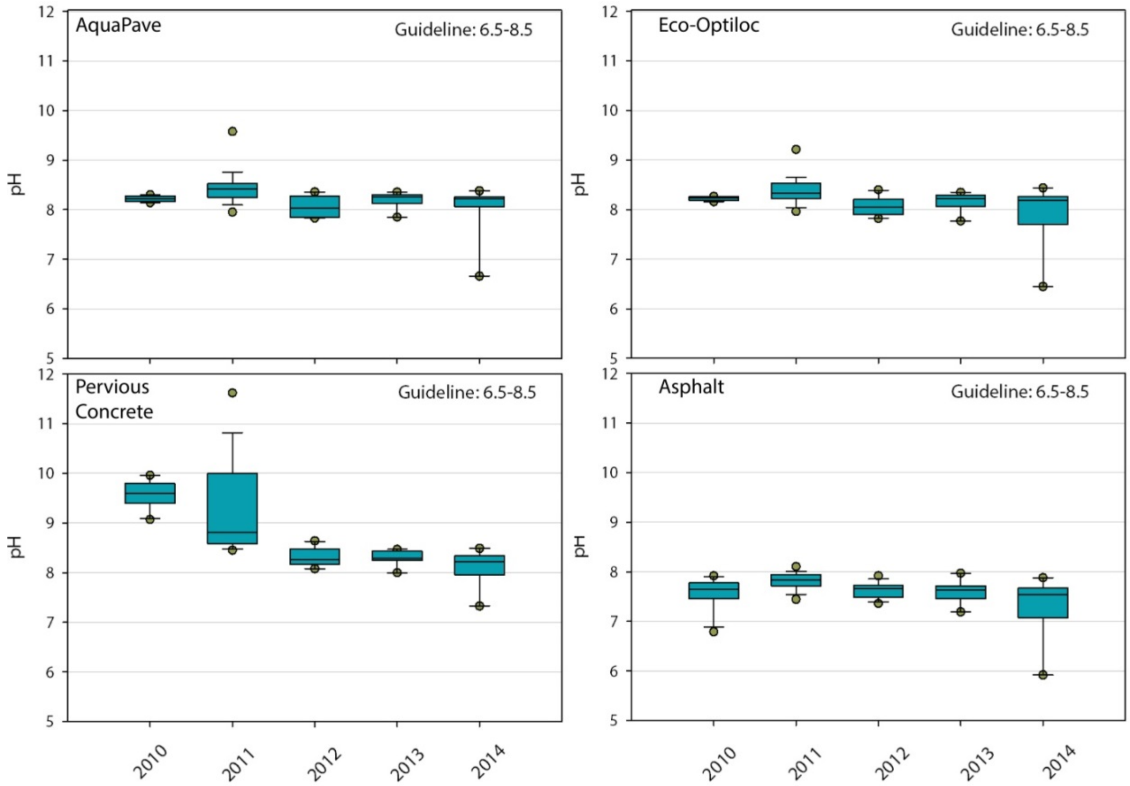

Figure 4.6: *Temporal changes in pH from 2010 to 2014.*

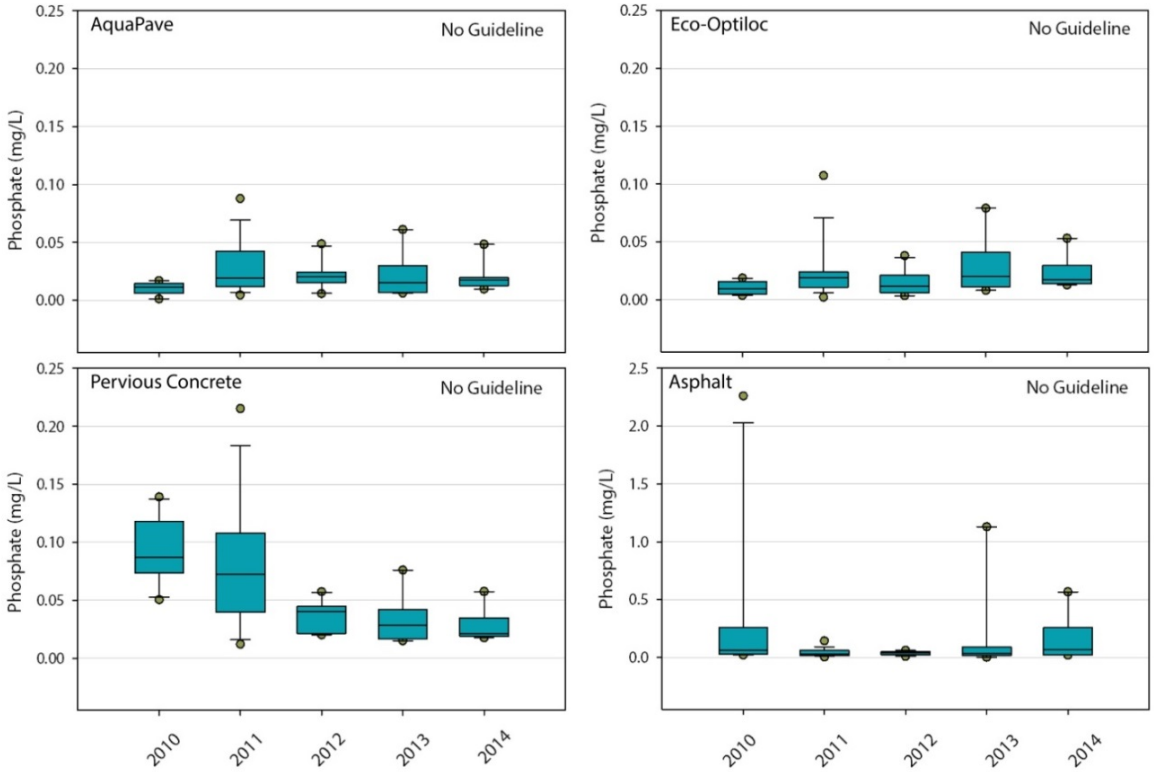

Figure 4.7: *Temporal changes in phosphate concentrations from 2010 to 2014. Note differences in vertical axes scales.*

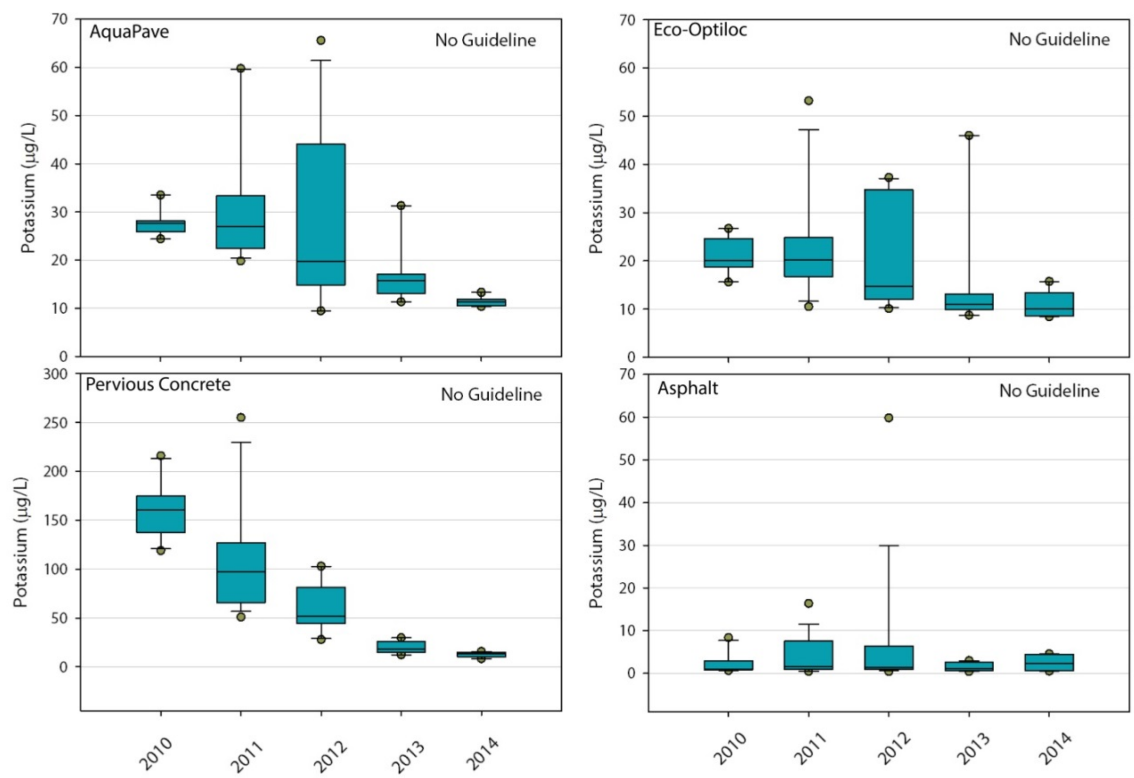

Figure 4.8: *Temporal changes in potassium concentrations from 2010 to 2014. Note differences in vertical axes.*

4.3.3 Potential for Groundwater Contamination

The research facility includes underdrains at the interface between the base and native soils, as well as one additional underdrain below 0.5 to 1 m of native soil (see Figure 2.2 and 2.3 above). The second underdrain was installed to evaluate the quality of water that infiltrates through the native soil and into the groundwater, and assess how concentrations change over time as pollutants build up in the native soils. Previous studies have shown that road salt applications can enhance the mobility of some contaminants, such as metals (e.g. Backstrom et al., 2004; Norrstrom, 2005).

