Performance Evaluation of Permeable Pavement and a Bioretention Swale

Seneca College, King City, Ontario

Prepared by Toronto and Region Conservation

Final Report

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Seneca College, King City, Ontario

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EXECUTIVE SUMMARY

Background

Many of the adverse impacts of urban development on watercourses stem from the loss of natural infiltration and evapotranspiration functions when pervious vegetated areas are replaced with buildings and paved surfaces. As less rainwater infiltrates and evapotranspires, more runs off over the surface, causing increased flood risk, channel erosion, poor water quality, and degradation of aquatic habitat. Permeable pavement and bioretention swales are two examples of stormwater practices that help prevent these undesired consequences by filtering stormwater and preserving or re-instating natural hydrologic functions that existed prior to development.

While these stormwater infiltration practices have been implemented in some areas of the Greater Toronto Area (GTA), broader uptake has been limited by concerns about their long term effectiveness, the potential for infiltrated stormwater to contaminate soil and groundwater resources, and other factors. Initiated in the fall of 2004, this three year demonstration project helps to address these concerns by evaluating the benefits and limitations of the technologies under climate and soil conditions representative of watersheds in the GTA. An international review of literature on permeable pavements and bioretention swales provides a context for the study.

Study Sites

The main 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. Several older permeable pavement (n=7) and bioswale (n=5) sites in the Greater Golden Horseshoe were also surveyed to assess the effect that age may have on various aspects of the two infiltration practices.

For monitoring purposes, the parking lot at Seneca College was divided into three equal sized sections (286 m^2 each) consisting of permeable interlocking concrete pavers (PICP), asphalt draining to a bioretention swale (24 m^2), and a conventional asphalt control area (Figure 1). Parking lot runoff was collected both at the road surface level (asphalt and PICP) and as infiltrate from the soils approximately 1.5 meters beneath the PICP and bioretention swale (hereafter referred to as the bioswale). The PICP and bioswale areas were lined with impermeable plastic membranes overlaid with weeping tile to allow monitoring of water passing through the granular base course (60 cm) and soils.

The native soils below the PICP are clay loam with infiltration rates at the low end of the recommended range for these types of infiltration practices, but not uncharacteristic of soil permeability in many other parts of the GTA. The bioswale soils are a more permeable loam garden soil topped with cedar mulch and graded to form a shallow depression for temporary storage of runoff for storms up to approximately 15 mm. Drought and salt tolerant plants are planted on top of the swale. Flows overtopping the depression are directed towards grass swales, ultimately infiltrating into the ground. The seasonally high groundwater table is well over 3 m below the base of both installations.

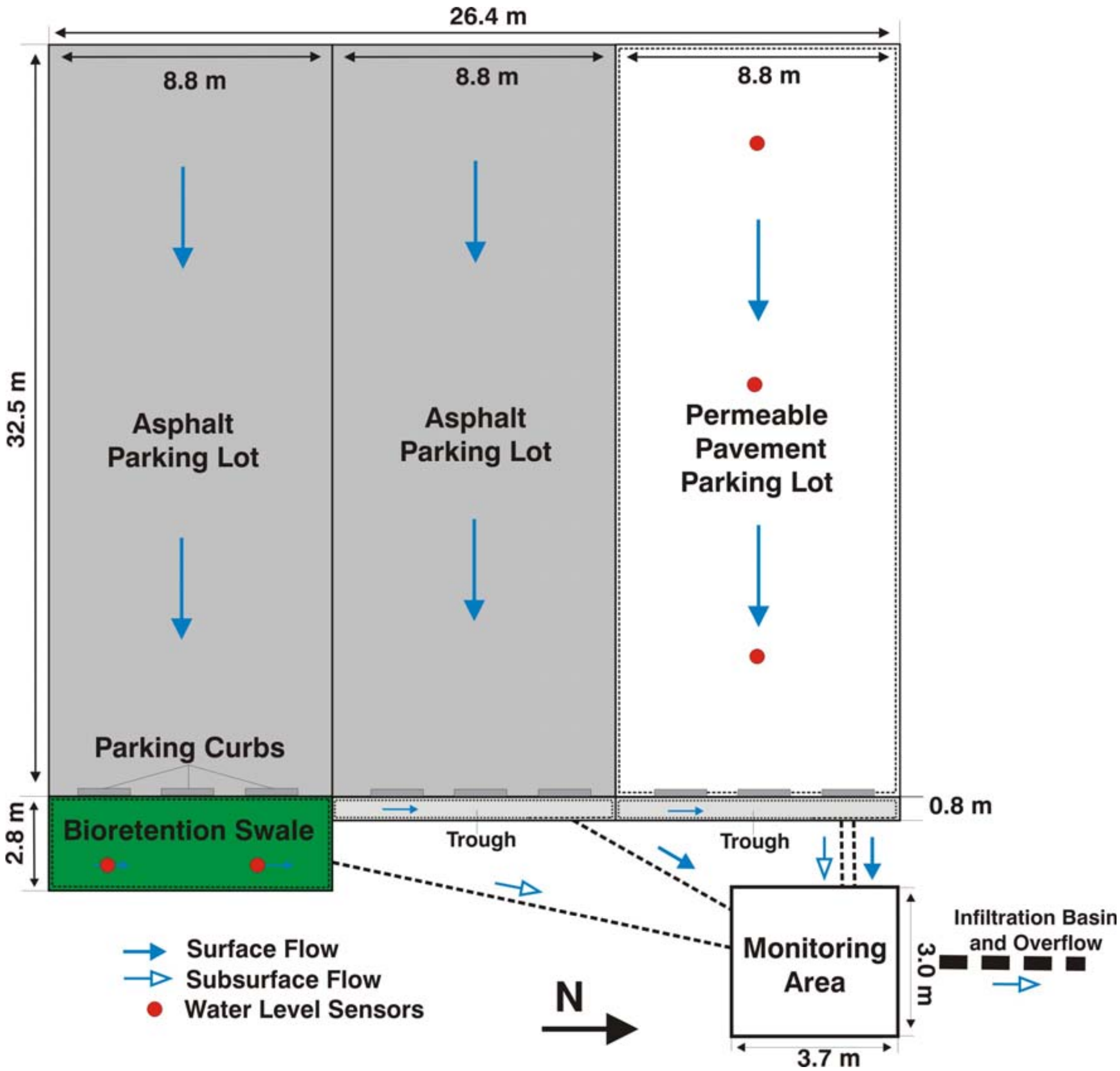


Figure 1: Parking lot design, plan view

Materials and Methods

Rainfall was measured using a standard tipping bucket rain gauge and logger set to record at 5 minute intervals. Surface flows and infiltrate from underdrains were measured using four magnetic induction flow meters connected to a single data logger located in an underground sampling vault. Starting in September 2006, water level fluctuations within the granular base reservoir and on the surface of the bioswale were monitored continuously with pressure transducers embedded in slotted wells with lock-down caps. Three sensors were located within the base, 55 cm below the pavers, and two were embedded in the surface soil of the bioswale (Figure 1).

Water quality samples were collected using four automated water samplers connected directly to the flow meters and triggered when flow rates exceeded 0.005 L/s. Samples were flow proportioned and submitted to the Ontario Ministry of the Environment Laboratory for analysis of general chemistry (*e.g.*

pH, alkalinity, total suspended solids), nutrients (phosphorus and nitrogen), metals and polycyclic aromatic hydrocarbons (PAHs).

