PERFORMANCE EVALUATION OF PERMEABLE PAVEMENT AND A BIORETENTION SWALE

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SUMMARY

The Toronto and Region Conservation Authority is currently evaluating the long term performance and effectiveness of permeable pavement (permeable pavers) and bioretention swales for stormwater management on a parking lot in King City, Ontario. Interim flow monitoring results indicated virtually no surface runoff from the permeable pavement, even during relatively large, high intensity rain events (up to 34 mm). The bioswale overflowed during events with more than approximately 20 mm of rain, but most of the runoff either infiltrated or was released back to the atmosphere through evapotranspiration. Both stormwater practices were extremely effective in reducing peak flows from the parking lot, temporarily storing the runoff and releasing it slowly through the under drains over a period of several days following a storm event. The limited water quality monitoring data collected to date (n=9 events) suggest that infiltration through the permeable pavement and bioswale soils generally results in improved water quality relative to conventional asphalt runoff for several constituents typically found in parking lot runoff. Leaching of nutrients from garden soils beneath the bioswale resulted in elevated levels of these constituents in the infiltrate. Future monitoring of soil chemistry beneath the permeable pavement and bioswale will help determine where stormwater contaminants are being attenuated within the soil profile and how quickly they are migrating through the underlying soils.

1. INTRODUCTION

Many of the impacts of urbanization on receiving waters result from the loss of natural infiltration functions when pervious vegetated areas are replaced with impervious roofs and paved surfaces. As less rainwater infiltrates, more runs off over the surface, carrying with it a variety of pollutants that ultimately end up degrading river ecosystems and contaminating swimming areas.

In Ontario, the approach to managing stormwater runoff has largely been focused on end-of-pipe controls such as ponds and wetlands. While these practices are relatively effective in treating stormwater and reducing peak flows, they invariably increase both the volume and temperature of runoff, which often results in a number of undesirable impacts on local streams and aquatic life (*e.g.* Jones et al, 1996; Maxted and Shaver, 1996; Stribling et al., 2001).

So called 'infiltration' stormwater best management practices have become increasingly popular because they avoid some of the flow volume and temperature related impacts of ponds on receiving waters. For parking areas, permeable pavement and bioretention swales stand out as being two of the most promising technologies. A permeable pavement or bioretention system allows runoff to infiltrate through voids in the pavement or through curb-side swales. Since runoff is infiltrated into the soil naturally, it reduces the need for treatment and eliminates the need for underground or site consuming detention facilities. In most cases, space normally reserved for detention facilities, in turn, can be used for green space or other developments (City of Tacoma, 2003).

Several monitoring studies have demonstrated the benefit of permeable pavement in reducing stormwater runoff. Booth and Leavitt (1999) reported virtually no surface runoff from planted (i.e. Turfstone) and unplanted concrete block pavement at a Public Works parking lot in Renton, Washington. A follow up investigation at the same site four years later showed similar results. Even during a 121 mm rain event over 72 hours, only 3% of the total precipitation was observed as surface runoff (Brattebo and Booth, 2003). James (2002) also reported impressive runoff reduction from interlocking concrete pavers installed on a parking lot in Guelph, Ontario.

Less research has been conducted on the water quality impacts of permeable pavements and bioswales. In the Washington study, stormwater concentrations of motor oil and dissolved copper and zinc in infiltrated runoff were significantly less than runoff from a conventional asphalt control area (Brattebo and Booth, 2003). The study found that 88 and 100% of asphalt runoff samples exceeded Washington receiving water standards for zinc and copper, compared to exceedances of only 6 and 17% of permeable block pavement infiltrate samples (n=18). Motor oil was detected in asphalt samples but not in samples collected from subsurface runoff beneath the permeable pavements. In a laboratory study in Guelph, Shahin (1994) reported that concentrations of zinc and iron were much lower after infiltration through a permeable pavement installation.