Figure 4.9 presents results for selected water quality variables showing concentrations of outflows from the upper and lower underdrains (labelled as high and low respectively). There was little difference in water quality between the two underdrains. Total suspended solids concentrations in the lower underdrain were initially higher than the upper underdrain, but decreased over time, likely due to flushing of sediment that was inadvertently deposited in or around the perforated pipe during construction of the facility. Since flows in this pipe are very slow, fine sediments may take some time to disperse. There was no evidence of an increase in the concentration of metals or phosphate over the four years.

The concentration of stormwater pollutants in the upper and lower underdrains of the AP pavement are compared to drinking water standards in Table 4.3. Most pollutants were well below the limits for drinking water, with the exception of chloride, sodium, total dissolved solids, iron and lead. The limits for iron and total dissolved solids are aesthetic objectives. Lead was exceeded in 2% of samples from the lower underdrain, suggesting that the separation distance between the base of the system and seasonally high groundwater table may need to be greater than 0.5 m. Chloride and sodium are extremely mobile and are not effectively attenuated by soils. While the lower underdrain had higher median concentrations of chloride and sodium, these differences were not statistically significant. Petroleum hydrocarbons and *e..coli* were not assessed in this study, but are commonly found to be effectively treated through soil infiltration (Young and Van Seters, 2009).

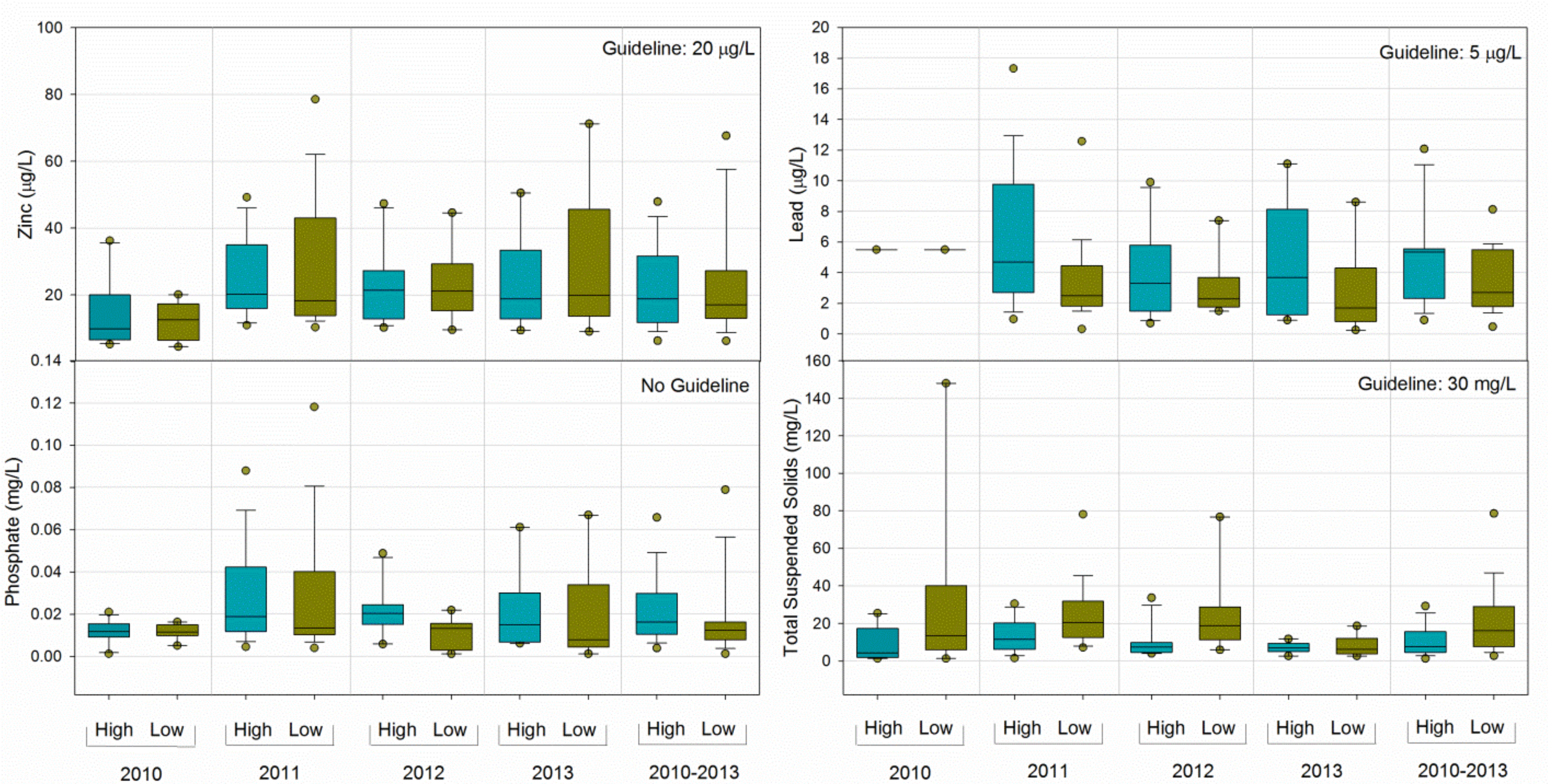

Figure 4.9: *Box plots for selected pollutants in the AP underdrains at the interface between the pavement base and native soil (high), and below 0.5 to 1 m of native soil (low).*

***Table 4.3:** The concentration of stormwater pollutants from the underdrain at the base of the AP permeable pavement (AP High) and from the underdrain below 0.5 – 1.0 m of native soil (AP Low)*

Parameters (mg/L)	CGDWQ	Type of Guideline	AP High (n = 51)		AP Low (n = 40)	
			Median	% Exceedance	Median	% Exceedance
Antimony	0.006	IMAC	0.0008	0	0.0007	0
Arsenic	0.025	IMAC	0.0014	0	0.0005	0
Barium	1	MAC	0.0500	0	0.0455	0
benzo(a)pyrene	0.00001	MAC	0.0000015	0	0.0000015	0
Boron	5	IMAC	0.027	0	0.031	0
Cadmium	0.005	MAC	0.0003	0	0.0003	0
Chloride	≤250	AO	10.9	17	23.9	30
Chromium	0.05	MAC	0.0025	0	0.0025	0
Copper	≤1.0	AO	0.0052	0	0.0065	0
Iron	≤0.3	AO	0.140	26	0.220	32
Lead	0.01	MAC	0.0041	12	0.0026	2
Manganese	≤0.05	AO	0.0115	0	0.0163	0
Nitrate-N	10	MAC	0.71	0	0.75	0
pH	6.5-8.5	AO	8.25	10	8.01	4
Selenium	0.01	MAC	0.0025	0	0.0025	0
Sodium	≤200	AO	29.3	14	49.8	23
Total Dissolved Solids	≤500	AO	254	26	335	40
Zinc	≤5	AO	0.179	0	0.017	0

Note: CGDWQ = Canadian Guidelines for Drinking Water Quality; MAC= maximum acceptable concentration; IMAC = interim maximum acceptable concentration; AO = aesthetic objective

4.4 Thermal Loading

Water temperature is a critical element of stream health as it regulates biotic and abiotic processes in streams. The proliferation of dark impervious surfaces in urban areas generates thermal pollution by increasing the temperature of runoff. Since most aquatic organisms have a preferred temperature range they can tolerate, warmer water can result in the loss of species from streams and disrupt ecological processes that support aquatic communities. Low impact development practices such as permeable pavements can help mitigate these effects by reducing the temperature and volume of water discharged to receiving waters from urban surfaces.