Sediment cores were extracted from the bioswale, the native soils (or subgrade) beneath the PICP base course, and a reference site unimpacted by runoff 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. Seven older permeable pavement sites and five older bioswale 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, surface infiltration, durability, and swale vegetation were also recorded at these sites.

Temperature sensors were installed on the PICP and bioswale late in 2006 to assess freeze-thaw cycles and surface and subsurface air and water temperatures year round. The sensors were embedded inside the pavers and conventional asphalt, in the granular filled paver drainage cells, below the pavers in the bedding course, within the base course (50-55 cm deep), and below the bioswale surface at the same depth. Measurements were continuous throughout the summer and winter.

Study Findings

Runoff and Infiltration

Among the 71 runoff events monitored, only one produced surface flow from the PICP. This storm was the largest event monitored, producing 72 mm of rain over a period of 5.5 hours. The overflow volume during this event was less than 10% of total runoff from the asphalt pavement. The bioswale overflowed during events greater than approximately 20 mm, but most of the annual runoff infiltrated into the ground and was released back to the atmosphere through evapotranspiration. While the reduction in runoff in both cases was probably enhanced to some degree by the presence of a liner and underdrain, the results nevertheless suggest that these technologies can contribute to restoring or maintaining infiltration functions in an urban landscape, even on low permeability clay-based soils.

In addition to reducing surface runoff, these infiltration practices also helped to delay and reduce peak flows by storing water and releasing it slowly over several days. Peak infiltrate flows were less than 5% of asphalt peak flows. The slower and more controlled flows help protect downstream watercourses and infrastructure by reducing flood risk and preventing stream erosion caused by post-development changes to the flow regime.

The 60 cm base course was thicker than it needed to be. Water levels in the base reservoir rarely exceeded two thirds of the full base depth (60 cm). Storage per unit depth may have been increased further had clear washed stone been used, instead of granular ‘A’, which includes fines. Relationships between rainfall and water level rise in the base reservoir indicated that the effective porosity of the granular ‘A’ base (<5%) was only a fraction of that specified in the design of the installation (35%).

Winter data show the PICP functioning well during cold weather with air temperatures as low as -25°C. The base course layer continued to function as an effective storage unit, even during sub-zero temperatures. Minimum base course temperatures in 2007 and 2008 were -2°C and -5°C, respectively. The probability of ice formation in the base course tended to increase during the late winter period when snow melt or rain was followed by a sudden drop in temperatures. A similar phenomenon was not evident in the early winter because higher base course temperatures provided a good buffer against sudden changes in air temperature.

The bioswale also performed well during the winter. Soil temperatures remained above freezing and infiltration occurred throughout cold weather. There was no evidence of melt waters backing up onto the parking lot as a result of ice and snow build-up around the perimeter of the swale.

Tests of surface infiltration showed that older PICP sites tended to have lower rates (36 mm/h) than newer installations (1200 mm/h). The use of sand instead of gravel as a bedding layer and joint filler, and in some cases as a winter maintenance practice, were identified as possible factors contributing to lower infiltration rates at older sites. Current guidelines from most jurisdictions recommend using clear stone free of sand or fine particles in the base and surface joints of PICPs.

Water Quality

The potential for infiltrated stormwater to contaminate groundwater was determined by comparing the quality of asphalt runoff with the quality of water after infiltration through one metre of soil below the two installations (hereafter referred to as the 'infiltrate'). Relative to asphalt runoff, the PICP and bioswale infiltrates were characterized by significantly higher levels (α=0.05) of pH, hardness (as $CaCO_3$), and alkalinity. These properties of the water help to buffer the effects of acid precipitation and reduce the aquatic toxicity of trace metals in surface water. Median PICP concentrations of zinc, phosphorus, total suspended solids and oil and grease (extractable solvents) were significantly lower (α=0.05) than those in asphalt runoff. PAHs were rarely detected, but concentrations were generally higher in asphalt runoff. The organic bioswale soils acted as a source of phosphorus, ammonia, and organic nitrogen resulting in significantly higher (α=0.05) concentrations of these constituents in bioswale infiltrate relative to both the asphalt and PICP infiltrate.

Chloride and sodium were the major groundwater contaminants of concern. Infiltrate concentrations of both constituents were frequently above drinking water standards. These soluble constituents are highly mobile, and are able to bypass treatment processes of most conventional stormwater practices. The road salts may have also increased the mobility of trace metals as concentrations of several trace metals rose midway through the second winter of monitoring. Several studies have shown relationships between de-icing chemicals and increased mobility of metals, particularly the more soluble metals such as cadmium and zinc. The observed rise in metal concentrations may also be attributed to higher surface loading and preferential pathways through cracks in the soil matrix or along the liner. In this study, cadmium and lead were of greatest concern as both were occasionally observed in infiltrate samples at concentrations above drinking water standards. The processes governing the transport of metals through soils under permeable pavements and bioswales where road salts are applied is a topic that requires further investigation.

Temperature

The temperature of the asphalt surface exceeded 20°C roughly 12% more often than the pavers, suggesting that PICPs may help to mitigate against heat induced smog and other undesirable effects associated with the urban heat island. The lighter colour (*i.e.* higher reflectivity) of the pavers and their ability to dissipate heat through open joints may explain much of the difference. During the winter, asphalt and PICP surface temperatures were very similar. The main winter benefit of the PICP lay in its ability to infiltrate snowmelt and thereby reduce ponding and ice build-up.

Soil Quality

Soil sampling of 7 older PICP parking lots and 5 older swales or ditches suggest that long term accumulation of contaminants in soils beneath the pavements and swales was not a significant concern. Contaminant levels at all sites were generally below Ontario soil 'background' concentrations for non-agricultural land uses. There were a few exceptions, but even in these cases, concentrations were still well below levels that would trigger the need for remediation or landfilling.

At the Seneca site, soil cores were extracted for analysis from the swale and PICP subgrade in 2005, and again in late 2007. Although more samples would be needed to establish a statistically significant difference, the absence of any change in swale or PICP subgrade soil chemistry over this time period is consistent with generally low soil contamination observed at other older sites.

Durability

Visual observations from older PICP sites showed that, from a structural point of view, the pavements continued to meet the expectations of users, with few signs of slumping or heaving. Tests using a Portable Falling Weight Deflectometer at the Seneca and Earth Rangers sites during the fall, winter and spring indicated that the asphalt and PICPs were comparable in strength. Both pavement types were weaker during the summer, rendering them more susceptible to damage from heavy truck loading during this time.

Recommendations

Results of this study indicate that permeable pavements and bioretention swales can be effective measures for maintaining or restoring infiltration functions on parking lots and other low volume traffic areas. The following recommendations on PICP and bioswale design and maintenance are based on study findings and observations. Suggested topics for further research in the GTA are listed in the final section.