The study builds and expands on the previous research in evaluating the effectiveness of permeable concrete interlocking pavers and bioretention swales for stormwater management under climate and soil conditions representative of watersheds in the Greater Toronto Area. Since only 4 months of data were available at the time of writing, results presented here should be regarded as preliminary.

2. STUDY AREA

The site for this study is located on a parking lot at Seneca College's King Campus in the Township of King, roughly 25 km north of Toronto. The parking lot is heavily used during the school year, and only occasionally during the summer.

Permeameter testing of native soils beneath the parking lot have a field saturated hydraulic conductivity of approximately 10^{-4} to 10^{-5} cm/s, which is roughly equivalent to silty clay. This is at the low end of the recommended range for these types of infiltration practices (OMOE, 2003) but not uncharacteristic of soil permeability in many other parts of the GTA. The groundwater table is well over 3 m below the surface.

2.1 Site Design and Construction

The portion of parking lot used for the study was divided into three equal areas. On one third of the total area, the asphalt was removed and resurfaced using permeable pavement (Unilock® interlocking

pavers). The middle third remained unaltered and served as a control area for the study (*i.e.* conventional asphalt surface). The final third had a bio-retention swale constructed at the drainage edge of the asphalt to treat runoff from the existing pavement. Catchment areas were separated by narrow 'speed bumps' to prevent intermixing of runoff.

Figures 1 and 2 depict the surface and subsurface flow collection system that was constructed to allow for monitoring and evaluation of the technologies. The permeable pavement portion of the study area was excavated to a depth of approximately 1.4 m and lined with an impermeable geotextile. Three rows of weeping tile, wrapped in filter socks, were placed on top of the liner, and covered with a granular material for structural stability. The entire excavation was subsequently backfilled to an average depth of 1.0 m using the native soil, topped with a 300 mm granular base and a 150 mm layer of high performance bedding (screening). The native soil was used because the experimental set-up was designed to mimic a typical permeable pavement installation, which rarely requires excavation of the native soil beyond the base course layer depth (in this case, 450 mm).

The weeping tile was connected to a tank collection system, which directs the infiltrated water to a sampling vault for quantity and quality monitoring. A similar collection trough was constructed at the edge of the parking area to collect surface runoff from the permeable pavement area during heavy rainfall and this trough also drained to the sampling vault.

To provide an adequate structural foundation for the parking lot, the backfilled native soil was compacted to approximately 100 % Standard Proctor Maximum Dry Density (SPMDD); a similar compaction level to that of the original undisturbed soils under the parking lot. A geotextile was placed over the compacted soil and covered with the sub-base, compacted to 97 % SPMDD, a layer of screening, and permeable pavers. The voids between the pavers were filled with screenings to allow rapid infiltration. The base course layer is capable of storing runoff from storms up to 50mm.

The bioswale was excavated in a similar manner to that of the permeable pavement area, with an impermeable liner and one row of weeping tile draining to the sampling vault. In this case, however, the native soil was replaced with screened 3:1 garden soil topped with cedar mulch, compacted lightly and graded to form a shallow depression for surface storage of storms up to approximately 15 mm. Drought tolerant plants were then planted on top of the swale (Figure 3). Flows overtopping the depression are directed towards grass swales, ultimately infiltrating into the ground. These overflows were not monitored.

3. MONITORING METHODS

All monitoring of flow and water quality was conducted within the sampling vault shown in Figure 1. Electrical supply was provided by one 300w wind turbine and 3 solar panels (1 x 165w and 2 x 170w).