Table 4.4: *Precipitation, air temperature, event mean and maximum water temperature and thermal loads and load reduction rates for four summer rain events*

Parameters	**Events**			
	19-Jul-13	**31-Jul-13**	**26-Aug-13**	**11-Sep-13**
Precipitation (mm)	*12.8*	*42.2*	*38.4*	*13.8*
Air Temperature (°C)				
Min	18.0	11.2	16.4	18.6
Max	35.1	26.7	30.1	29.3
Avg	25.2	18.8	22.1	21.9
Event Mean Water Temperature (°C)				
Asphalt Control	28.9	19.1	24.2	24.1
AquaPave	27.8	24.6	24.9	23.4
Event Maximum Water Temperature (°C)				
Asphalt Control	31.4	28.2	30.2	25.8
AquaPave	28.2	25.4	25.3	23.6
Thermal Load (MJ)				
Asphalt Control	347.5	718.2	811.6	320.6
AquaPave	147.6	463.2	420.1	123.7
Thermal Load Reduction (%)				
AquaPave relative to Asphalt	*57.5*	*35.5*	*48.2*	*61.4*

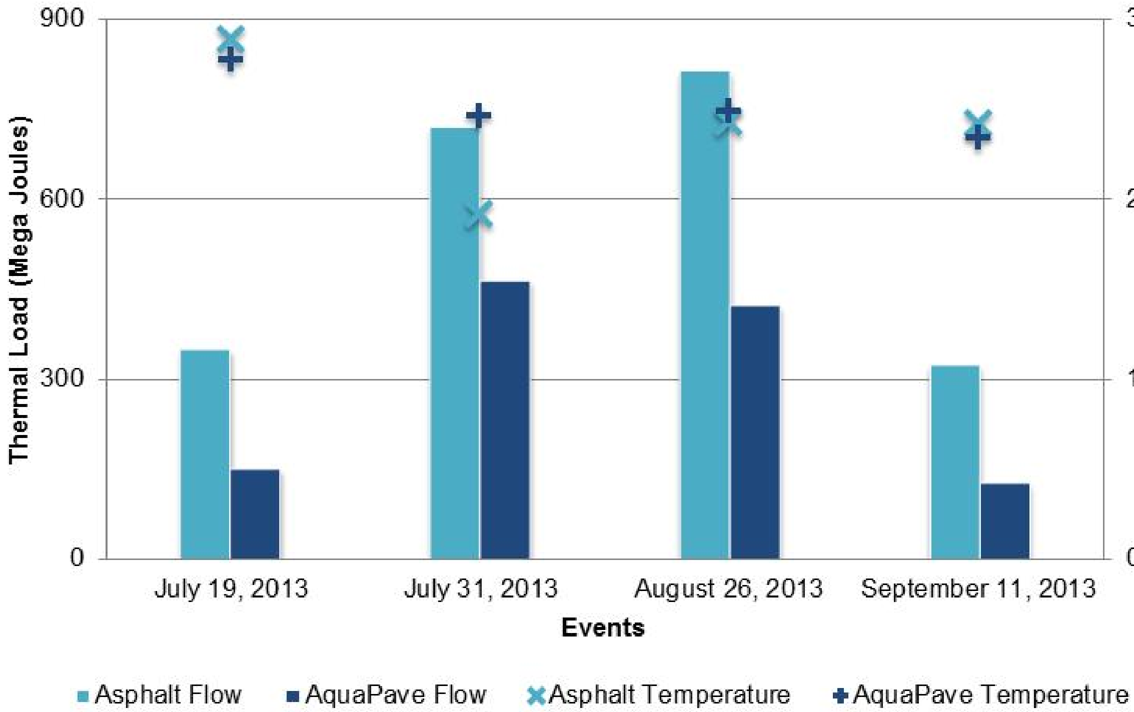

Figure 4.10: *Thermal loads for four rain events proceeded by warm weather*

To understand the thermal characteristics of runoff from the asphalt and permeable pavements, four events that were preceded by maximum air temperatures between 27 and 35^{0}C were selected for analysis. Warm weather events were chosen because this is when thermal impacts to receiving waters are greatest. The air temperature, event mean water temperature and thermal loads for asphalt and permeable pavement are presented in Table 4.4. Figure 4.10 shows the thermal loads and event mean temperature for asphalt and permeable pavements. Appendix C presents time series temperature and flow data over the course of the events. Only one permeable pavement (AP) was monitored because the pavement type was not expected to significantly influence water temperature.

Results show that maximum outflow temperatures from the permeable pavement were consistently lower than asphalt runoff, while event mean temperatures were similar or higher. On July 13th, asphalt runoff event mean temperature was over 5^{0}C lower than that of permeable pavement outflows. The much lower asphalt temperatures during this event occurred because rain fell during the night, when air temperatures dropped to 11^{0}C. Also, permeable pavement outflows occur over a much longer time period allowing for additional heating from solar radiation during the day. Despite lower asphalt runoff event mean temperatures, the thermal loads from the permeable pavement were 36 to 61% lower than the asphalt pavement, due primarily to lower runoff volumes.

4.5 Surface Elevation

The surface of the permeable pavements and asphalt were surveyed with a total station for elevation changes twice a year from November 2009 to June 2012, and once each in 2013 and 2014 (Table 4.5). Measurements were taken at half meter intervals in a grid pattern over the four pavements. Over the 5 year period, there have been no significant movements in the surface of the four pavement cells, and no signs of slumping or heaving.

Table 4.5: *Survey results: Elevation (m)*

Date	Asphalt		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	196.04	0.04	196.30	0.03	196.35	0.03
Fall 2013	--	--	196.09	0.04	196.05	0.03	196.09	0.02

5.0 CONCLUSIONS

Results of this study indicate that permeable pavements are an effective practice for maintaining or restoring infiltration functions on parking lots and other low volume traffic areas, even in areas with low permeability soils. Over the five year monitoring period, the permeable pavements reduced runoff volumes by 45% and effluents were generally much cleaner than runoff from the asphalt pavement. As expected, the surface infiltration capacity of permeable pavements declined over time, but otherwise age did not have any measurable adverse effects on performance over the course of this study.

Key findings of the extended monitoring program, initiated in mid-2012, include the following:

- The rate of infiltration through the surface of the three permeable pavements was initially very high but declined rapidly over the first two years. Vacuum cleaning in June 2012 partially restored permeability to the pavements. However, by December 2014, infiltration rates on the AquaPave® and Eco-Optiloc® pavements had declined below thresholds established to avoid surface runoff during intense rain events. The PC had a surface infiltration rate over 30 times that of the AP and EO pavements after 4 years and one maintenance cycle. While this pavement continues to infiltrate well, it is not yet clear how effective vacuum maintenance will be in reversing clogging on this type of pavement
- The pavements were found to reduce runoff volumes consistently over the course of the five year study, despite the presence of fine grained native soils. This finding suggests that native soils below the pavements retain their capacity to infiltrate and that the geotextile below the base layer does not inhibit the movement of water into the underlying soils. The first 5 mm of most events was almost completely retained and infiltrated despite location of the perforated pipe at the bottom of the pavement structure.
- The permeable pavement effluents had lower concentrations of most pollutants relative to asphalt runoff. Reductions in median total suspended solids EMCs by the permeable pavements over the study period were between 88 and 89%. Load reductions would be considerably higher due to the much smaller volumes of outflow generated from the permeable pavements. The quality of outflows from the permeable pavements was comparable, but the PC pavement showed higher levels of pH, phosphate and potassium than the pre-cast pavers. Concentrations of these constituents in PC outflows stabilized at levels similar to the AP and EO pavements after two to four years. Effluent quality from the AP and EO pavements were very similar despite differences in the size of joints, filler material and the presence of geotextile below the bedding layer of the AP pavement.
- Effluent from underdrains placed in the base above and below a 0.5 to 1.0 m of native soil showed similar concentrations of pollutants, and little change over time. At this site, there was

no evidence to suggest that road salts have caused metals to become more mobile, as has been found by other researchers (*e.g.* Norrstrom, 2005; Backstrom et al., 2004). This may be in part due to the relatively low use of salt at the Kortright site. With the exception of salt (NaCl), pollutant concentrations in the lower underdrain were rarely at concentrations that would pose a health threat to the use of groundwater for drinking water. Lead exceeded the guideline in 2% of samples from the lower underdrain, suggesting that a separation distance between the base and seasonally high water table would need to be greater than 0.5 m to prevent contamination from lead. Iron and total dissolved solids were also above the aesthetic objective for drinking water in up to 40% of samples.

- Permeable pavement generated lower thermal loads to receiving waters than the asphalt pavement during hot summer days, primarily due to lower outflow volumes. While the permeable pavement had lower maximum temperatures than asphalt, event mean temperatures (EMT) were higher than asphalt during two of the four events analyzed. During these two events, runoff from the asphalt occurred at least partially during the cool night hours, while the permeable pavement drained more gradually (up to 36 hours) and was therefore subject to greater solar heating.
- Elevation surveys showed that the permeable pavement surfaces have been relatively stable over time with no obvious signs of heaving or slumping.

It is recommended that the monitoring be continued in a reduced form beyond 2014 to characterize trends in performance and provide one of the only long term datasets for permeable pavements available in North America. This may involve continued monitoring, or a repeat of the monitoring at some date in the not too distant future. Additional questions that should be considered in future monitoring include the following:

- *Improved methods for maintenance of permeable pavements.* The first phase of this study showed that vacuum and regenerative air maintenance methods are only partly effective in restoring infiltration properties to PICPs, and may not work at all on pervious concrete. Improved methods, which may involve pre-treating the pavements prior to cleaning, need to be tested and quantified to provide a more effective range of options for pavement cleaning.
- *Quantification of road salt application rates for permeable pavements*. Some researchers have suggested that less salt may need to be applied on permeable pavements, but the scientific evidence currently available is not sufficient to recommend changes in application practices. To provide the necessary data, research is needed to document application rates on conventional asphalt and the permeable pavements in a controlled setting based on common indicators such as friction and time-to-bare pavement.
- *Continuous monitoring of road salt loads discharged from asphalt and permeable pavements*. The timing of chloride release from permeable pavements and amount of infiltration to groundwater relative to conventional pavements and other non-infiltrating stormwater BMPs

is not currently well understood. Delayed timing of salt release can reduce the impact of road salts on receiving waters by discharging at times when receiving waters have greater dilution capacity, thereby avoiding adverse impacts on aquatic life. Documenting loads through continuous monitoring of flows and conductivity would improve our understanding of how road salts are processed through permeable pavements.