Design

- Measurements of water level fluctuations in the PICP base course indicated that, at this particular site, a base course depth of 40 cm would have provided sufficient storage capacity for most rainfall events.
- Applications of PICPs and bioswales on low permeability soils with underdrains in the base reservoir should include a flow restrictor on the drainage pipe to maximize infiltration by allowing water to slowly drain and seep into the ground after an event. Water levels in the base reservoir should be monitored to ensure that the drawdown period is well suited to the particular soil and climate conditions for a given area.
- The potential for de-icing salts to mobilize heavy metals may warrant an increase in the current allowable depth to the seasonally high ground water table from one meter to two or more meters below the base of the PICP or bioswale installation.
- Effective porosity of the granular ‘A’ sub-base materials was very low, limiting the capacity of the reservoir to detain stormwater runoff. Use of clear washed stone would help improve the storage capacity of the base reservoir.
- Surface infiltration tests in this and other studies confirm that using sand as a bedding layer or applying sand on pavements during the winter slows surface infiltration and significantly increases the risk of premature clogging.
- In bioswales, garden soils with high organic content should be limited to the upper 20 cm and underlain with a sandy soil mix to reduce the export of nutrients through underdrains while maintaining good permeability.

Operation and Maintenance

- Alternative deicing products such as calcium magnesium acetate should be considered in the winter on permeable parking lots to prevent excessive build-up of sodium and chloride in groundwater.
- Good infiltration through the pavers after 3 years of operation suggested that vacuum washing of PICPs may be needed only once every three to four years. Higher maintenance frequencies may be required in areas with greater traffic volumes.
- Base course water levels should be monitored periodically to provide early warning of potential reductions in subgrade infiltration rates.
- Soil quality results from older PICP and bioswale sites indicate that land fill disposal or remediation of the underlying soils would typically not be required when the pavers or swales need to be replaced.

Topics for Further Research

- *The quality of effluents from underdrain applications of PICPs.* This study examined water quality after infiltration through the base reservoir and one meter of native soil. In most installations on low permeability soils, the underdrain is placed within the base course to ensure sufficient storage capacity is available for subsequent storms. Monitoring of water quality should be undertaken to determine whether these types of underdrain applications provide an acceptable level of water quality control. Tests should be conducted over varying detention times (*e.g.* 12, 24, 48 hours) as contaminant loading from underdrains will be strongly influenced by residence time in the base reservoir and the volume of water that infiltrates.

- *Impact of de-icing salts on the mobility of metals beneath PICPs and bioswales.* While previous studies have shown that de-icing salts can increase the mobility of some heavy metals in stormwater runoff, few researchers have examined the specific chemical and physical processes responsible for enhanced metal mobility beneath permeable pavements and bioswales. Data collected at the Seneca site suggest that this could be an important issue that requires further investigation.
- *Long term infiltration beneath PICPs and bioswales.* While several studies have examined surface clogging of pavements, few have evaluated the long term effects of stormwater infiltration on the infiltration capacity of subgrade soils and bioswale media. This may be particularly relevant in cold climates where de-icing salts can affect infiltration rates by altering the physical structure of soils.
- *The structural and hydrologic attributes of open and dense graded bases.* In Ontario, most PICP bases have been constructed using standard Ontario 'granular A' media, which includes a mixture of fines, sand and gravel up to 20 mm in diameter. Guidelines from Vancouver and other jurisdictions in the United States and Britain recommend using 'open graded' media (or clear stone), which have a narrower particle size range, and exclude fines. The comparative influence of clear stone and granular 'A' on PICP structural integrity, infiltration and water storage properties needs to be examined further.
- *The role of reactive media in improving water quality.* Heavy metals are a major contaminant of concern in runoff. Further research is needed on the potential for reactive media to reduce the export of heavy metals and other contaminants by retaining them within the base course or bioswale soils.
- *Microbial degradation of hydrocarbons within PICP installations.* Some European studies of permeable pavements have shown that vehicle oils and greases are degraded by microbes living on the geotextile located between the granular media and native soils. The effectiveness of these processes under local conditions, particularly during the winter, is a topic requiring more study.
- *The hydrologic characteristics of PICPs on clay based soils.* Most of the remaining buildable area in the Greater Toronto Area is located on low permeability (hydrologic group C and CD) soils. There has been little PICP research conducted on these types of soils as they are often regarded as providing limited infiltration benefits. This and other studies of infiltration systems in the GTA have demonstrated that these soils can have significant infiltration potential. More monitoring of permeable pavements is needed to quantify the flow reduction and water quality benefit of PICPs on clay based soils.
- *Structural characteristics of PICPs in cold climates.* The pavement structural tests showed greater stiffness during cold weather than in warm weather, but on all three test days, the base was partially filled with water. Further structural tests should be conducted under dry, wet, frozen and partially frozen states, as well as on bases of different depths, to determine the extent to which these different parameters affect the structural integrity of the pavement relative to a conventional asphalt surface.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Background

The natural hydrologic cycle is fundamentally altered during the course of urbanization as vegetated areas are replaced with buildings and paved surfaces. The rainwater that would have infiltrated and evaporated under natural conditions instead runs off over the impervious surfaces. Without treatment, this increased runoff leads to stream channel erosion, increased flood risk and degradation of aquatic habitat. The quality of receiving waters is also affected as dirt, dust, oils, feces, fertilizers and other contaminants are transported with uncontrolled stormwater into freshwater ecosystems.

Vehicular traffic accounts for much of the build-up of contaminants on roads and parking surfaces. Wear from tires, brake and clutch linings, engine oil and lubricant drippings, combustion products and corrosion, all contribute to the build up of sediment particles, metals, and oils and grease. Degradation of road surfaces also generates derivatives from asphalt, and runoff from residential driveways and parking areas can contain driveway sealants, oil, salt, and car care products. All of these different elements and compounds can accumulate and degrade local water courses over time (Table 1.1).

Table 1.1: Typical sources of contaminants in runoff from parking lots (Burton and Pitt, 2002)

Variable	Source
Particulates	Pavement wear, vehicles, atmosphere, road maintenance
Nitrogen, phosphorus	Atmosphere, roadside fertilizer application
Lead	Tire wear (lead oxide .filler material, lubricating oil and grease, bearing wear), metal deterioration
Zinc	Tire wear (filler materials), motor oil (stabilizing additive), grease, metal deterioration
Iron	Auto body rust, steel highway structures (guard rails, etc.), moving engine parts, metal deterioration
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, fungicides and insecticides, metal deterioration
Cadmium	Tire wear (filler material), insecticide application, metal deterioration
Chromium	Metal plating, moving engine parts, break lining wear, metal deterioration
Nickel	Diesel fuel and gasoline (exhaust), lubricating oil, metal plating, bushing wear, brake lining wear, asphalt paving, metal deterioration
Manganese	Moving engine parts
Cyanide	Anti-cake compound (ferric ferrocyanide, sodium ferrocyanide, yellow prussiate of soda) used to keep de-icing salt granular
Sodium, Chloride	De-icing salts
Sulphate	Roadway beds, fuel, de-icing salts
Petroleum, Oil, and Grease	Spills, leaks, or blow-by of motor lubricants, antifreeze and hydraulic fluids, asphalt surface leachate, fuel and oil spills and leaks
PAHs	Asphalt, fuel and oil spills and leaks
Suspended Solids	Sanding in winter, tire wear, tire tread deposits

Land use is one of the most important factors governing the level and type of pollutants present in stormwater runoff. Based on an extensive monitoring data set, the United States Environmental Protection Agency (USEPA, as cited by Burton and Pitt, 2002) estimated typical pollutant yields from various land uses to local watercourses per year (Table 1.2). While pollutant loads to watercourses will vary, Table 1.2 provides some perspective on what could be expected in the GTA. Parking areas, to which permeable pavement and bioswales are most often applied, have among the highest pollutant yields.

