PERFORMANCE EVALUATION OF PERMEABLE PAVEMENT AND A BIORETENTION SWALE

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INTRODUCTION

There is a growing body of evidence demonstrating the limitations of traditional end-of-pipe stormwater management controls, such as ponds and wetlands, in protecting watercourses (*e.g.* ABL, 2006; Jones et al, 1996; Maxted and Shaver, 1996; Stribling et al., 2001). 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.

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, 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 this is an ongoing study, now in its third year, results presented here should be regarded as preliminary.

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 often full during the school year, but is used less frequently during the summer, except during special events.

Permeameter testing of compacted native soils beneath the parking lot indicated a field saturated hydraulic conductivity of approximately 10^{-4} to 10^{-5} cm/s, which is roughly equivalent to a clay loam. The clay loam classification was confirmed through grain size analysis. The hydraulic conductivity 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 base of the installation.

Study Design and Construction

The portion of parking lot used for the study was divided into three equal 286 m^2 areas (Figure 1). 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.

Surface and subsurface flow collection systems were constructed to allow for monitoring and evaluation of the technologies (Figure 1). The permeable pavement portion of the study area was excavated to a depth of approximately 1.6 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 and compacted to approximately 100 % Standard Proctor Maximum Dry Density (SPMDD). A geotextile was placed over the compacted soil and covered with a 45 cm granular sub-base, compacted to 97 % SPMDD, and a 15 cm layer of high performance bedding (screening). Permeable pavers were laid on top and voids between the pavers were filled with screenings to allow rapid infiltration.

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 and conventional asphalt areas during heavy rainfall. These troughs also drained to the sampling vault.

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 2) Flows overtopping the depression are directed towards grass swales, ultimately infiltrating into the ground. Surface ponding and overflow frequencies were monitored starting in the fall of 2006 with pressure transducers programmed to record water levels at 5 minute intervals. The ratio of paved drainage area to bioswale area was about 12 to 1.