- *Tracking the fate of particulate pollutants entering permeable pavements*. The fate of particulates (suspended solids and associated contaminants) entering permeable pavements can be assessed by examining their distribution within cores of permeable pavements that have been in place for several years. This knowledge contributes to our understanding of the function of the pavements as a water quality treatment system and helps in predicting long term requirements for maintenance and rehabilitation at the end of their life cycles.

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APPENDIX A

Water Quality Descriptive Statistics

Table A1. *Descriptive statistics for general chemistry parameters for all four study plots for the 2010-2014 study period. MDL: method detection limit; GL: provincial or federal guideline; N: number of observations*

General Chemistry				N	Min	Max	Mean	Median	%>MDL	%>GL
Alkalinity	Unit	mg/L $CaCO_3$	Asphalt	84	15.40	255	49.96	41.65	100	NA
	MDL	2.5	AquaPave	58	48.90	164	94.37	91.90	100	
	GL		Eco-Optiloc	59	57.90	156	104.92	102	100	
	Source		Pervious Concrete	58	70.90	421	155.23	144.50	100	
Conduc-tivity	Unit	uS/cm	Asphalt	84	40	96200	5327.88	242.50	100	NA
	MDL	5	AquaPave	58	203	5460	913.33	389.50	100	
	GL		Eco-Optiloc	59	232	5140	1067.05	454	100	
	Source		Pervious Concrete	58	238	5680	1067.64	673.50	100	
Hardness	Unit	mg/L	Asphalt	74	22	790	127.96	57.90	100	NA
	MDL	1	AquaPave	51	43	560	128.78	92	98	
	GL		Eco-Optiloc	50	53	720	164.49	110	100	
	Source		Pervious Concrete	49	23	640	85.34	57.60	88	
pH	Unit		Asphalt	84	5.92	8.15	7.68	7.73	100	1
	MDL		AquaPave	58	6.66	9.72	8.24	8.25	100	10
	GL	6.5 to 8.5	Eco-Optiloc	59	6.45	9.44	8.23	8.24	100	15
	Source	PWQO	Pervious Concrete	58	7.33	11.80	8.91	8.56	100	55
Solids; dissolved	Unit	mg/L	Asphalt	84	25	68500	3356.87	164.50	81.0	NA
	MDL	50	AquaPave	58	132	3450	543.38	253.50	100	
	GL		Eco-Optiloc	59	151	3190	648.53	295	100	
	Source		Pervious Concrete	58	155	2920	619.79	438	100	
Solids; suspended	Unit	mg/L	Asphalt	84	12	313	83.78	59.15	100	83
	MDL	2.5	AquaPave	58	1.25	33.60	9.85	7.15	93.1	3
	GL	30[1]	Eco-Optiloc	59	1.25	45.10	9.31	6.60	91.5	2
	Source	CWQG	Pervious Concrete	58	1.25	101.00	14.08	6.35	94.8	14
Solids; total	Unit	mg/L	Asphalt	84	53	68600	3443.00	235	100	NA
	MDL	50	AquaPave	58	146	3460	553.24	266	100	
	GL		Eco-Optiloc	59	157	3190	657.93	302	100	
	Source		Pervious Concrete	58	164	2930	634.14	443.50	100	
Solvent Extractable	Unit	mg/L	Asphalt	84	0.50	28	3.06	1.85	83.3	NA
	MDL	1	AquaPave	58	0.50	1.20	0.52	0.50	3.5	
	GL		Eco-Optiloc	59	0.50	2.00	0.53	0.50	1.7	
	Source		Pervious Concrete	58	0.50	1.50	0.54	0.50	5.2	

[1]The Canadian Water Quality Guideline for TSS is a narrative guideline that suggests a limit of 25 mg/L plus the background concentration of the local stream under investigation. In the GTA, natural streams have background concentrations that are roughly equivalent to 5 mg/L. Hence the TSS guideline for this report was set at 30 mg/L.

Table A2. *Descriptive statistics for nutrients for all four study plots for the 2010-2014 study period. MDL: method detection limit; GL: provincial or federal guideline; N: number of observations.*

Nutrients				N	Min	Max	Mean	Median	%>MDL	%>GL
Nitrogen; ammonia + ammonium	Unit	mg/L	Asphalt	84	0.005	3.900	0.400	0.270	99	NA
	MDL	0.01	AquaPave	58	0.005	0.320	0.044	0.027	88	
	GL		Eco-Optiloc	59	0.005	0.157	0.032	0.025	86	
	Source		Pervious Concrete	55	0.005	0.165	0.038	0.027	89	
nitrogen; nitrate+ nitrite	Unit	mg/L	Asphalt	84	0.013	3.120	0.724	0.510	98	NA
	MDL	0.025	AquaPave	58	0.325	2.650	0.876	0.747	100	
	GL		Eco-Optiloc	59	0.310	2.010	0.788	0.665	100	
	Source		Pervious Concrete	55	0.196	2.100	0.636	0.456	100	
Nitrogen; nitrite	Unit	mg/L	Asphalt	84	0.003	0.275	0.066	0.041	98	38
	MDL	0.005	AquaPave	58	0.003	0.200	0.016	0.010	71	3
	GL	0.06	Eco-Optiloc	59	0.003	0.065	0.011	0.008	69	2
	Source	CWQO	Pervious Concrete	55	0.003	0.056	0.019	0.014	93	0
Nitrogen; TKN	Unit	mg/L	Asphalt	84	0.230	9.650	1.709	1.275	100	NA
	MDL	0.05	AquaPave	58	0.050	0.650	0.193	0.180	74	
	GL		Eco-Optiloc	59	0.025	0.700	0.184	0.150	76	
	Source		Pervious Concrete	55	0.050	0.900	0.304	0.230	95	
Phosphorus; phosphate	Unit	mg/L	Asphalt	84	0.001	2.260	0.119	0.038	98	NA
	MDL	0.0025	AquaPave	58	0.001	0.091	0.023	0.017	98	
	GL		Eco-Optiloc	59	0.001	0.120	0.021	0.017	98	
	Source		Pervious Concrete	55	0.011	0.219	0.066	0.050	100	
Phosphorus; total	Unit	mg/L	Asphalt	84	0.030	2.980	0.285	0.170	100	99
	MDL	0.005	AquaPave	58	0.008	0.116	0.031	0.026	97	28
	GL	0.03	Eco-Optiloc	59	0.009	0.960	0.052	0.026	95	47
	Source	PWQO	Pervious Concrete	55	0.022	0.655	0.111	0.088	100	88

Table A3. *Descriptive statistics for pathogens for all four study plots for the 2010-2014 study period. MDL: method detection limit; GL: provincial or federal guideline; N:number of observations.*

Pathogens				N	Min	Max	Mean	Median	%>MDL	%>GL
E coli	**Unit**	c/100mL	**Asphalt**	43	0	360	23.67	4	91	5
	MDL	0	**AquaPave**	25	4	400	37.92	4	100	8
	GL	100	**Eco-Optiloc**	24	4	100	8	4	100	0
	Source	PWQO	**Pervious Concrete**	24	4	40	5.83	4	100	0
Fecal Streptococcus	**Unit**	c/100mL	**Asphalt**	43	0	7000	616.74	130	91	NA
	MDL	0	**AquaPave**	25	24	13000	1952.16	430	100	
	GL		**Eco-Optiloc**	24	4	42000	2879.92	114	100	
	Source		**Pervious Concrete**	24	4	920	208.04	130	100	
Pseudomonas aeruginosa	**Unit**	c/100mL	**Asphalt**	43	0	3200	252.42	20	91	NA
	MDL	0	**AquaPave**	26	4	51000	4488.69	450	100	
	GL		**Eco-Optiloc**	24	4	150000	8911.58	34	100	
	Source		**Pervious Concrete**	25	2	39000	1685.04	4	100	

Table A4. *Descriptive statistics for metals for all four study plots for the 2010-2014 study period. MDL: method detection limit; GL: provincial or federal guideline; N: number of observations.*