Table 1.2: Typical urban area pollutant yields (lb/acre/year or kg/ha/year) (Burton and Pitt, 2002)

Land Use	Total Solids	Suspended Solids	Chloride	Total Phosphorus	TKN	NH_3	NO_3 + NO_2	BOD_5
Commercial	2100	1000	420	1.5	6.7	1.9	3.1	62
Parking lot	**1300**	**400**	**300**	**0.7**	**5.1**	**2.0**	**2.9**	**47**
High-density residential	670	420	54	1.0	4.2	0.8	2.0	27
Medium-density residential	450	250	30	0.3	2.5	0.5	1.4	13
Low-density residential	65	10	9	0.04	0.3	0.02	0.1	1
Freeways	1700	880	470	0.9	7.9	1.5	4.2	NA
Industrial	670	500	25	1.3	3.4	0.2	1.3	NA
Parks	NA	3	NA	0.03	NA	NA	NA	NA
Shopping center	720	440	36	0.5	3.1	0.5	1.7	NA

Land Use	COD	Lead	Zinc	Chromium	Copper	Cadmium	Arsenic
Commercial	420	2.7	2.1	0.15	0.4	0.03	0.02
Parking lot	**270**	**0.8**	**0.8**	**NA**	**0.06**	**0.01**	**NA**
High-density residential	170	0.8	0.7	NA	0.03	0.01	NA
Medium-density residential	50	0.05	0.1	0.02	0.03	0.01	0.01
Low-density residential	7	0.01	0.04	0.002	0.01	0.001	0.001
Freeways	NA	4.5	2.1	0.09	0.37	0.02	0.02
Industrial	200	0.2	0.4	0.6	0.10	0.05	0.04
Parks	NA	0.005	NA	NA	NA	NA	NA
Shopping center	NA	1.1	0.6	0.04	0.09	0.01	0.02

In the development of an effective stormwater management plan, the effect of land use change on the site water budget must be carefully considered to ensure that appropriate stormwater control measures are selected and implemented (OMOE, 2003). The Ontario Ministry of the Environment (OMOE) and other municipal agencies suggest using a combination of practices that store, infiltrate and evaporate water in order to minimize changes to the pre-development water budget. In parking areas, recommended approaches include decreasing the size of parking stalls to reduce the overall area impervious surfaces and incorporating effective parking lot runoff designs.

Permeable pavement and bioretention swales are two of the most promising technologies currently used to infiltrate runoff and reduce pollutant loads from parking areas. A permeable pavement or bioretention system allows runoff to infiltrate through voids in the pavement or through curb-side swales. Infiltration of runoff in this manner reduces the need for treatment by 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).

Permeable pavement systems rely almost exclusively on pollutant removal through filtration and adsorption to soil particles. Bioretention swales may not be as efficient as permeable pavements in terms of infiltration, as such systems are generally small in surface area relative to the size of the contributing drainage area. However, bioretention swales offer alternative potential water quality benefits through such mechanisms as plant uptake of pollutants, microbial degredation, and other chemical and biological processes. There is, therefore, value in carrying out monitoring of field applications of both permeable pavement and bioretention swales to assess their suitability as stormwater management options for managing existing and new development.

1.2 Study Objectives and Report Outline

This study assesses the long term stormwater management performance of permeable interlocking concrete pavers (PICP) and bioretention swales under soil and climate conditions representative of watersheds in the Greater Toronto Area (GTA). While there has been a considerable amount of research conducted on these practices, there are few practical applications of such measures in Southern Ontario. Of those that have been installed, few have been comprehensively monitored, especially over the winter period. Field data on the quality of infiltrated water and soils beneath the installations are particularly sparse. This study helps to fill these knowledge gaps by:

- Evaluating the capacity of PICPs and bioswales to infiltrate rainwater and reduce runoff;
- Assessing the potential for infiltrated stormwater to contaminate groundwater and soils;
- Investigating potential issues relating to long term durability, soil contamination and clogging potential of PICPs and bioswales, and
- Assessing the structural integrity of PICPs under varying moisture and temperature conditions

Results of the study will be used to help tailor existing guidelines for bioswales and PICPs to better suit local climate, soil and geologic conditions.

The next chapter of this report sets a context for the study through a review of international literature on permeable pavements and bioretention swales. Chapter 3 describes the study site and provides design details on the technologies and experimental set-up. Chapter 4 outlines the overall study approach, including the runoff streams to be measured and sampled, the frequency of sampling and the laboratory and data analysis methodologies. Monitoring results are presented and discussed in Chapter 5, followed by conclusions and recommendations in Chapter 6.

2.0 LITERATURE REVIEW

2.1 Permeable Pavement

2.1.1 Types of Permeable Pavement

The term permeable pavement is a general term used to describe pavements that allow stormwater to infiltrate into a gravel-filled reservoir (hereafter referred to as base course) below the pavement surface. This reservoir provides temporary storage of stormwater before it infiltrates into the subsoil or is drained away by perforated pipes (CWP, 2000). While all varieties of permeable pavements are designed to reduce surface runoff volumes, permeable pavement designs can differ significantly. Three main categories of permeable pavement are commonly used:

- Permeable interlocking concrete pavement (PICP)
- Concrete or plastic lattice or grid systems
- Porous asphalt or pervious concrete

PICP consists of impervious concrete blocks that allow water to infiltrate into the base course through gravel-filled voids within or between the pavers. Grid systems consist of plastic or concrete interlocking units with very little impervious surface area. Grid spaces may be planted with grass or left unplanted and filled with gravel. The grids are designed to provide structural stability and prevent settling while providing a large amount of void space for infiltration of stormwater. Porous asphalt pavement consists of standard bituminous asphalt in which the finer aggregates have been removed. Removal of these fine materials results in an asphalt with a matrix of pores that allows water to permeate through to the base course and infiltration bed. Pervious concrete works on the same principle as porous asphalt with the finer aggregates omitted from the concrete mix resulting in increased void space.

The following review of permeable pavement literature is largely limited to studies associated with PICPs, as this is the type of pavement evaluated in this study.

2.1.2 Performance

2.1.2.1 <u>Surface Runoff Reduction</u>

Permeable pavements help preserve natural hydrologic functions by infiltrating stormwater runoff and promoting groundwater recharge. Several field studies have quantified the runoff reduction benefit of permeable pavements. At a Public Works parking lot in Renton, Washington, Booth and Leavitt (1999) reported virtually no surface runoff from planted (*i.e.* turfstone) and unplanted concrete grid pavements for all rain events monitored during the autumn and early winter of 1996/97. Runoff remained low in a repeat study conducted at the same site four years later. Among the 15 storms monitored in the second study, only one 44 mm rain event generated runoff, representing a mere 3% of the total precipitation (Brattebo and Booth, 2003). In both studies, the subsurface flows occurred after a significant delay even though the flow path through the underlying soil was less than 10 cm (Brattebo and Booth, 2003; Booth and Leavitt, 1999).