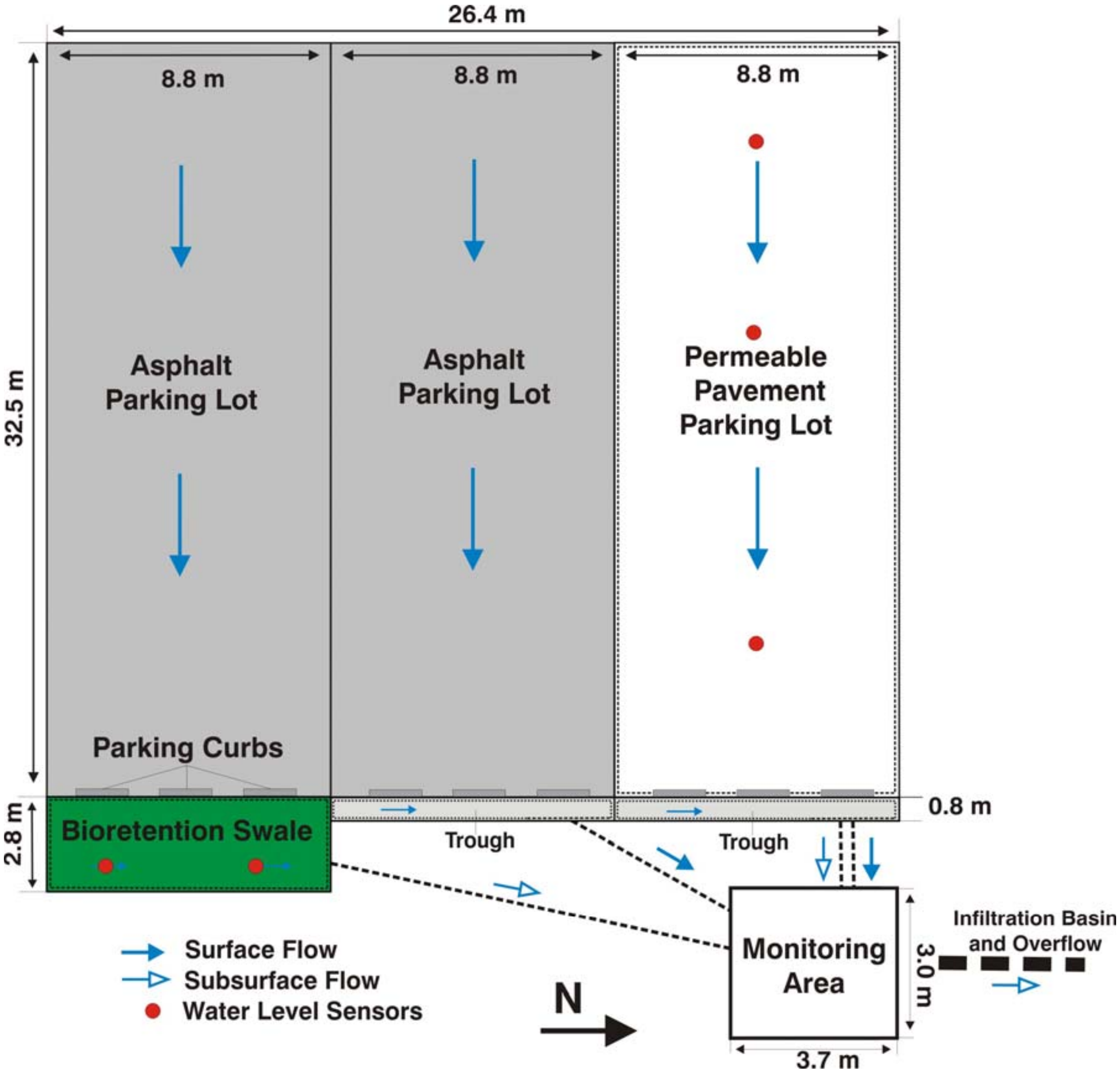

Figure 1: Parking Lot Design

Figure 2 Bioswale during dry weather (left) and wet weather (right).

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).

Rainfall is measured using a tipping bucket rain gauge and logger set to record at 5 minute intervals. In 2005, the meteorological 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 meters connected to a single data logger located in the underground sampling vault. Flows are subsequently directed to an underground trench, where water infiltrates. Water level fluctuations within the base course layer and on the surface of the bioswale were monitored continuously with pressure transducers embedded in slotted wells. Three of these were placed within the permeable pavement base course layer, and the other two were embedded in the surface soil of the bioswale (Figure 1).

Water quality samples were 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. 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 submitted 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 native soils (or subgrade) beneath the base course layer and permeable pavement to document potential effects of stormwater infiltration on soil quality. 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. Five older permeable pavement sites in the GTA were sampled in the same manner. These older sites were a useful addition to the study as changes in soil chemistry often only become evident after at least 3 to 5 years of operation. Observations of pavement structural condition and durability were also recorded at these sites.

INTERIM RESULTS AND DISCUSSION

Water Quantity

A total of 37 events with precipitation depths greater than 5 mm were captured between September 15, 2005 and October 22, 2006. Twelve of these occurred during the winter (December to April). Only one produced surface runoff from the permeable pavement. This storm was the largest event monitored, producing 72 mm of rain over a period of 5.5 hours. Runoff from the permeable pavement measured less than 10 percent of total runoff for the event. The surface flow occurred late in the storm after approximately 48 mm of rain had fallen. During the same event, the bioswale experienced significant overflow, infiltrating only 11% of total runoff from the pavement.

Table 1 shows preliminary hydrologic statistics for 12 runoff events that had clear start and end times. A 'runoff event' was defined as the period between the beginning of flow to the return to no flow, and as such often included several discrete rainfall periods. Surface flows from the two BMPs are not included because, as indicated previously, there was only one event with surface flow from the permeable parking lot, and bioswale overflow volumes were not monitored. Rainfall during these 12 events ranged from 6 to 35 mm.