Metals				N	Min	Max	Mean	Median	%>MDL	%>GL
Aluminum	Unit	µg/L	Asphalt	84	35.90	1700	476.39	370	100	99
	MDL	1 (3)	AquaPave	58	43.70	1100	257.13	164	100	93
	GL	75	Eco-Optiloc	59	44.20	1460	243.04	140	100	76
	Source	PWQO	Pervious Concrete	58	47.70	1260	448.51	372	100	97
Antimony	Unit	µg/L	Asphalt	59	0.25	1.70	0.84	0.80	88	0
	MDL	0.5	AquaPave	46	0.25	1.30	0.77	0.80	85	0
	GL	20	Eco-Optiloc	46	0.25	1.30	0.73	0.80	83	0
	Source	PWQO	Pervious Concrete	45	0.25	1.50	0.77	0.80	80	0
Arsenic	Unit	µg/L	Asphalt	59	0.50	8.70	0.86	0.50	15	2
	MDL	1	AquaPave	46	0.50	6.60	1.59	1.40	61	4
	GL	5	Eco-Optiloc	46	0.50	3.50	1.23	1.20	61	0
	Source	PWQO	Pervious Concrete	45	0.50	24.40	4.23	2.00	93	18
Barium	Unit	µg/L	Asphalt	84	7.10	520	52.83	18.35	100	NA
	MDL	0.5 (0.2)	AquaPave	58	25.40	555	83.88	50	100	
	GL		Eco-Optiloc	59	35.40	512	95.68	53.70	100	
	Source		Pervious Concrete	58	14.10	303	44.62	31.80	100	
Beryllium	Unit	µg/L	Asphalt	84	0.02	1.06	0.20	0.25	6	0
	MDL	0.5 (0.03)	AquaPave	58	0.02	0.25	0.20	0.25	0	0
	GL	11	Eco-Optiloc	59	0.02	0.25	0.20	0.25	0	0
	Source	PWQO	Pervious Concrete	58	0.02	0.25	0.20	0.25	2	0
Boron	Unit	µg/L	Asphalt	59	5	60	10.71	5	32	0
	MDL	10	AquaPave	46	5	103	31.91	27	91	0
	GL	200	Eco-Optiloc	46	5	128	40.15	31	96	0
	Source	PWQO	Pervious Concrete	45	11	82	34.42	29	100	0
Cadmium	Unit	µg/L	Asphalt	84	0.25	17.70	1.60	0.25	29	MDL>GL
	MDL	0.5 (0.8)	AquaPave	58	0.25	1.72	0.39	0.25	14	MDL>GL
	GL	0.1	Eco-Optiloc	59	0.25	1.79	0.40	0.25	12	MDL>GL
	Source	PWQO	Pervious Concrete	58	0.25	1.55	0.32	0.25	5	MDL>GL

Metals				N	Min	Max	Mean	Median	%>MDL	%>GL
Calcium	Unit	mg/L	Asphalt	74	8.17	289	46.36	21.20	100	NA
	MDL	0.05	AquaPave	51	12.50	148	34.94	25	98	
	GL		Eco-Optiloc	50	15.30	203	45.37	30.25	100	
	Source		Pervious Concrete	49	6.06	175	20.72	13.80	88	
Chloride	Unit	mg/L	Asphalt	83	0.50	43100	2234.22	19.50	89	31
	MDL	1	AquaPave	58	0.50	1700	195.22	10.90	98	29
	GL	120	Eco-Optiloc	59	0.50	1470	238.28	18.10	98	37
	Source	CCME	Pervious Concrete	58	0.50	1560	170.94	16.70	98	34
Chromium	Unit	µg/L	Asphalt	84	0.50	16.90	2.41	2.50	15	1
	MDL	5 (1)	AquaPave	58	0.50	6.66	2.66	2.50	22	0
	GL	8.9	Eco-Optiloc	59	0.50	5.34	2.39	2.50	19	0
	Source	PWQO	Pervious Concrete	58	2.38	19.50	3.78	2.50	29	7
Cobalt	Unit	µg/L	Asphalt	84	0.50	10.40	1.25	0.50	25	MDL>GL
	MDL	1 (1.5)	AquaPave	58	0.50	1.80	0.66	0.50	10	MDL>GL
	GL	0.9	Eco-Optiloc	59	0.50	2.60	0.66	0.50	10	MDL>GL
	Source	PWQO	Pervious Concrete	58	0.50	5.00	0.79	0.50	19	MDL>GL
Copper	Unit	µg/L	Asphalt	84	0.50	160	20.48	14.05	99	98
	MDL	5 (1)	AquaPave	58	1.19	17.70	5.50	5.20	64	50
	GL	5	Eco-Optiloc	59	0.50	122	7.17	5.47	63	54
	Source	PWQO	Pervious Concrete	58	2.50	56.60	9.18	6.09	66	66
Iron	Unit	µg/L	Asphalt	84	140	3850	840.57	595	100	80
	MDL	30 (3)	AquaPave	58	40	950	226.97	140	100	26
	GL	300	Eco-Optiloc	59	15	1200	209.59	140	97	20
	Source	PWQO	Pervious Concrete	58	15	970	317.98	269.50	98	45
Lead	Unit	µg/L	Asphalt	84	0.90	98.00	7.16	5.50	80	52
	MDL	0.5 (11)	AquaPave	58	0.70	18.00	4.84	4.05	83	43
	GL	5	Eco-Optiloc	59	0.60	14.60	3.73	3.00	81	34
	Source	PWQO	Pervious Concrete	58	0.60	12.40	4.35	4.50	79	47
Magnesium	Unit	mg/L	Asphalt	74	0.39	16.70	2.95	1.52	100	NA
	MDL	0.01	AquaPave	51	2.91	46.10	10.01	6.65	98	
	GL		Eco-Optiloc	50	3.60	54.30	12.54	7.74	100	
	Source		Pervious Concrete	49	1.93	49.50	8.23	5.57	88	

Metals				N	Min	Max	Mean	Median	%>MDL	%>GL
Manganese	**Unit**	µg/L	**Asphalt**	84	2.00	845.00	132.88	77.10	100	NA
	MDL	0.5 (0.3)	**AquaPave**	58	0.70	56.70	15.68	11.50	100	
	GL		**Eco-Optiloc**	59	0.25	84.20	14.10	10.10	98	
	Source		**Pervious Concrete**	58	0.60	72.10	20.24	15.60	100	
Molybdenum	**Unit**	µg/L	**Asphalt**	84	0.25	155	9.10	0.25	32	13
	MDL	0.5 (1.5)	**AquaPave**	58	0.25	10.90	4.18	3.67	93	2
	GL	40	**Eco-Optiloc**	59	0.25	11.80	4.67	4.40	93	3
	Source	PWQO	**Pervious Concrete**	58	0.90	19.40	6.12	4.75	100	19
Nickel	**Unit**	µg/L	**Asphalt**	84	0.75	67	6.64	2.65	64	7
	MDL	2 (1.5)	**AquaPave**	58	0.75	6.80	1.97	1	45	0
	GL	25	**Eco-Optiloc**	59	0.75	7.90	1.92	1	37	0
	Source	PWQO	**Pervious Concrete**	58	0.75	8.35	2.35	1.99	59	0
Potassium	**Unit**	mg/L	**Asphalt**	74	0.36	59.80	4.14	1.30	100	NA
	MDL	0.02	**AquaPave**	51	9.45	65.60	24.77	22.50	98	
	GL		**Eco-Optiloc**	50	8.42	53.20	19.51	18.15	100	
	Source		**Pervious Concrete**	49	8.47	255.00	85.54	66.00	88	
Selenium	**Unit**	µg/L	**Asphalt**	59	2.50	2.50	2.50	2.50	0	0
	MDL	5	**AquaPave**	46	2.50	2.50	2.50	2.50	0	0
	GL	100	**Eco-Optiloc**	46	2.50	2.50	2.50	2.50	0	0
	Source	PWQO	**Pervious Concrete**	45	2.50	2.50	2.50	2.50	0	0
Silver	**Unit**	µg/L	**Asphalt**	59	0.25	0.25	0.25	0.25	0	MDL>GL
	MDL	0.5	**AquaPave**	46	0.25	0.25	0.25	0.25	0	MDL>GL
	GL	0.1	**Eco-Optiloc**	46	0.25	0.25	0.25	0.25	0	MDL>GL
	Source	PWQO	**Pervious Concrete**	45	0.25	0.25	0.25	0.25	0	MDL>GL
Sodium	**Unit**	mg/L	**Asphalt**	74	0.29	27900	1475.98	9.61	100	NA
	MDL	0.02	**AquaPave**	51	10.20	972	124.43	29.30	98	
	GL		**Eco-Optiloc**	50	7.76	936	140.02	45.05	100	
	Source		**Pervious Concrete**	49	14.80	780	123.54	36.60	88	