In North Carolina, Collins et al. (2006) reported similar results in an ongoing investigation of the hydrologic and water quality performance of four permeable pavements relative to an asphalt control. The plots in this study consisted of two types of interlocking concrete pavers, concrete grid pavers and pervious concrete. All were underlain by a 10 cm bedding layer and 23 to 25 cm stone gravel storage layer with a perforated underdrain placed in the base. The native soils were sandy loam underlain by clay loam. At the time of writing, eight events had been monitored in the spring of 2006 ranging in size from 4 to 27 mm. Surface runoff from the interlocking pavers and porous concrete was generally less than 5% of total rainfall. The grid paver produced more surface runoff than the other pavements, likely because sand in the bedding layer limited infiltration. Peak flows from the permeable pavement underdrains were also shown to be between 72 and 88% less than the conventional asphalt control.

Field research led by William James at the University of Guelph in Ontario has focused on investigating the performance of permeable interlocking concrete pavers in comparison to other traditional pavements such as impervious asphalt and concrete. Outdoor experiments conducted by James and his graduate students indicated that this type of permeable pavement provides a 90% reduction in surface runoff volume compared to traditional impervious pavements (James, 2002).

There is a paucity of studies on permeable pavements installed over fine grained soils, as many stormwater BMP manuals (*e.g.* EPA, 1999; OMOE, 2003) do not consider them suitable for these soil types. In Georgia, Dreelin et al. (2006) tested the effectiveness of a grassed, plastic grid pavement with a sand bedding layer, 25 cm gravel base and perforated underdrain constructed over soils with a clay content of 35 to 60%. Although the native soils were clay based, infiltration rates were good, ranging from 4.8 to 16.7 cm/h. During nine rain events between 0.3 and 18.5 mm, total runoff from the grid pavers was 93% less than from a nearby conventional asphalt pavement.

Runoff volumes are reduced in permeable pavement systems even when runoff is prevented from infiltrating into the subgrade by an impermeable membrane, as is common in areas where the native soils below the base course layer have low permeability. In the UK, Anderson et al. (1999) examined rainfall, runoff and evaporation from permeable pavers with different bedding materials (25 to 50 mm deep) on a full scale model car park underlain by a drainage collection system. The researchers found that, for a one-hour duration 15 mm simulated rainfall event, an average of 55% and 30% of rainfall was retained when the structure was initially air dried and wet, respectively. Daily evaporation rates from a fully drained structure averaged approximately 20% that of an open water evaporation pan, with fine bedding materials producing the highest rates of evaporation. Higher evaporation rates would be expected under field conditions where water is stored in the base course layer for 24 to 48 hours after a rain event.

Allowing rainfall to infiltrate into the subsoil rather than run off over the surface helps to recharge groundwater. Depending upon site design and subsoil type, permeable pavement may allow as much as 70-80% of rainfall to recharge groundwater (Gburek and Urban, 1980). In theory, the increase in recharge should enhance groundwater discharge to streams. However, this effect has not been quantified because most field studies of permeable pavement are conducted on relatively small areas and seepage rates into streams are notoriously difficult to estimate with a high degree of accuracy.

During the winter, water will continue to infiltrate as temperatures permit, but at a slower rate. In a laboratory investigation of porous asphalt in Sweden, Backstrom and Bergstrom (2000) reported a 50% reduction in surface infiltration rates as temperatures declined from 20°C to 0°C. When the pavement was subjected to alternate freezing and melting over two days, the infiltration rate fell to 90% of the rate observed at 20°C. Even at this rate, however, the pavement still infiltrated at a rate of between 1 and 5 mm/min, which is similar to that of a relatively well drained agricultural soil.

2.1.2.2 Clogging

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

Clogging has been a serious issue in some of the early permeable pavement installations. Lindsey et al (1992) surveyed several infiltration facilities in Maryland, including 13 'porous pavement' installations, most of which were between 5 and 6 years old. Their survey found that only 2 of the 13 pavements were operating according to design, mostly due to sediment clogging. The authors did not provide details on the type of porous pavement (*e.g.* interlocking pavers, porous asphalt) or materials used in construction; hence it was difficult to evaluate the reasons for failure. Many of the early permeable pavement installations in Ontario and elsewhere were constructed with sand as a bedding layer and surface joint filler. Garden and grassed areas around the perimeter often drained onto the pavement, rather than away from it. These conditions tended to increase the potential for clogging.

More recent installations use washed stone in the pavement openings and bedding layer because these resist breakdown into smaller particles with age, and the pore spaces are large enough to transmit fine particulate matter into the base course layers, thereby reducing the potential for surface sealing. At the Guelph University experimental plots referred to earlier, Gerrits (2001) reported considerably better infiltration on 8 year old permeable pavers constructed with a bedding layer of 7.5 cm of clear washed stone than those with a 10 cm mixture of clear washed stone and sand (both installations used 40 cm of granular 'A' as the sub-base). The pure washed stone bedding layer installation also responded much more effectively to maintenance efforts directed at restoring the original surface infiltration capacity (see section 2.1.4). These results are consistent with laboratory tests of various interlocking pavement surface drainage materials (e.g. sand, gravels) that have shown uniform sized washed gravel (2 – 5 mm) to provide the best infiltration capacities (Shackel, 1995).

Bean *et al.* (2007) examined surface infiltration rates on concrete grid pavement (n = 16) and PICPs (n = 11) located in Maryland and North Carolina. The pavements ranged in age from six months to 20 years. The concrete grid pavers had much lower infiltration rates (average 6.9 cm/h) than the interlocking pavers (average 2000 cm/h). Infiltration tests conducted on the original condition of the pavement and after removal of the 13 to 19 mm of surface residue indicated a 60% increase in permeability. Location of PICPs close to sources of fine sediment (*e.g.* beach, construction site, river bed) was found to dramatically reduce surface infiltration rates, although even these sites had infiltration rates comparable to a grassed sandy loam soil.

2.1.2.3 Surface Water, Soil and Groundwater Quality

Stormwater infiltration technologies help improve the quality of urban stormwater by allowing water to percolate through the subsurface media and trap or break down contaminants through filtration, adsorption, microbial decomposition and other chemical and biological reactions within the soil (Pitt *et al.*, 1996). The capacity of permeable pavements to improve the quality of infiltrated water depends on several factors, particularly the chemical characteristics of water entering the pavement and the texture, permeability and organic content of the underlying soils. All else remaining the same, dirtier water infiltrated through very porous soils with low fractions of organic content and low sorption capacities will tend to pose a higher risk to groundwater than if the opposite were true (Pitt *et al.*, 1996). Karst soils and other fractured geologic media that allow stormwater to pass rapidly through the unsaturated zone to the water table are considered unsuitable for stormwater infiltration.

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

Several studies have indicated that soils and granular media can retain heavy metals in urban runoff, thereby preventing transport to lower soil horizons and groundwater. In the Washington study discussed earlier (Brattebo and Booth, 2003), stormwater concentrations of copper, zinc and motor oil were significantly improved through infiltration via a PICP installation that received constant traffic over a period of 6 years. The researchers reported that 88 and 100% of asphalt runoff samples exceeded Washington receiving water standards for zinc and copper, respectively. By contrast, only 6 and 17% of PICP infiltrate samples (n=18) exceeded the standards for copper and zinc, and motor oil was consistently below analytical detection limits, even though the soil through which water infiltrated was only 10 cm deep. A study conducted at Guelph University in Ontario reported similar water quality improvements, especially for zinc and iron, after infiltration of stormwater through permeable pavers and a shallow base course (Shahin, 1994).