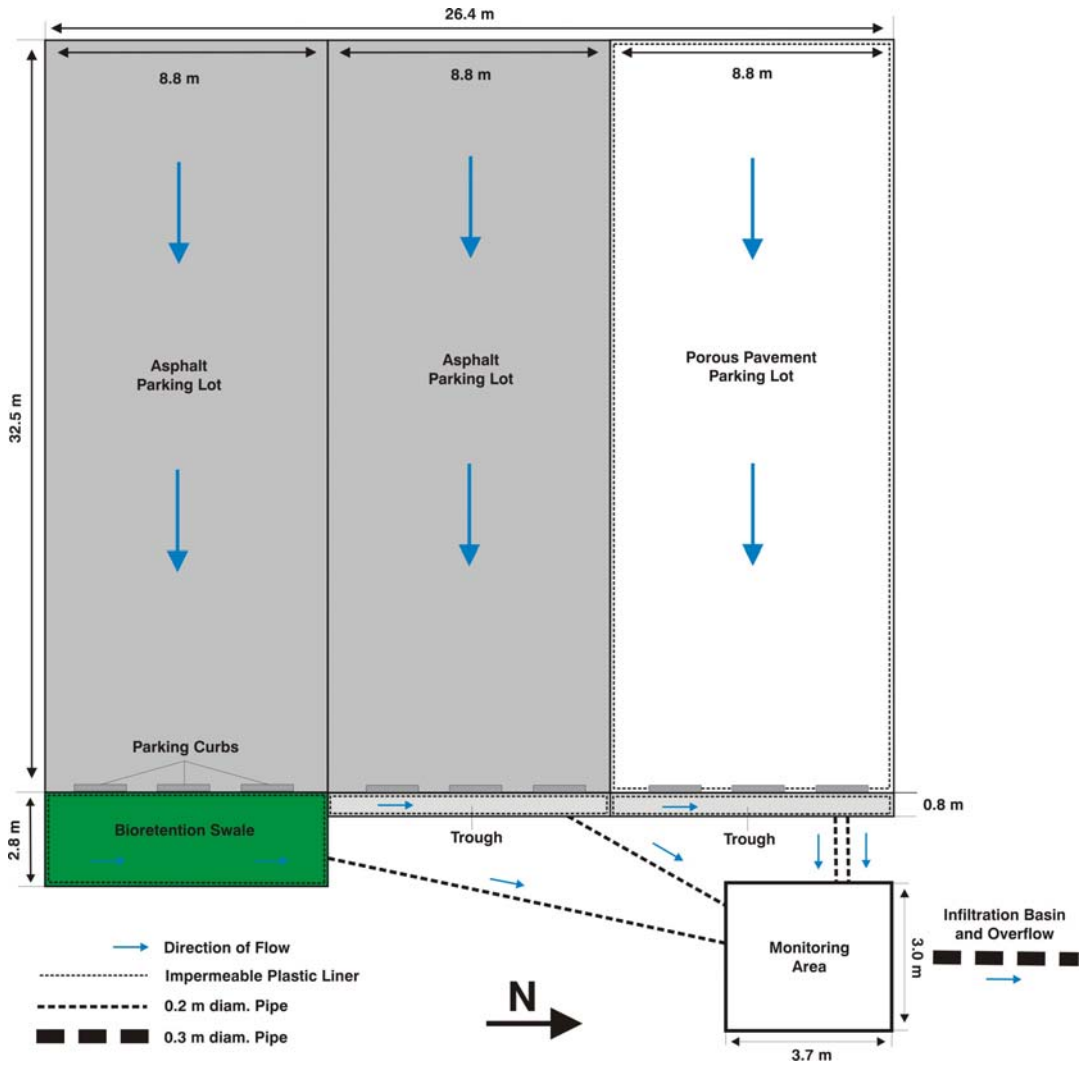


Figure 1. Parking Lot Design Plan View.