Table 1: Hydrologic statistics for selected runoff events (n = 12)

Hydrologic Parameter	**Control**	**Infiltrate**	
		Permeable Pavement	**Bio-retention Swale**
Total Flow Volume (m^3)	37.0 [1]	33.5	16.7
Average Peak flow (L/s)	2.2	0.05	0.04
Average Flow Duration (hrs)	2.0	73.3	43.3
Average Rainfall-Runoff Lag (hrs)[2]	negligible	5.5	2.5

1. Control volumes were adjusted upwards by 20% based on known losses within the pipe connecting the collection trough to the sampling vault (this problem has since been rectified). 2. Lag times were calculated from the beginning of rainfall to the beginning of runoff.

Volumes and peak flows were greatest from the conventional asphalt surface, followed by the permeable pavement and bio-retention swale underdrains. The difference in runoff volumes between the control and permeable pavement may be a result of evaporation, but unintentional losses of infiltrated water through tears in the impermeable liner could not be ruled out. Some losses through leaks in the liner may also have occurred in the bioswale system, but most of the volume differences in this case are likely due to higher evapotranspiration rates and overflows during runoff events greater than 15 to 20 mm in size. The permeable pavement responded to rainfall events and drained more slowly than the bioswale because of the less permeable soils and lower hydraulic head (*i.e.* the smaller mass of water per unit area).

Hydrographs and hyetographs for a rainfall event on November 16th, 2006 are presented in Figure 3. During this event, 31 mm of rain fell over 18 hours. The top graph shows water level responses to rainfall within the base course layer and on the surface of the bioswale. Water levels initially increase slowly in the base course as granular surfaces are wetted. Once the base course void spaces were partially filled, subsequent rainfall caused a rapid rise in water levels, with water level peaks occurring only about 30 minutes after the rainfall peaks. Bioswale water levels increase to the overflow point (a small channel along one edge) and then decline rapidly once rainfall has ceased. The higher infiltration capacity of the more permeable swale soils is evident from the difference in drawdown times. Whereas the ponded water on the swale lasts less than two days, water levels in the permeable pavement base course layer draw down over a period of approximately four days. The long draw down times meant that the base course layer remained partially saturated through successive rain events.

The lower graph shows the flow response at the control surface and within the two underdrains (Figure 3). Runoff from the conventional asphalt parallels that of the rainfall, as would be expected. Flow appears first in the swale underdrain as water ponds, infiltrates and then drains through the garden soils over a period of 17 hrs. Flow in the permeable pavement underdrain starts approximately 6 hours after the initial increase in base course water levels. Once an infiltration pathway through the soil has been established, flow in the underdrain more closely mimics base course water levels. Drawdown of flow occurs over approximately four days.