On porous asphalts, pollutants accumulate mainly within the surface pores and, to a lesser extent, on the geotextile layer separating the base course layer from the underlying native soil (Legret *et al*., 1996). Copper, lead, zinc, and cadmium are retained near the surface in association with clogging particles (Legret *et al*., 1999). Sampling of water percolating through a porous asphalt pavement in Rhode Island, New York also showed good removal of PAHs within the base course (Boving *et al*., 2006). In the Rhode Island study, dissolved nutrients (PO_4, NO_3) from wind blown dust and atmospheric deposition were less effectively attenuated. In North Carolina, Bean *et al.* (2007) compared water that had filtered through a 275 mm open graded PICP base with conventional asphalt runoff. They reported significantly lower PICP infiltrate concentrations of zinc, total phosphorus, ammonia and TKN, but no significant differences in total nitrogen, nitrates, dissolved phosphorus, TSS and copper.

Further evidence demonstrating the capacity of soils to mechanically filter, biodegrade and retain urban runoff contaminants through physicochemical processes is documented in studies of infiltration basins and road side ditches or trenches. Runoff entering these systems originates from large drainage areas, often with multiple land uses. Hence, infiltrated water contains both a larger mass and more diverse range of contaminants than is characteristic of infiltrated water on permeable pavements. Despite high loading rates, however, studies of these systems show that attenuation of contaminants occurs predominantly within the upper soil layer beneath the base of the systems. In France, for instance, Barraud *et al.* (2005) reported that soil contamination (metals, PAHs, hydrocarbons, nutrients) in 4 infiltration basins ranging in age between 2 and 21 years was limited to less than 50 cm below the surface. Investigations of lead, zinc and copper in 12 urban runoff retention basins in California showed soil contamination to a depth of only 15 cm (Nightingale, 1975). In the same county, Salo *et al.* (1986) reported sharp declines in soil concentrations of lead, arsenic, nickel, and copper in the first 1 m below five groundwater recharge basins, two of which had been in operation for more than 20 years at the time of the study. Several organic compounds were monitored in this study both in the soil and groundwater, including chlorinated pesticides, organo-phosphorus pesticides, chlorophenoxy herbicides and phenolic compounds. Examination of these samples revealed no adverse effects on groundwater as a result of infiltrating stormwater. Citing several studies of infiltration systems conducted in western European countries, Mikkelsen *et al.* (1994) reached a similar conclusion about the potential for groundwater contamination associated with stormwater infiltration.

A German study investigating the impacts of highway runoff on roadside soils concluded that the age of roadside soils was positively correlated with the concentrations of polycyclic aromatic hydrocarbons and several heavy metals. Leaching of contaminants to the groundwater was limited, however, even for soil ages greater than 20 years. Soil characteristics such as organic content and pH were found to be important factors controlling the buffering capacity of the soils (Dierkes and Geiger, 1999). Studies that have shown groundwater impacts from organic compounds are typically from industrial source areas (*e.g.* dry cleaners) where the chemical signature of runoff is somewhat unique among urban land use types (Clark and Pitt, 2007).

2.1.2.4 Structural Integrity

Permeable pavements present special challenges to pavement designers because, unlike conventional impermeable pavements, they allow water to saturate the base course which can adversely affect structural integrity, especially under heavy loads and winter freeze-thaw conditions. The pavement design factors that affect structural performance include the paver shape, size and orientation of jointing, the thickness and type of materials used in the bedding and sub-base layers, as well as the type of edging used. Designed and installed appropriately, permeable interlocking concrete pavers have been shown to remain structurally sound under a range of loading and climatic conditions (Ferguson, 2005; Shackel, 2006).

Extensive testing of bedding and jointing materials has shown that a clean 2 to 5 mm aggregate both for the bedding and jointing provides the best compromise between permeability and structural performance

(Shackel, 2006). As noted above in section 2.1.2.2, sand is generally not acceptable when infiltration of surface runoff is a primary goal because fine textured media has a lower initial infiltration rate and will clog more quickly than coarse textured media as the pavement ages.

The base course layer typically consists of an open graded base comprised of unbound granular materials. Laboratory testing has shown that permeability is enhanced when fines are removed, but structural capacity is compromised (Shackel, 2006). As with the bedding layer, the selection of base course gradations must strike a balance between the two objectives of structural capacity and permeability. Thicker base course layers distribute traffic loads more broadly onto the subgrade and can provide additional structural capacity in designs with fines removed or where subgrade soils have a low bearing capacity (Ferguson, 2005). Compaction of base layers also improves load bearing capacity, especially in open grade bases that have relatively low cohesion (Huurman and Boomsma, 2006).

Freezing of water in the subgrade can cause heaving of the pavement surface as the expanding ice crystals exert pressure on the overlying structure. When the ice thaws, the pressure is released and melting water suspends soil particles leaving the pavement susceptible to slumping or deformation. Freezing of the subgrade beneath permeable pavements may occur in the Toronto area because the frost line lies at roughly 1.2 m below the surface.

Frost damage to the pavement can be prevented by constructing a thicker base course than would be specified in areas with warmer climates (Ferguson, 2005). The U.S. Federal Aviation Administration (1995, as cited in Ferguson, 2005) standards suggest that the upper 65% of the 10-year frost penetration depth should be constructed of granular materials that are not susceptible to frost damage. However, several permeable pavements on frost susceptible subgrade soils (*i.e.* clays and silts) in the GTA have thinner base courses but do not show signs of deformation, suggesting that this standard may be too conservative.

Backstrom (2000) monitored winter temperatures of a porous asphalt and conventional asphalt in a residential area of Lulea, Sweden. The porous asphalt base (1.6 to 8 cm) was drained with a pervious pipe and was installed on silty moraine soils with high clay content. The two pavements were found to freeze in much the same way. However, mid winter temperatures of the subgrade beneath the conventional asphalt was lower and the pavement thawed in the spring 3 to 4 weeks after the porous asphalt. The maximum depth of frost penetration tended to be slightly greater beneath the conventional asphalt, and frost heave of the impermeable asphalt during the colder of the two winters (minimum temperature of approximately -25°C) was more pronounced (Table 2.1).

The shallower frost penetration beneath the porous asphalt was attributed to the heat insulating effect of air in the porous pavement and moisture in the base course, which increases the latent heat available. The porous asphalt surface thawed earlier because infiltration of melting snow and ice helped to warm the underlying base course and the snow free surface allowed solar radiation to be absorbed by the black surface earlier than the conventional asphalt. More rapid infiltration of melt water has the additional benefit of reducing the potential for slip hazards as there is less water on the surface that can freeze during cold nights. Backstrom (2000) concluded from these data that porous pavement is more resistant to freezing and has a lower risk of frost heave damage relative to conventional impervious pavements.

Table 2.1: Frost heave and frost penetration depths below a porous asphalt and conventional asphalt in Lulea, Sweden (Backstrom, 2000)

Season	Porous Asphalt		Conventional Asphalt	
	Frost heave (cm)	Maximum frost penetration (m)	Frost heave (cm)	Maximum frost penetration (m)
1994/95	1.9	1.1	1 - 2	1.1
1995/96	1 - 2	1.4	7 - 8	1.6

2.1.2.5 Heat Flux

Permeable pavement installations have also been studied as a means of reducing the warming effects of impervious surfaces on ambient air temperature. Types of permeable pavement that allow for greater evapotranspiration (as compared to asphalt or concrete) will reduce the urban heat island effect (Asaeda and Vu Thanh, 2000). A Japanese study investigating the thermal characteristics of permeable and impermeable pavements concluded that unplanted PICP did not perform better than asphalt in terms of radiative heating of the thermal environment due to similar rates of evaporation (Asaeda and Vu Thanh, 2000).