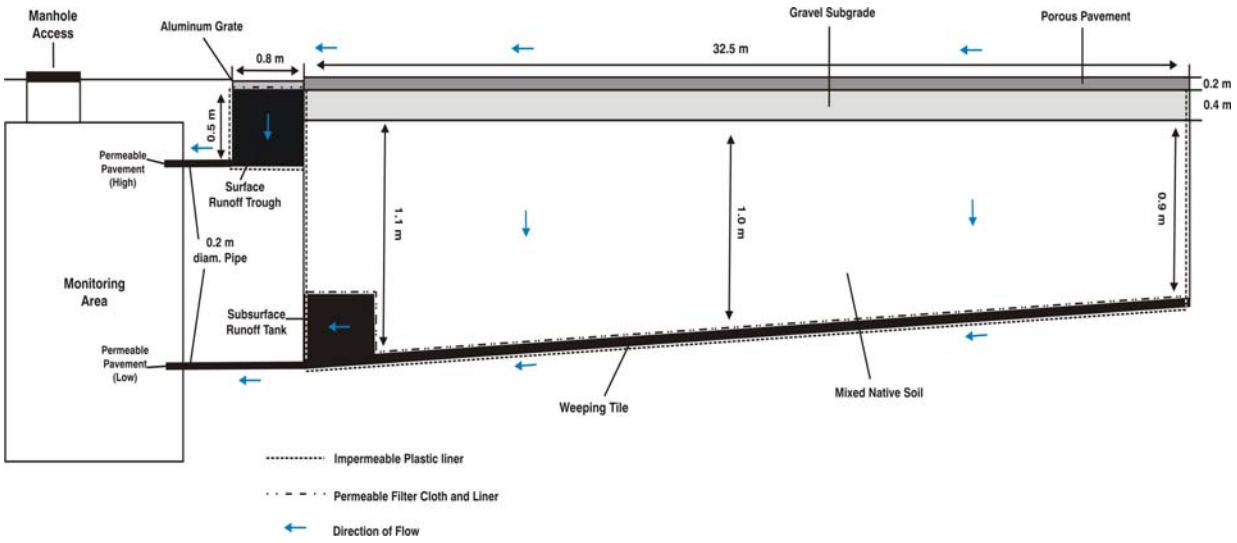


Figure 2. Permeable Pavement Design Cross Section.



Figure 3. Bioswale during dry weather (left) and wet weather (right).

Rainfall was measured using a tipping bucket rain gauge and logger set to record at 5 minute intervals. The station was located approximately 4 km away on top of a pump station in the regional municipality of York. On site rain gauges were installed in the spring of 2006.

Surface and under drain flows are measured using four electromagnetic flow metres connected to a single data logger located in the underground sampling vault. Flows are subsequently directed to an underground trench, where water infiltrates.

Water quality was collected using four automated water samplers, each containing 24 1L Teflon bottles. The samplers were connected directly to the flow meters and triggered when flow rates exceeded 0.005 L/s. Samplers were programmed to collect samples at fixed time intervals according to the duration of flow at each of the outlets. Sampling intervals for the surface runoff troughs (control and permeable pavement surface) are set at 2 min intervals with 2 aliquots per bottle. The bioswale and permeable pavement under drain samplers also collect two aliquots per bottle, but in this case samples are collected at hourly intervals.

Flow proportioned sample composites were formed by measuring out a volume of water from each bottle proportional to the volume of flow since the previous sample. Composite samples were subsequently bottled, preserved and delivered to the Ontario Ministry of the Environment Laboratory for analysis immediately following each event. Water chemistry variables analyzed included general chemistry (e.g. pH, alkalinity, chloride), nutrients, metals and polycyclic aromatic hydrocarbons.

Sediment cores were extracted from the bioswale and the permeable pavement native soil to document changes in soil quality over time. The cores were cut into 76 mm segments to a depth of at least 300 mm, and submitted to the Ontario Ministry of the Environment laboratory for chemical analysis. Older permeable pavement sites in the GTA are also being sampled as changes in soil chemistry often only become evident after at least 3 to 5 years of operation. Observations on pavement durability will also be recorded at these sites. Data on soil quality and durability were not available at the time of writing.