Metals				N	Min	Max	Mean	Median	%>MDL	%>GL
Strontium	Unit	µg/L	Asphalt	84	37	2840	362.60	152.50	100	NA
	MDL	1 (0.3)	AquaPave	58	1400	33400	5592.90	3610	100	
	GL		Eco-Optiloc	59	1850	40400	7366.93	4280	100	
	Source		Pervious Concrete	58	550	26900	3527.31	1900	100	
Thallium	Unit	µg/L	Asphalt	59	0.25	0.25	0.25	0.25	0	MDL>GL
	MDL	0.5	AquaPave	46	0.25	0.25	0.25	0.25	0	MDL>GL
	GL	0.3	Eco-Optiloc	46	0.25	0.25	0.25	0.25	0	MDL>GL
	Source	PWQO	Pervious Concrete	45	0.25	0.25	0.25	0.25	0	MDL>GL
Titanium	Unit	µg/L	Asphalt	84	0.78	24.70	6.97	5.55	67	NA
	MDL	5 (0.3)	AquaPave	58	0.15	21.20	3.24	2.50	28	
	GL		Eco-Optiloc	59	0.15	24.60	3.27	2.50	29	
	Source		Pervious Concrete	58	2.50	19.50	4.03	2.50	34	
Uranium	Unit	µg/L	Asphalt	59	0.25	0.25	0.25	0.25	0	0
	MDL	0.5	AquaPave	46	0.25	2.30	1.00	0.90	89	0
	GL	5	Eco-Optiloc	46	0.25	2.10	1.02	1.00	91	0
	Source	PWQO	Pervious Concrete	45	0.25	1.60	0.71	0.70	71	0
Vanadium	Unit	µg/L	Asphalt	84	0.50	66.80	5.74	3.69	94	19
	MDL	0.5 (1)	AquaPave	58	0.25	12.60	2.37	1.60	90	5
	GL	6	Eco-Optiloc	59	0.25	9.72	2.19	1.80	92	3
	Source	PWQO	Pervious Concrete	58	0.25	15.90	4.53	2.20	97	33
Zinc	Unit	µg/L	Asphalt	84	0.40	789.00	88.75	53.30	99	88
	MDL	2 (0.8)	AquaPave	58	5.19	50.50	20.89	17.95	100	40
	GL	20	Eco-Optiloc	59	1.11	55.50	15.66	13.40	100	24
	Source	PWQO	Pervious Concrete	58	2.17	27.50	11.84	10.95	100	16

APPENDIX B

Runoff volume and reduction rates for events occurring between April and November, 2010 to 2014

Table B1. *Runoff volume (V) and reduction rates (VR) for warm weather events between 2010 and 2014*

Event	Rainfall (mm)	V_T (L)		VR (%)
		Asphalt	PP	
September 2, 2010	6.6	1221	0	100
September 11, 2010	6.6	1449	0	100
September 16, 2010	21.9	5115	3042	41
September 22, 2010	6.2	1098	0	100
September 27, 2010	31.4	6696	4445	34
October 5, 2010	23.5	5589	2853	49
October 14, 2010	21.4	5514	2801	49
October 20, 2010	2.3	894	0	100
October 23, 2010	16.8	3759	1634	57
October 26, 2010	7.7	1821	886	51
November 3, 2010	0.7	129	0	100
November 5, 2010	3.7	816	0	100
November 16, 2010	21.7	5085	2389	53
November 22, 2010	10.6	2622	963	63
November 25, 2010	9.4	2262	952	58
November 30, 2010	26.6	6516	4217	35
April 10, 2011	7.6	1638	859	48
April 16, 2011	17.6	4257	2088	51
April 20, 2011	15.6	3762	2684	29
April 23, 2011	7.7	1831	1101	40
April 26, 2011	14	3255	1854	43
April 27, 2011	7.7	1617	1330	18
May 1, 2011	10.8	2574	1330	48
May 6, 2011	4	843	616	27
May 14, 2011	46	10968	7888	28
May 17, 2011	1.8	459	0	100
May 18, 2011	19.6	4530	4082	10
May 22, 2011	0.2	45	0	100
May 23, 2011	0.5	111	0	100
May 24, 2011	7	1839	380	79
May 25, 2011	20	4761	1993	58
May 29, 2011	4.2	609	0	100
June 4, 2011	13.7	3168	1508	52
June 7, 2011	6.1	1251	286	77
June 11, 2011	-	4710	4143	12
June 22, 2011	2	666	0	100
June 23, 2011	49.4	11247	9093	19
June 28, 2011	0.2	402	0	100
July 18, 2011	4.2	18	0	100
July 22, 2011	0.2	807	0	100
July 25, 2011	31.7	6300	3597	43
July 29, 2011	0.6	132	0	100
July 29, 2011	1.1	180	0	100
July 31, 2011	0.5	87	0	100
August 1, 2011	8.2	1152	664	42

Event	Rainfall (mm)	V_T (L)		VR (%)
		Asphalt	PP	
August 3, 2011	15.6	3612	1832	49
August 6, 2011	0.3	45	0	100
August 7, 2011	1.8	282	0	100
August 7, 2011	10	1839	1075	42
August 9, 2011	14.9	3231	1993	38
August 17, 2011	0.6	207	0	100
August 20, 2011	0.4	24	0	100
August 21, 2011	0.6	90	0	100
August 21, 2011	15.2	2026	1317	35
August 24, 2011	18.6	3740	2454	34
September 1, 2011	9.2	1538	491	68
September 3, 2011	1.4	240	0	100
September 4, 2011	9.6	1992	1077	46
September 14, 2011	3.2	549	0	100
September 19, 2011	20.8	4617	2127	54
September 21, 2011	6.8	1629	835	49
September 23, 2011	19.6	4602	3081	33
September 28, 2011	21.8	4182	1914	54
October 2, 2011	2.2	462	0	100
October 3, 2011	7.4	1626	665	59
October 12, 2011	20.4	4842	1734	64
October 19, 2011	35.6	8634	6214	28
October 24, 2011	2.2	528	0	100
October 25, 2011	26.7	6351	4554	28
September 11, 2011	5.6	1344	0	100
November 14, 2011	3.6	768	0	100
June 9, 2012	4.4	1068	0	100
June 11, 2012	14.8	3354	1537	54
June 21, 2012	21.8	4387	2822	36
June 24, 2012	12.8	2371	1026	57
July 7, 2012	8.4	1647	70	96
July 22, 2012	0.6	84	0	100
July 22, 2012	2.4	264	0	100
July 22, 2012	2.4	471	0	100
July 23, 2012	0.8	120	0	100
August 4, 2012	5.2	1206	0	100
August 5, 2012	3	624	32	95
August 9, 2012	6.2	1245	10	99
August 27, 2012	7.2	1563	14	99
September 4, 2012	43.4	9112	4474	51
September 8, 2012	34.6	7275	4545	38
September 14, 2012	9.8	2262	701	69
September 18, 2012	35	12186	6079	50
September 29, 2012	1.8	327	0	100
October 3, 2012	2.4	489	0	100
October 5, 2012	4.2	744	0	100
October 10, 2012	1	153	0	100
October 11, 2012	0.6	90	0	100

Event	Rainfall (mm)	V_T (L)		VR (%)
		Asphalt	PP	
October 13, 2012	9.8	2316	617	73
October 17, 2012	2.6	576	0	100
October 18, 2012	10.4	3075	1602	48
October 23, 2012	19.8	21592	15389	29
November 10, 2012	1.2	336	0	100
November 12, 2012	6.4	1410	307	78
November 23, 2012	0.8	108	0	100
April 17, 2013	5.4	1164	0	100
April 18, 2013	1.2	1275	793	38
April 24, 2013	12.8	2997	1409	53
April 28, 2013	6	1491	444	70
May 9, 2013	0.6	54	0	100
May 10, 2013	7	1550	488	69
May 15, 2013	1	129	0	100
May 20, 2013	5	686	0	100
May 21, 2013	18.6	4146	2612	37
May 23, 2013	2.8	444	0	100
May 28, 2013	2.4	495	0	100
May 28, 2013	38.6	9906	6735	32
June 6, 2013	7.0	1398	180	87
June 10, 2013	32.8	11588	6779	41
June 22, 2013	4.6	890	54	94
June 25, 2013	3.6	658	0	100
June 25, 2013	1.0	204	0	100
June 28, 2013	27.2	5021	3095	38
July 4, 2013	3.4	561	0	100
July 4, 2013	1.4	207	0	100
July 5, 2013	7.2	22899	11263	51
July 19, 2013	9.0	2860	1026	64
July 27, 2013	17.4	4720	1711	64
July 29, 2013	1.0	78	0	100
July 31, 2013	40.6	8961	7289	19
August 7, 2013	14.2	3877	2425	37
August 25, 2013	2.0	349	0	100
August 26, 2013	22.0	7982	5804	27
August 30, 2013	2.0	201	0	100
September 7, 2013	23.2	4615	3029	34
September 11, 2013	10.8	3169	1889	40
September 15, 2013	1.8	288	0	100
September 20, 2013	40	9085	6705	26
September 29, 2013	0.6	39	0	100
April 22, 2014	4.0	402	270	33
April 25, 2014	5.6	702	413	41
May 23, 2014	1.0	115	0	100
June 2, 2014	0.8	165	0	100
June 3, 2014	12.0	3358	1583	53
June 8, 2014	5.0	1035	0	100
June 11, 2014	6.2	5497	3771	31