To provide cooler surface temperatures, researchers in Japan have developed PICPs that provide better retention of moisture than traditional pavers. Research on several varieties of these pavements has showed cooling effects of between 2 and 6 °C relative to conventional dense graded asphalt. Lighter coloured pavers with higher solar reflectance indices were also found to reduce surface temperatures (Karasawa et al., 2006).

2.1.3 Site Selection Criteria

There are several factors to be considered in determining whether or not a site is suitable for a permeable pavement installation. One of the most important from a groundwater contamination perspective relates to the quality of runoff to be infiltrated. Areas prone to spills such as gas stations, recycling facilities or loading docks, for instance, are not recommended for permeable pavements (CWP, 1997). Roads that may be subject to heavy tracking of soils from construction sites or work yards would also not be suitable.

The depth to the water table at a prospective site is an important consideration in preventing groundwater contamination below a permeable pavement installation. The recommended minimum distance between the bottom of an infiltration installation and the seasonally high groundwater table is typically between 0.6 and 1.5 m (CWP, 2000). Prospective sites should also be located a safe distance from any drinking water supply wells. A distance of 30 meters is recommended (CWP, 1997), but in areas with steep hydraulic gradients or high conductivity soils, a larger buffer zone around the well may be warranted.

Soil characteristics and topography help ensure proper drainage. A suitable permeable pavement site should have soils with a clay content of less than 30%, a silt/clay content of less than 40%, and a percolation rate of more than 1.3 cm per hour (CWP, 2000). Perforated underdrains may be needed to ensure water is drained from the base course over a reasonable time period (typically 24 to 28 hours). Areas with cracked soils or karst topography that allow contaminants to move rapidly through the vadose zone into the groundwater would not be suitable. Slopes should be less than 15% in order to ensure adequate drainage and to prevent erosion of the aggregate materials in the void spaces (SCDEP, 2004).

Clogging of void spaces can impair the long-term function of a permeable pavement installation. Clogging may occur during construction, or as a result of sand application for vehicle safety during winter months (CWP, 1997). Permeable pavement is not recommended for areas where elevated loads of sand and dirt from vehicles may cause premature clogging of surface voids (Tan *et al*., 2003).

2.1.4 Operation and Maintenance Considerations

Clogging of surface voids and loss of permeability over time can be minimized through regular maintenance and appropriate design of the pavement. Table 2.2 lists recommendations from various sources regarding the type and frequency of maintenance required for permeable pavements. Most sources recommend vacuum sweeping over power washing as the latter pushes sediments into the pavement rather than removing them. The frequency of vacuuming will vary depending on site conditions but once or twice a year is generally regarded as sufficient. If aggregate in the pavement openings is suctioned out, these will need to be replaced. More substantial maintenance involving removal of pavers may be required to restore permeability if regular maintenance is not conducted on a routine basis. Replacement of the pavement and/or base course will vary depending on use, but when the pavements are properly constructed and installed, replacement is generally not required before 20 to 25 years (Smith, 2006).

Table 2.2: Permeable pavement recommended maintenance

Source	Site inspections	Ensuring drainage between storm events	Vacuum Sweeping of pavement	Check Pavement for deterioration	Replace base and/or pavement
CWP, 1997	Monthly	monthly	3-4x per year	1x per year	not specified
Smith, 2006 (Interlocking Concrete Paving Institute)	Routinely	routinely through use of observation well in base course	at least 1-2x per year	not specified	pavement should provide 20-25 years of service
Lake County Forest Preserves, 2003	not specified	not specified	2x per year	not specified	base - once every 25 years
California Stormwater Quality Association, 2003	not specified	not specified	2-3x per year	not specified	as needed (max 15-20 yrs)
Urban Drainage and Flood Control District, 2004	routinely (as needed)	routinely	1x per year	not specified	10-25 years depending upon traffic

The effectiveness of maintenance has been the subject of a few studies. Gerrits (2001) simulated the effect of vacuum maintenance by removing incremental quantities of void space material up to 2.5 cm in depth and measuring the infiltration rate. The tests were performed in the parking stalls, between the stalls and driving lane, and in the main driving lane that received the greatest amount of traffic and heaviest loads. Pavements constructed with bedding layers of clear washed stone (7.5 cm) and mixed stone and sand (10 cm) were examined. As shown in Figure 2.1, infiltration capacity on the pavement constructed with a granular bedding layer was substantially improved with removal of between 2 and 3 cm of void space material. Including sand in the bedding layer appeared to have the effect of both inhibiting infiltration and reducing the effectiveness of maintenance, especially in the medium traffic area. On both pavements, the high traffic driving lane improved only slightly because of greater accumulation of fine particulate matter and the effects of compaction. The driving lane was the low point in the drainage area and was subject to heavy loads during construction of a nearby building a couple of years earlier.

In Maryland and North Carolina, Bean *et al.* (2007) simulated maintenance of permeable pavements using an approach similar to Gerrits (2001). Of the 14 concrete grid paver sites tested, 13 exhibited notably higher infiltration rates than the pavers that had not undergone maintenance. The mean infiltration rate increased by 66%. The surface infiltration rate also increased substantially on the one interlocking concrete paver site subjected to maintenance.

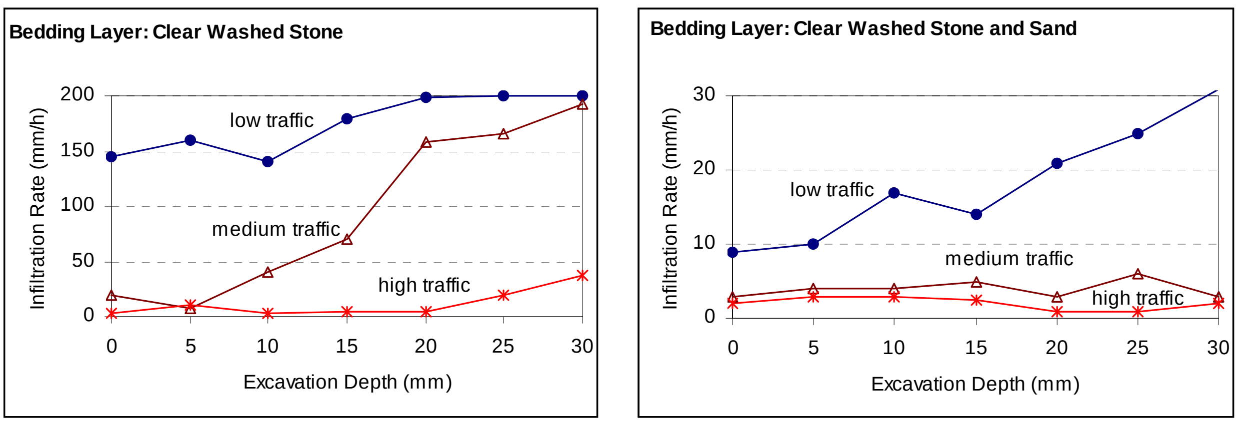


Figure 2.1: Infiltration rates on two 8 year old un-maintained permeable pavements after removal of void space material of varying depths. The bedding layers of one permeable pavement contained sand (right), the bedding layer of the other did not. Bedding layers beneath both pavements were underlain by a 40 cm sub-base of granular 'A'. Note differences in vertical scales. Source: Gerrits, 2001.