A permeameter was used to assess the infiltration capacity of the soil prior to site selection and during the construction period. Additional tests will be conducted at the end of each year on the permeable pavement and bioswale soils to determine whether or not flow through the system is causing a reduction in infiltration rates over time.

4. INTERIM RESULTS AND DISCUSSION

4.1 Water Quantity

A total of 9 storm events with rainfall depths greater than 5 mm were captured during the 2005 monitoring season. Table 1 shows the properties of recorded rainfall events and runoff volumes generated from the conventional asphalt (control) and permeable pavement and bioretention swale under drains. Surface flows from the two BMPs are not included because there was no surface flow from the permeable parking lot, despite rainfall events with significant volumes (several larger than 30 mm) and high intensities (up to 31 mm/hr over a 5 minute period), and bioswale overflow volumes were not monitored.

Table 1. Properties of recorded rainfall events and runoff volumes

Storm Event	Inter—Event Period (hrs)	Total Rainfall Depth (mm)	Maximum Sustained Rainfall Intensity (mm/hr)[1]	Runoff Volumes (m^3)		
				Control	Permeable Pavement Underdrain[3]	Bioretention Swale Underdrain[4]
9/16/2005	32.9	34.4	24.0	5.6	3.8	2.6
9/25/2005	53.9	33.8	31.2	7.1	7.7	3.2
9/29/2005	57.5	5.8	7.2	1.7	1.7	1.5
10/22/2005	74.6	19.2	4.8	4.0	5.4	3.9
11/5/2005	102.1	14.8	12.0	5.2	4.2	2.1
11/9/2005	66.9	12.4	14.4	3.6	3.7	1.9
11/15/2005	131.8	33.0	14.4	5.0	7.4	2.8
11/28/2005	8.7	31.6	12.0	6.8	10.0	4.6
12/28/2005	89.6	9.8 [2]	-[2]	1.8[5]	4.2[5]	3.6[5]
Total Volumes (non winter events)				39.0	44.0	22.5

1 maximum intensity sustained over a 5 minute period.
2 rainfall data from nearest Atmospheric Environment Service station (Lester B Pearson International Airport)
3. No direct runoff was measured from the surface of the permeable pavement.
4. Surface overflows from the swale during large events were not measured.
5. On December 28th, snow piled along the perimeter of the parking lot and directly on the bio-swale allowed more water to infiltrate in the swale and permeable pavement and blocked runoff from entering the control surface runoff collection trough.

The storms monitored include a range of event sizes and intensities and one snowmelt event (Dec. 28, 2005). During several storms, volumes measured from the permeable pavement under drain were larger than from the control, which is technically impossible, since the catchment sizes are the same. These discrepancies are attributed to a combination of flow measurement errors and the presence of a small sump in the control collection trough, which allowed for some storage and infiltration of runoff. In 2006, instruments were re-calibrated and the control collection trough was replaced.

Comparing results from the control and permeable pavement to those from the bioretention swale shows that runoff volumes from the bioretention swale were significantly less for most storm events. The lower volumes are a result of storage, evapotranspiration and overflows. The latter occurs only

during events larger than approximately 15 mm. While these overflows were not monitored, hydrograph response patterns strongly suggest that several overflows did occur.

The December runoff results are more difficult to interpret because of the presence of snow, which was plowed on top of the swale and around the perimeter of the parking lot. Rain and warm temperatures in late December caused some of the plowed snow to melt onto the permeable pavement and bioretention swale, and eventually infiltrate. The snow and ice piled on the conventional asphalt runoff collection grate blocked surface runoff, causing it to pond and potentially overflow into neighbouring drainage sections. For these reasons, flow balances during the winter may be difficult to achieve. Nevertheless, winter monitoring continues to be a useful means of understanding contaminant flow through the soils as well as differences in melt water dynamics among the pavement management systems.