Event	Rainfall (mm)	V_T (L)		VR (%)
		Asphalt	PP	
June 17, 2014	19.6	4830	3145	35
June 24, 2014	0.6	23	0	100
June 24, 2014	7.2	1564	395	75
June 29, 2014	6.2	1311	190	86
July 2, 2014	6.2	1311	253	81
July 7, 2014	17.0	8326	5599	33
July 13, 2014	4.0	805	0	100
July 15, 2014	3.6	713	0	100
July 19, 2014	3.0	575	0	100
July 20, 2014	2.6	483	41	92
July 26, 2014	0.8	69	0	100
July 27, 2014	0.6	23	0	100
July 27, 2014	50.4	11868	10937	8
August 1, 2014	7.6	1633	683	58
August 4, 2014	21.0	4922	3101	37
August 11, 2014	15.4	3427	1968	43
August 16, 2014	1.2	161	0	100
August 16, 2014	1.8	336	0	100
August 20, 2014	2.4	437	0	100
August 22, 2014	5.4	1127	34	97
September 1, 2014	3.6	713	0	100
September 1, 2014	2.8	529	0	100
September 2, 2014	43.2	9821	5803	41
September 5, 2014	32.8	7429	5819	22
September 10, 2014	33.2	7734	5794	25
September 13, 2014	3.4	667	164	75
September 15, 2014	1.8	299	0	100
September 21, 2014	1.6	1585	130	92
September 30, 2014	0.6	23	0	100
October 3, 2014	18.2	4311	2392	45
October 6, 2014	1.0	115	0	100
October 6, 2014	3.4	1472	863	41
October 14, 2014	5.2	1081	45	96
October 16, 2014	21	4715	4806	-2
October 20, 2014	3.8	1415	616	56
October 28, 2014	1.0	198	0	100
October 31, 2014	12.0	2858	1531	46
November 4, 2014	3.4	667	0	100
November 6, 2014	1.4	345	0	100
November 8, 2014	1.0	267	0	100
November 11, 2014	1.0	192	0	100
November 20, 2014	1.2	161	0	100
November 22, 2014	0.6	129	0	100
November 24, 2014	19.2	4301	3352	22
November 30, 2014	0.8	123	0	100

APPENDIX C

Time series plots of water temperature

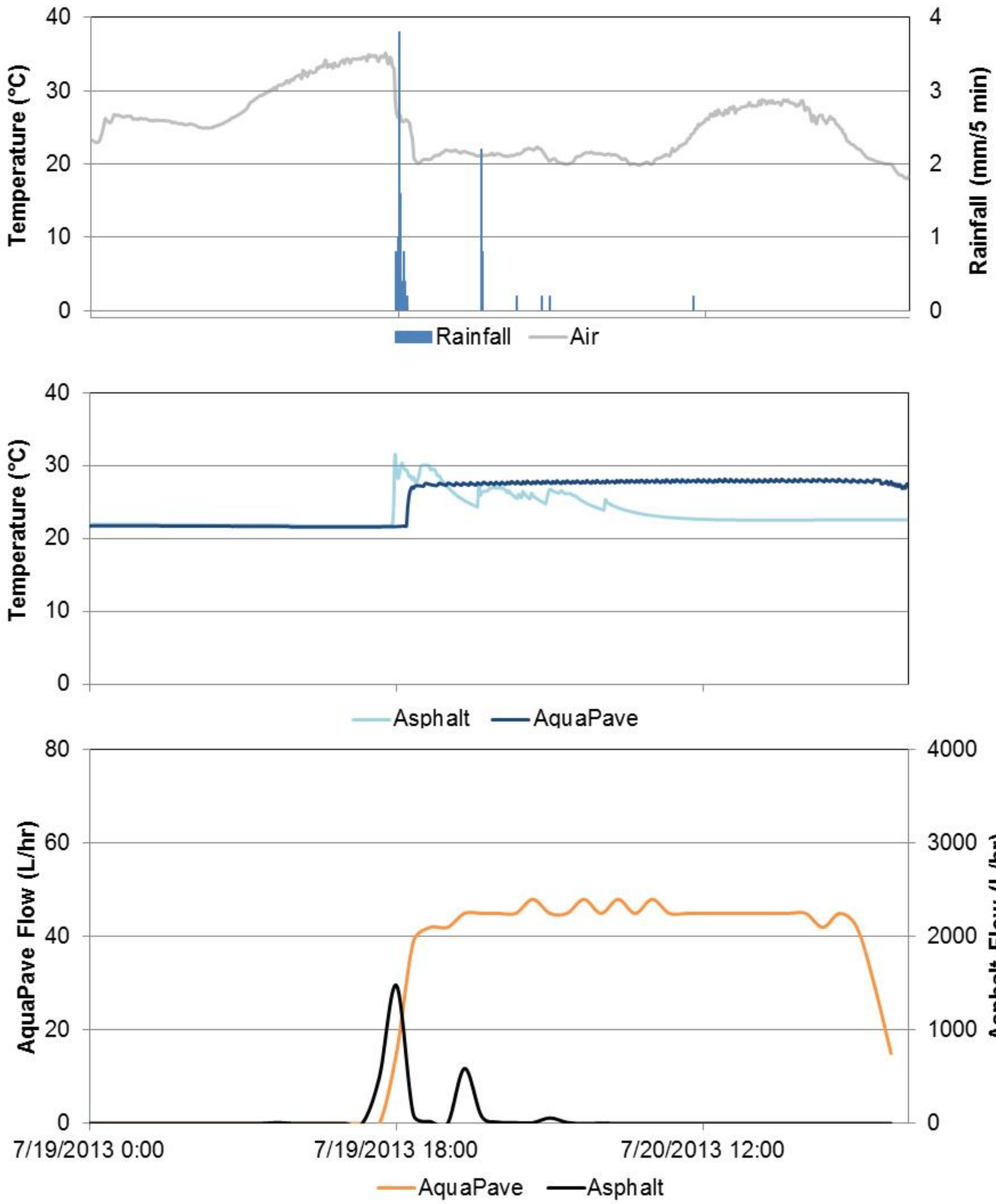

Figure C1: *Time series plots of flow, precipitation, air temperature and water temperature during a rain event on July 19th, 2013. Note that water temperatures occurring outside of the period of flow reflect stagnant water in the pipe, and are therefore not representative of water discharged to receiving waters. See table 4.4 in the main body of the report for event mean and maximum temperatures and thermal loads.*

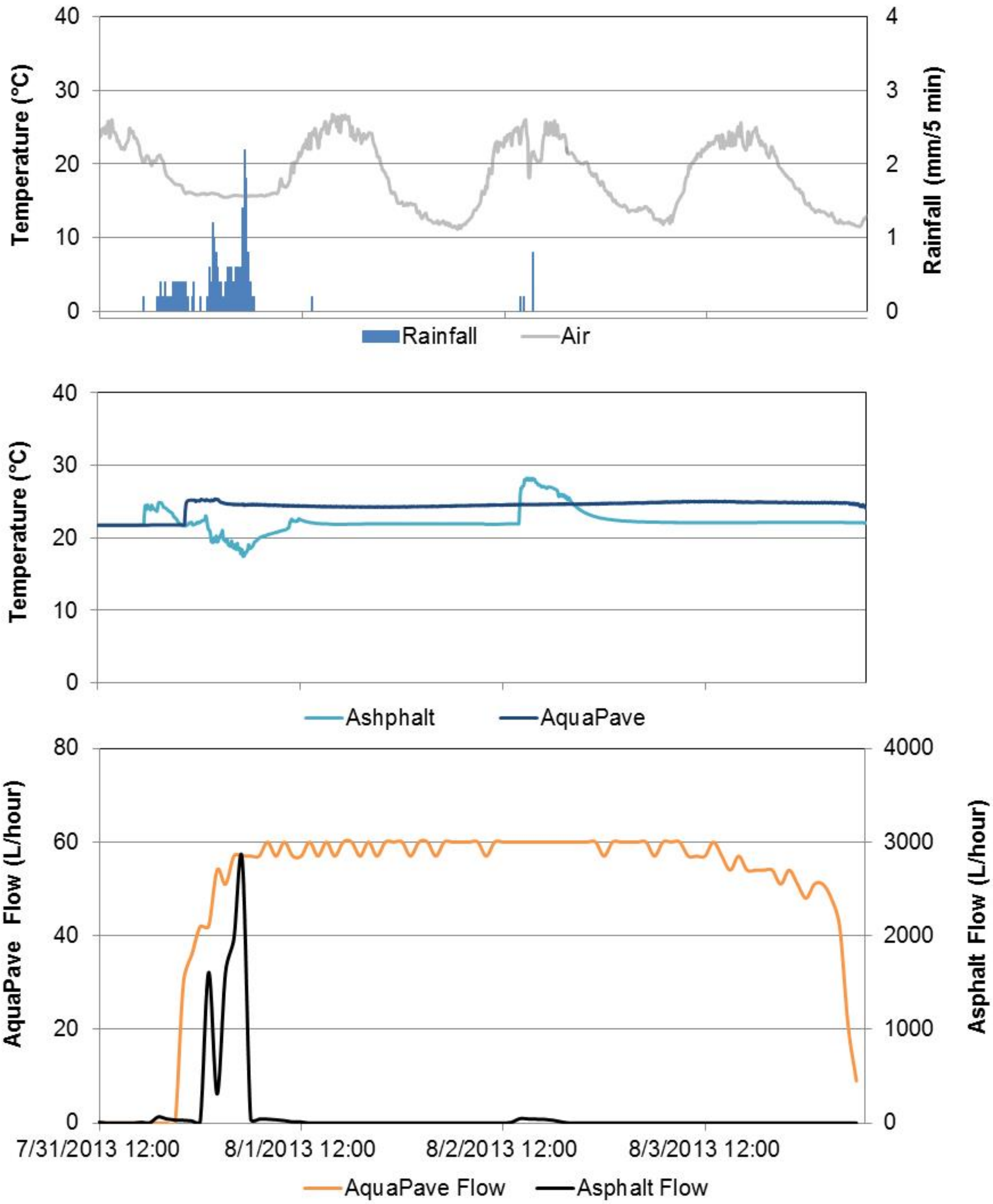

Figure C2: *Time series plots of flow, precipitation, air temperature and water temperature during a rain event on July 31st, 2013 . Note that water temperatures occurring outside of the period of flow reflect stagnant water in the pipe, and are therefore not representative of water discharged to receiving waters. See table 4.4 in the main body of the report for event mean and maximum temperatures and thermal loads.*