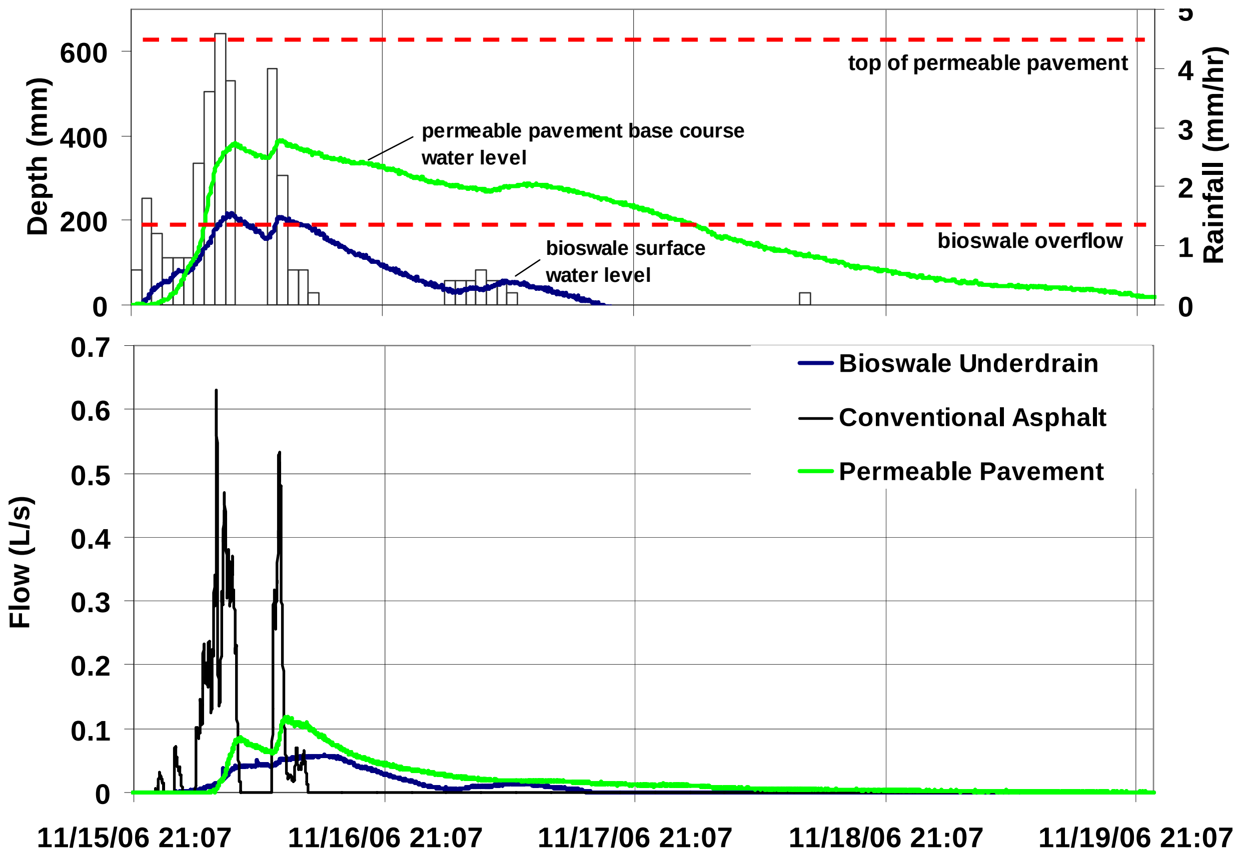

Figure 3: Storm hydrographs and hyetograph on November 15th, 2006. Total rainfall: 31 mm

Water Quality

Water samples were collected during 40 storm events between September, 2005 and November, 2006. Figure 4 presents box plots of concentrations for total suspended solids (TSS), three heavy metals, oil and grease (solvent extractable), and fluoranthene – a polycyclic aromatic hydrocarbon (PAH). Among the 15 PAHs analyzed, only two others were observed at concentrations above laboratory detection limits, and these showed patterns similar to fluoranthene.

The results generally indicate that stormwater filtered through the subgrade and bioswale soils was cleaner than runoff from the conventional asphalt surface. Suspended solids do not travel through soils, hence observed TSS levels largely reflect the capacity of the perforated drain geotextile to filter out solid particles. The higher concentrations in the bioswale infiltrate are likely due to a tear in the filter cloth and/or algae growth observed within the pipe draining the swale. Loss on ignition tests indicated that the proportion of organic content in bioswale infiltrate TSS was about twice that of the permeable pavement infiltrate.

Permeable pavement infiltrate concentrations of oil and grease were frequently below laboratory detection limits, and appeared to decrease over time. The bioswale infiltrate contained lower concentrations than the control runoff, but mean concentrations were not statistically different. The elevated levels of oil and grease in the bioswale infiltrate likely originate from undegraded oils in the manure and compost rich garden soils.