4.2 Hydrograph Analysis

Hydrographs and hyetographs from two sample rainfall events are presented in Figures 4 and 5. The first event, beginning on September 29, 2005, was a low volume, low intensity storm, with less than 6 mm of rain (Figure 4). The control parking lot area responded instantly to the storm event, with a peak flow of approximately 0.7 L/s. Subsurface runoff from the permeable parking area and the bioretention swale peaked much later, at flow rates of less than 4% of the control peak flow. Flows also receded more slowly from the two infiltration practices.

As would be expected, the bio-retention swale peaked sooner and at a higher rate than the permeable pavement. The quicker response from the bioswale reflects the shorter travel distance for infiltrated runoff, higher ponding depths, and more permeable organic and mineral soils under the swale. Runoff entering the swale need only move vertically through a few feet of relatively permeable (and less compacted) garden soil before reaching the under drain. By contrast, most rain water entering the permeable pavement must infiltrate first vertically and then horizontally through the compact native soil towards the three weeping tiles positioned longitudinally along the impermeable liner.

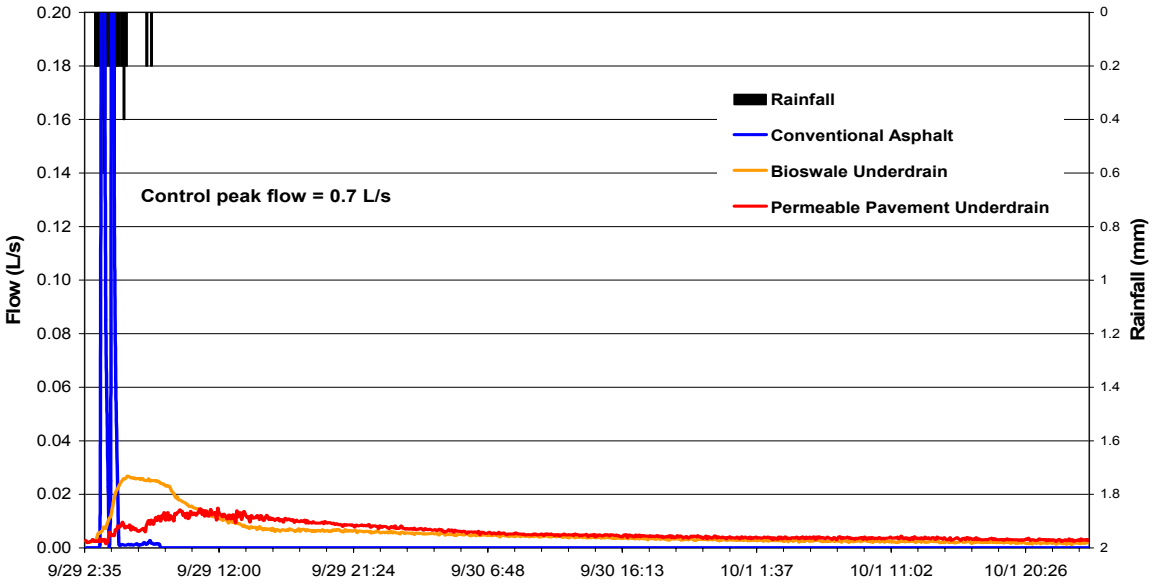


Figure 4. Storm hydrographs and hyetograph on September 29, 2005. Total rainfall: 5.8 mm.

The November 28th storm event is representative of a large, low intensity storm event (Figure 5). The storm had two distinct pulses of rainfall through the event that dropped a total of approximately 32 mm of rain over approximately 24 hours. During the first 4 hours of the storm and near the end of the storm when there was an obvious discrepancy between rainfall at the site (as evident from control runoff rates) and measured rainfall at the gauge 4 km away. This problem was rectified in 2006 by locating two rain gauges on site.