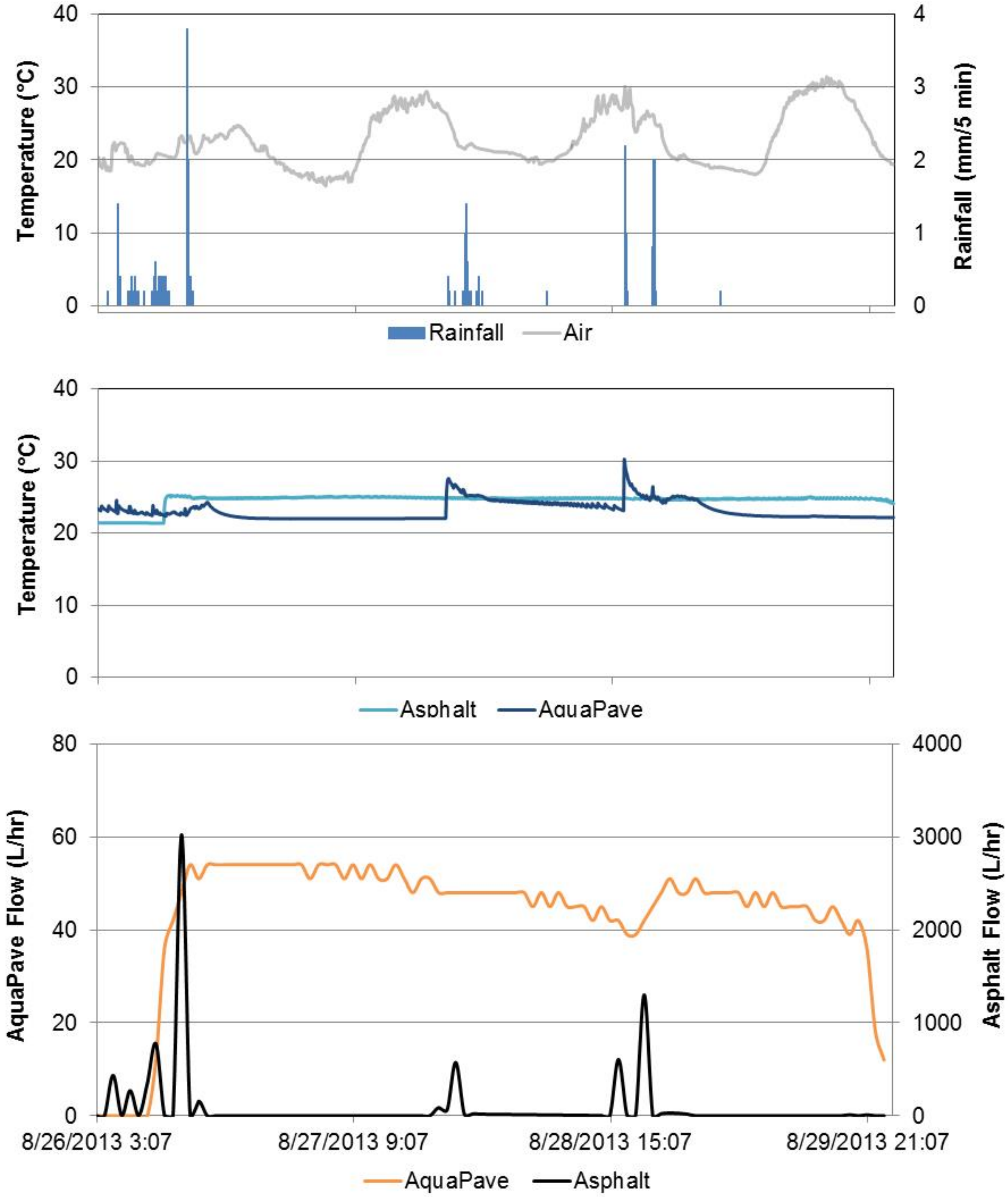

Figure C3: *Time series plots of flow, precipitation, air temperature and water temperature during a rain even on August 26th, 2013. Note that water temperatures occurring outside of the period of flow reflect stagnant water in the pipe, and are therefore not representative of water discharged to receiving waters. See table 4.4 in the main body of the report for event mean and maximum temperatures and thermal loads.*

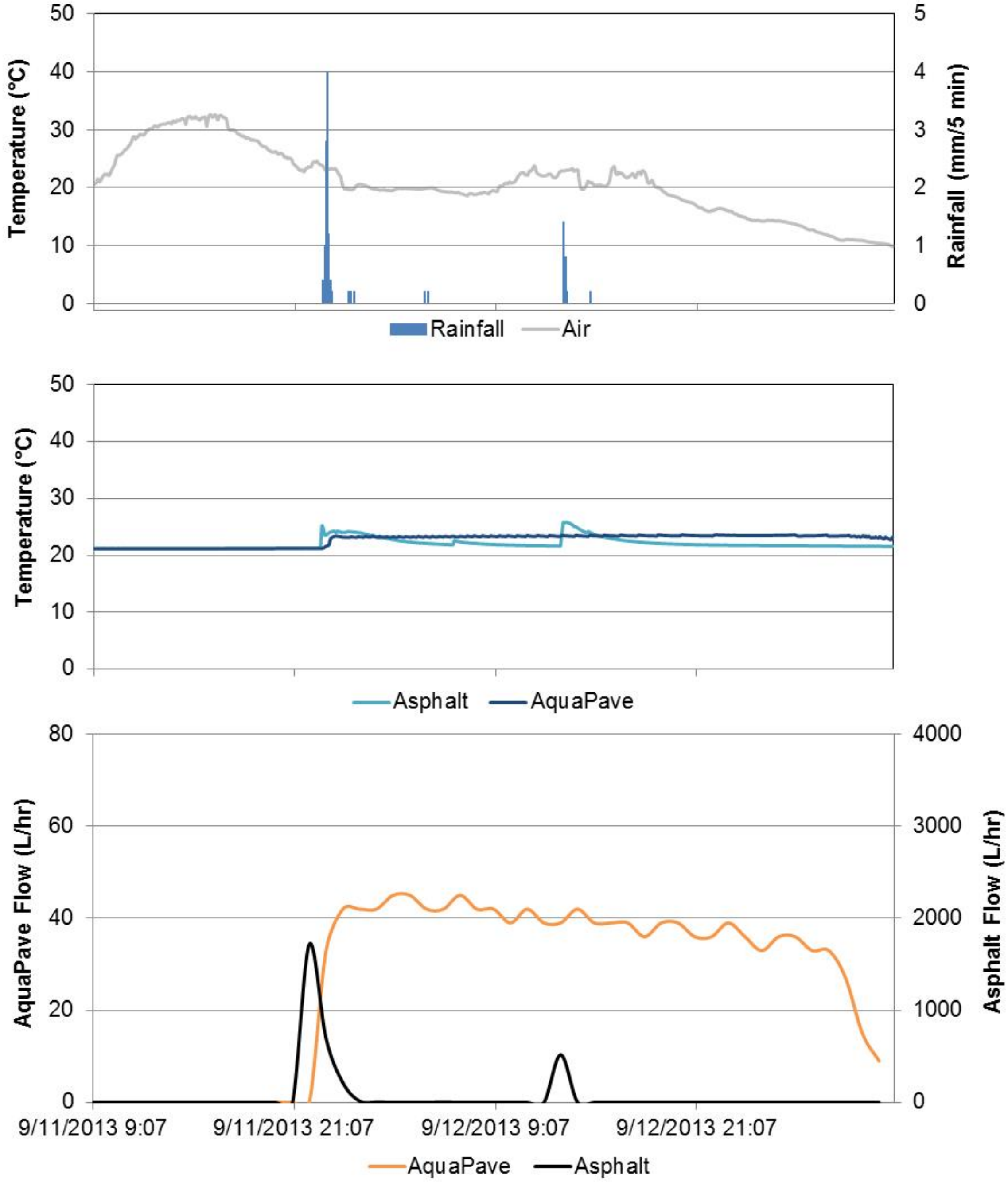

Figure C4: *Time series plots of flow, precipitation, air temperature and water temperature during a rain event on September 11, 2013. Note that water temperatures occurring outside of the period of flow reflect stagnant water in the pipe, and are therefore not representative of water discharged to receiving waters. See table 4.4 in the main body of the report for event mean and maximum temperatures and thermal loads.*

FIVE YEAR PERFORMANCE EVALUATION OF PERMEABLE PAVEMENTS

Final Report

2015

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