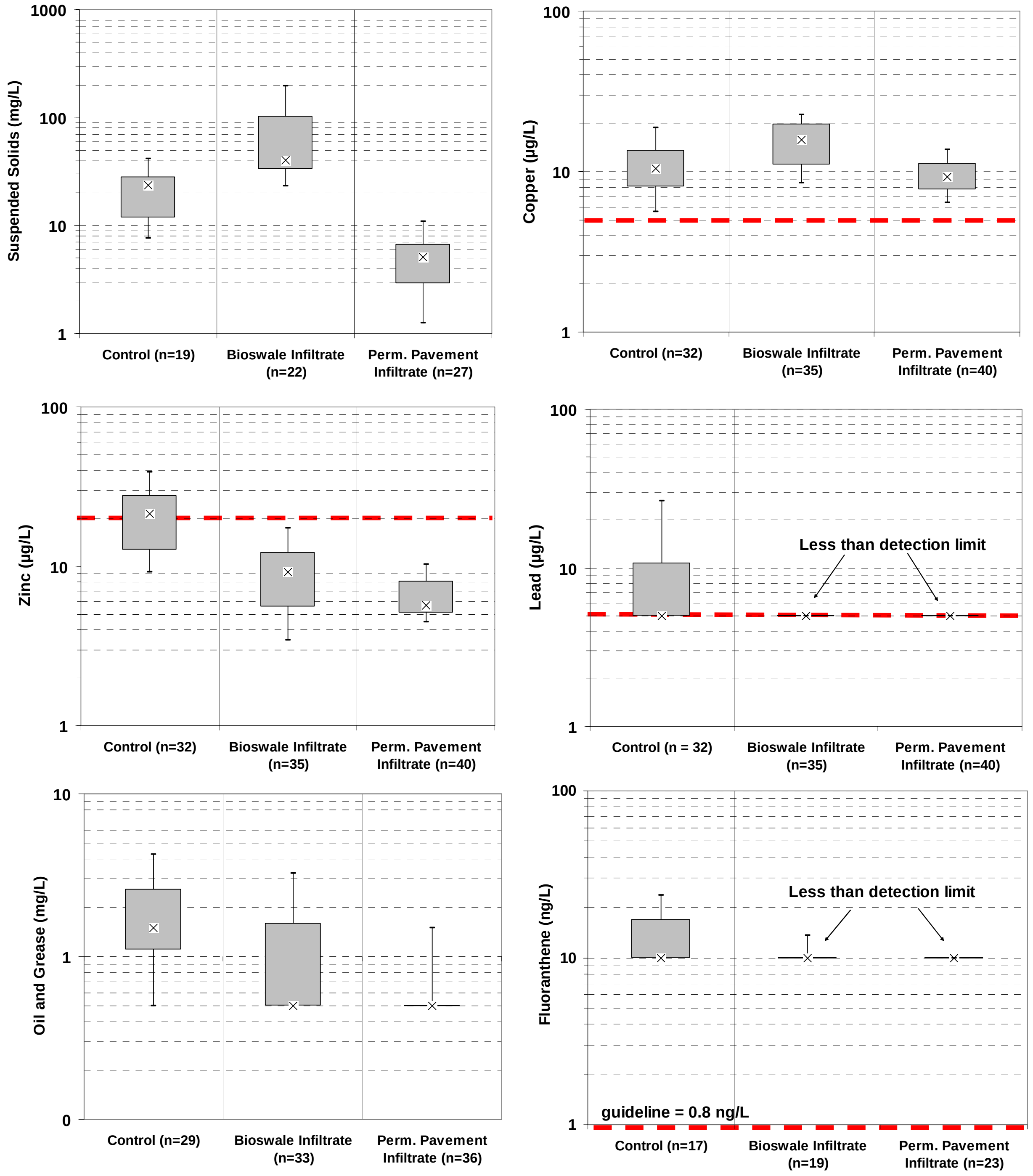

Figure 4: Contaminant concentrations in asphalt runoff, bioswale infiltrate and permeable pavement infiltrate. Thick dashed lines represent Ontario surface water quality guidelines. Box plots represent the 90th, 75th, 50th, 25th and 10th percentile concentrations.