Overall, the general shapes of the hydrographs for the November 28th storm are similar to those from the smaller September event. The conventional asphalt reacted instantly to the rainfall, with much higher peak flow rates, and rapid recession times. It is clear from the hydrograph that much of the available storage in the base course and soil layers under the permeable pavers was consumed by the rain from the first pulse of the storm. The permeable pavement subsurface flow rate during the second rainfall pulse was nearly double that from the first pulse and closer in magnitude to peak flows from the conventional asphalt area (though still less than half of the conventional asphalt peak flow). Despite the large rainfall volume, no surface runoff was measured from the permeable pavement.

The differences in rainfall-runoff response between the permeable pavement and the bioretention swale are more pronounced for the larger storm event. Note that the discharge from the bioretention swale is much lower than that from the permeable pavement, particularly following the second rainfall pulse. Indeed, the bioretention swale showed little response to the second pulse of rainfall, indicating that maximum ponding depths in the swale were reached and the runoff overflowed into the grassed area behind the swale.

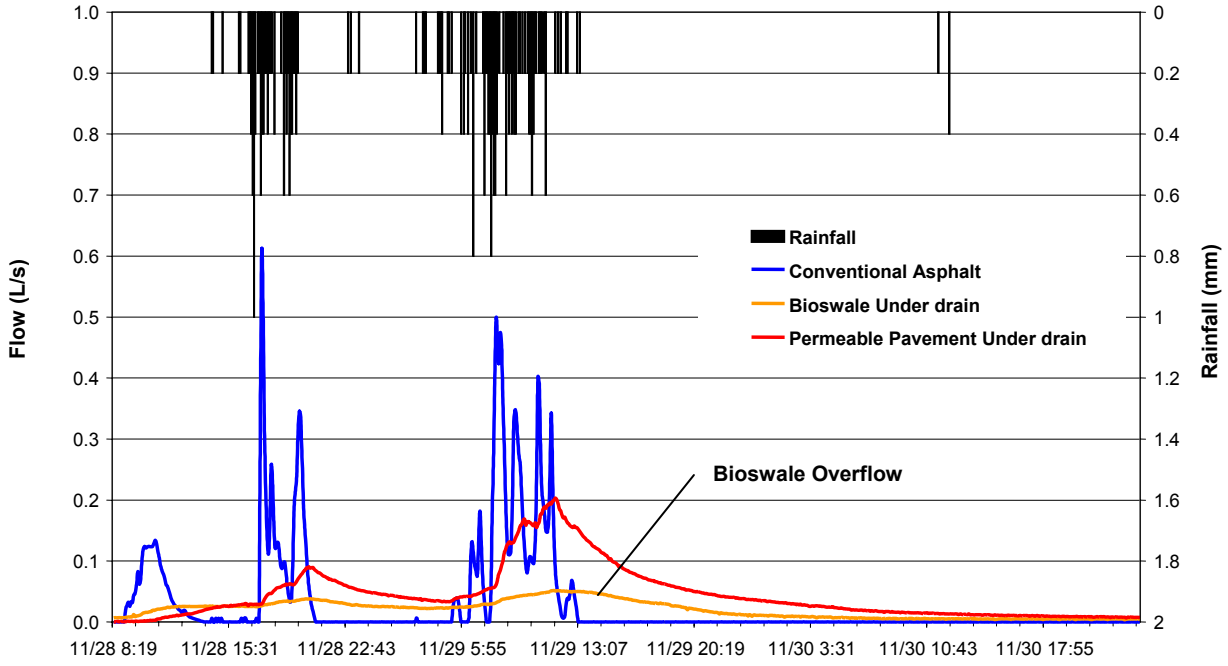


Figure 5. Storm hydrographs and hyetograph on November 28, 2005. Total rainfall: 31.6 mm.

4.3 Water Quality

Water samples were collected during 9 storm events between early September and late November. Table 2 presents a summary of water quality results for selected variables. The sample size was too

small at this early stage of the study to determine statistical differences among control and infiltrated runoff. However, some general observations may be noted.

Table 2. Interim water quality results for selected variables

		TP mg/L	*TKN mg/L*	*Copper ug/L*	*Zinc ug/L*	*Lead ug/L*	*Oil/Grease mg/L*
Control	***Min***	0.02	0.22	4.7	1.95	<mdl	1.07
(n =7-8)	***Max***	0.05	0.8	9.2	25.2	10.6	2.6
	Median	0.03	0.34	5.83	10.94	<mdl	1.38
Perm.	***Min***	0.01	0.2	6.33	3.07	<mdl	0.5
Pavement	***Max***	0.04	0.35	10.4	10.6	<mdl	4.1
(n =7-8)	***Median***	0.02	0.25	7.49	4.91	<mdl	0.5
Bioswale	***Min***	0.87	3.04	5.66	0.87	<mdl	0.5
(n = 8-9)	***Max***	7.28	9.71	22.8	7.38	<mdl	3.6
	Median	1.65	5.55	8.58	4.46	<mdl	1.2
Ontario Receiving Water Guideline		***0.03***	***n/a***	***5***	***20***	***5***	***n/a***

Notes: 1. < mdl = less than laboratory analytical detection limit. 2. The permeable pavement and bioswale samples were collected from the subsurface drains. There was no surface runoff from the permeable pavement and overflows from the bioswale were not monitored.

Overall, discharge from the permeable pavement and bioswale under drains met Ontario receiving water standards for most constituents analyzed. Exceptions include copper and nutrients, the latter of which was elevated only in bioswale runoff. Both are a probably a result of leaching from soils. The swale was particularly rich in nutrients because the native soil was replaced with garden soil containing some composted animal manure.

The difference in water quality between infiltrated and conventional asphalt runoff was most pronounced for zinc, where median concentrations from the bioretention swale and permeable pavement were less than half that of the conventional asphalt. Lead results were less conclusive because all but two of the samples submitted were below the laboratory reporting method detection limit. Both samples were from the conventional asphalt, as would be expected. Copper concentrations from the two infiltration practices and control were similar. Booth and Leavitt (1999) reported a similar result for copper in their study of a new permeable pavement installation in Washington.

Oil and grease (solvent extractable) was detected in 100%, 38% and 56% of control, permeable pavement and bioswale samples, respectively. The source of oil and grease in infiltrate samples requires further investigation. Polycyclic aromatic hydrocarbons (not shown in Table 2) were analyzed only during three large events. Most samples had concentrations below laboratory detections. Benzo(a)pyrene was detected in two of three samples from the convention asphalt runoff, but in none of the samples from the permeable pavement and bioretention swale discharges.

5. CONCLUSIONS

Interim results show that permeable interlocking pavers and bioretention swales offer significant advantages over conventional asphalt. There was no measurable runoff from the permeable pavement surface, even during large (up to 34 mm), high intensity storm events. The bioswale was less effective in this regard, but most of the runoff infiltrated into the ground or was released back to the atmosphere through evapotranspiration. Measured runoff volumes from the bioswale under drain were about 60% that of the conventional asphalt.

The two infiltration practices were also effective in reducing and delaying peak flows. In typical installations without under drains, the infiltrated water would help to recharge groundwater and augment baseflows in local streams. These hydrologic properties of the practices help to eliminate the potential for downstream flooding and prevent stream erosion caused by post-development changes to the flow regime.

Although relatively few samples have been collected so far, the permeable pavement infiltrate generally exhibited better water quality than the asphalt surface runoff. The swale had lower zinc and lead levels, but much higher concentrations of nutrients because the swale was filled with soil which was organically enriched with these constituents. Future analysis of soil cores at this and other older sites will help to identify the source of contaminants observed in subsurface runoff and determine their rates of migration through the soils beneath the permeable pavement and bioswale installations.

Monitoring at this site will continue until 2008. The next interim report will be posted for download in April 2007 at www.sustainabletechnologies.ca.

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