Concentrations of copper were similar in samples from all three study areas. Zinc and lead concentrations were significantly lower in the bioswale and permeable pavement infiltrate than in runoff from the control. Copper and zinc are natural micronutrients in soils; hence low concentrations would be expected even in infiltrate samples from relatively undisturbed soils. The extent to which infiltrate concentrations differ from surface runoff concentrations will depend largely on the concentration at the surface. This is illustrated by the concentration ratios presented in Figure 5. As zinc levels in surface runoff increase beyond about 5 μg/L, levels of zinc in permeable pavement infiltrate become an increasingly smaller proportion of surface runoff levels (*i.e.* ratios in Figure 5 increase above 1). The relationship is similar for copper, but the threshold concentration at which ratios increase above 1 is higher, at roughly 8 μg/L. When surface runoff concentrations fall below this threshold, infiltrate concentrations tend to be greater than those measured at the surface.

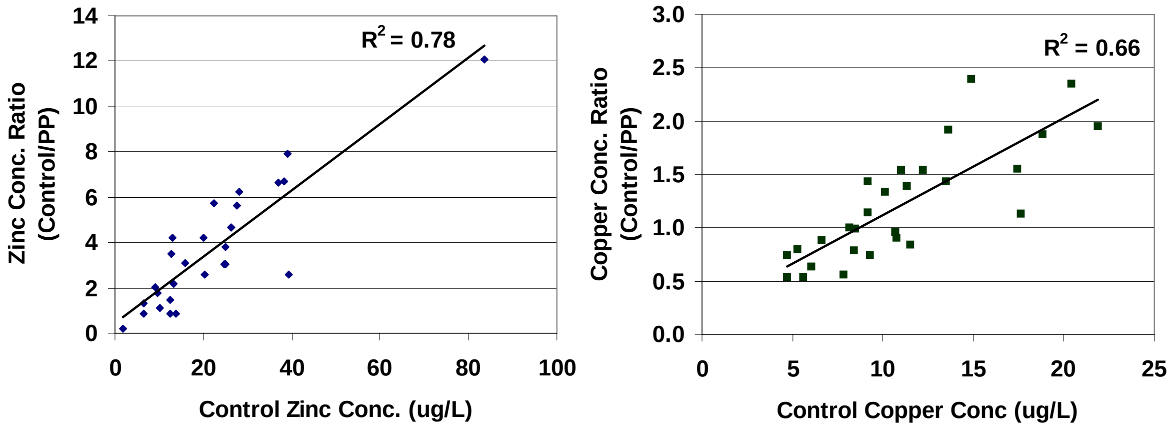

Figure 5: Relationship between control concentrations of zinc and copper and the ratio between control and permeable pavement concentrations for the same constituents

Surveys of Older Sites

Five older permeable pavement sites ranging in age from 3 to 16 years were surveyed in 2006. Soil permeability varied from good to poor and base course layers were between 20 and 40 inches thick. Three of the 5 sites used sand instead of gravel as a bedding layer, which is no longer considered good design practice. Structurally the pavements were in good condition, with few signs of slumping or heaving due to freeze-thaw conditions.

The quality of permeable pavement sediment samples (the subgrade or lower base course) was compared to samples taken from nearby reference sites to assess whether or not infiltration of road runoff contaminants had contaminated underlying soils. Results showed little variation in sediment quality with depth. Average permeable pavement concentrations were either similar to or lower than sediment concentrations from the reference sites (Figure 6), with no obvious relationship to pavement age, design or soil type. The one notable exception was chloride, which is a dissolved constituent that does not bind to soils like most other roadway contaminants. Chloride accumulates over time, but would be expected to eventually leach from the soil into groundwater.

These preliminary results imply that attenuation of most road runoff contaminants is occurring primarily in the bedding and upper sub-base layers, and that contamination of underlying soils is not a major concern for permeable pavements. Further sediment sampling, especially in the base course layer, on reference sites and at older bioswale sites, is planned for the summer of 2007.

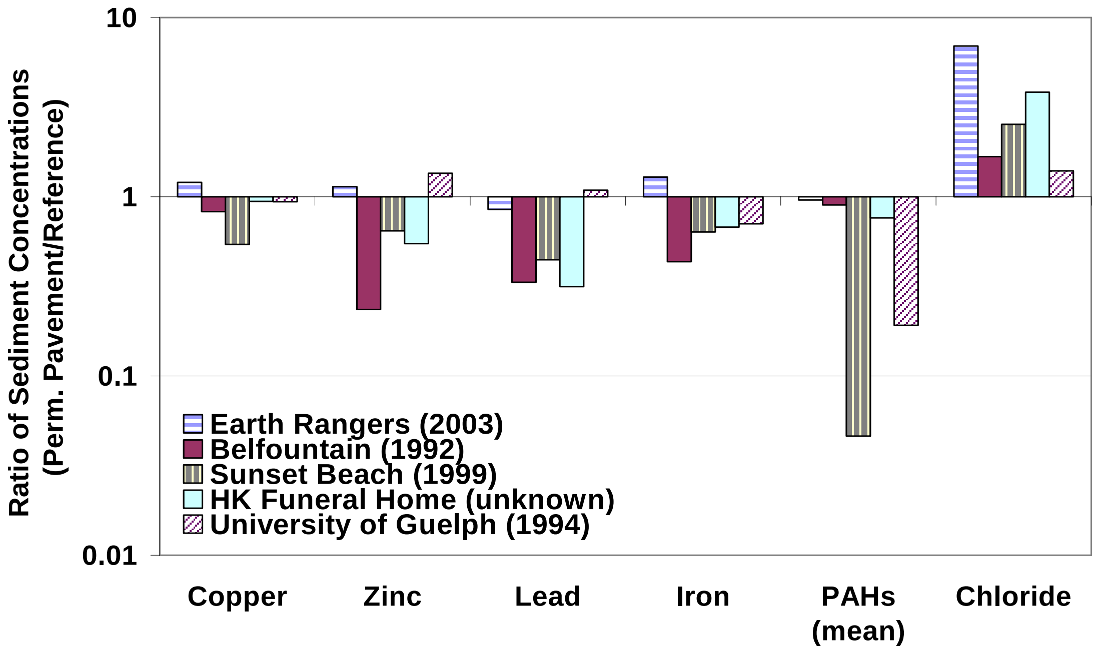

Figure 6: Sediment concentration ratios. Values greater than 1 indicate that permeable pavement concentrations were greater than the reference site, and vice versa.

CONCLUSIONS

Results of this study show that permeable interlocking pavers and bioretention swales offer significant stormwater management benefits over conventional asphalt. Only one very large event produced surface runoff from the permeable pavement and the overflow volume in this case was less than 10% of the total runoff volume. Rarely did base course water levels increase beyond two thirds of the total base course depth (60 cm). The bioswale overflowed more frequently, but most of the runoff infiltrated into the ground or was released back to the atmosphere through evapotranspiration.

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.

Water quality results so far indicate that both infiltration technologies provide good ‘removal’ of typical parking lot contaminants, such as zinc, lead and hydrocarbons. Surveys of older permeable pavement parking lots suggest that most of these contaminants are being captured in the base course layer, and that long term accumulation of contaminants in soils beneath the pavements is probably not a significant concern. Further soil and runoff monitoring is planned for 2007.

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