2.1.5 Cost Considerations

The installed capital cost of permeable interlocking pavers will vary on a site-by-site basis, but local industry sources indicate that the cost of traditional impervious asphalt is roughly 60% that of permeable pavers. The Lake County Forest Preserves in Illinois estimates a similar installed cost ratio (0.66) for a 40,000 square foot area. This cost differential is offset by the longer life of permeable pavements and the reduced need for stormwater conveyance and treatment infrastructure (Ferguson, 2005). A survey conducted by the Lake County Forest Preserves reported that two permeable pavement sites in Pennsylvania lasted as long, or longer than impervious asphalt. (Lake County Forest Preserves, 2003). If permeable pavements are used for stormwater detention, significant savings can be achieved by reducing the amount of piping and downgrading the size of end-of-pipe facilities (James, 2004). These savings, however, are contingent upon a local regulatory framework that allows for the use of permeable pavements and other infiltration practices to meet stormwater detention requirements.

Maintenance costs for permeable pavement installations will generally be higher than for conventional asphalt because, as mentioned previously, the pavements need to be routinely cleaned to avoid clogging. However, when impervious asphalt cracks or pits, expensive sealing and patching procedures may be required. By comparison, damaged stones on permeable pavement are much easier to replace (Lake County Forest Preserves, 2003). An overall comparison of maintenance costs must be conducted on a site-by-site basis due to the many variables that influence costs.

Permeable pavement may provide significant advantages for developments attempting to achieve certification under the *Leadership in Energy and Environmental Design* (LEED) rating system. Developments are certified under LEED based on meeting the requirements of a number of credits intended to promote energy and resource conservation, among other objectives. A minimum of 26 credits is required for a development to be certified as ‘sustainable’, and the top rating of ‘platinum’ requires 52 or more credits. Permeable pavements can qualify for up to 14 points under the general credit categories of *Sustainable Sites, Materials and Resources,* and *Innovation and Design Process* (Burak and Smith, 2006).

2.2 Bioretention Swales

A bioretention swale (or bioswale) is a stormwater best management practice that treats stormwater runoff from an impervious area by using soil, mulch and woody or herbaceous plants to enhance removal of contaminants through various physical and biological processes (USEPA, 1999). The swale forms a depression in the land surface and contains a permeable constructed subsoil planted with vegetation that is tolerant of a wide range of moisture conditions. Considerable volumes of drainage from adjacent impervious areas are temporarily stored on the surface prior to infiltration, while the excess during large storms overflows to the storm sewer.

2.2.1 Performance

The ability of a bioswale to remove stormwater contaminants may be significantly greater than that of other stormwater infiltration practices due to microbial activity and plant uptake (USEPA, 1999). Studies conducted at the University of Maryland found that bioswales are capable of removing 93-98% heavy metals, 70-83% of phosphorus and 68-80% of total Kjeldahl nitrogen. Most of these contaminants are captured within the first 61 cm (2 feet) of soil (Table 2.3). Like other infiltration BMPs, the water quality benefit of bioswales stem mainly from their capacity to reduce surface runoff volumes through infiltration and evapotranspiration.

Table 2.3: Percent removal of stormwater contaminants in a bioswale by depth (Modified from Davis et al. (1998) in USEPA, 1999)

	Cumulative Percent Removal by Depth							
Depth	**Cu**	**Pb**	**Zn**	**P**	**TKN**	**NH_4**	**NO_3**	**TN**
30 cm	90	93	87	0	37	54	-97	-29
61 cm	93	99	98	73	60	86	-194	0
91 cm	93	99	99	81	68	79	23	43

2.2.2 Site Selection Criteria and Design Considerations

Several aspects of site selection are common to permeable pavement and bioretention installations, such as runoff quality and groundwater contamination considerations. These are discussed in section 2.1.3. Considerations that are unique to a potential bioswale site include drainage area size, slope and the ability to disperse runoff flows so that they are uniformly distributed (Prince George's County Dept. of Environmental Resources, 2002). The Prince George's County Design Manual for Bioretention (2002) and the Metropolitan Council Urban Small Sites BMP Manual (2003) both suggest that bioswales should not be used for sites larger than 0.8 hectares due to increased clogging potential and the limited feasibility of conveying runoff volumes from a large site to the bioswale. For the same reasons, it is also recommended that the drainage area have a maximum slope of 20% (Prince George's County Dept. of Environmental Resources, 2002).

Many older guidelines suggest that the filter media should contain a sand content of between 50 to 75%, with relatively abundant organic matter (see Table 2.4). However, organic matter can contribute to nutrient export if underdrains are present. Based on extensive research in North Carolina, Hunt and Lord (2006) suggest a mix of 85-88% sand, 8-12% soil fines and 3-5% organic matter. The P-index should range from 10 to 30 ppm and the cation exchange capacity of the filter media should be greater than 10. More organic matter and a higher P index would be acceptable in areas where phosphorus release is not a concern, such as where runoff is mostly infiltrated. A mulch of hardwood bark is often placed on top to help prevent surface sealing from rain splash and inflow drainage.

With respect to climate, it is important to consider whether or not the bioswale area will be used for snow storage during the winter in a cold climate area. If this is the case, plants will need to be non-woody and tolerant to salt (Metropolitan Council, 2003). Further siting and design specifications recommended by various sources are summarized in Table 2.4.

2.2.3 Operation and Maintenance Considerations

According to the Prince George's County Department of Environmental Resources Bioretention Manual, the maintenance of a bioswale should involve several common gardening practices such as weeding, irrigating, fertilizing, trimming and overall maintenance of plant health. In circumstances when drainage appears to be comprised (*i.e.* water would pond for longer than guidelines specify), it may be necessary to investigate whether or not clogging is occurring and in which layer. The soil bed should be checked for clogging twice per year (New Jersey Department of Environmental Protection, 2003). Actions to correct clogging in a bioswale may include raking the surface, punching holes through the soil bed, or re-installing the entire bioswale as a last resort (Prince George's County Dept. of Environmental Resources, 2002).

Table 2.4: Design guidelines recommended by government agencies

Source	Unit Area Bioswale needed per unit drainage area	Max. ponding depth	Max. drainage time	Vegetation type	Characteristics of ground cover/mulch	Planting Soil Characteristics				
						Infiltration Rate	Composition	Layer Thickness	Sand Layer characteristics	Depth to water table
USEPA, 1999	• 5-7% of drainage area multiplied by runoff coefficient • Drainage area should be 0.1-0.4 ha • Min. size: 4.6x 12.2 m	15 cm	4 days	• Tolerant native • Dominated by understory trees with discrete soil zones, a mature canopy, and a distinct sub-canopy of understory trees, a shrub layer, and herbaceous ground cover • 1000 trees & shrubs per acre	• 5.0 - 7.6 cm of fine shredded hardwood mulch or shredded hardwood chips • aged at least 6 months	>1.25 cm/hr	• Sandy loam, loamy sand or loam texture • 10-25% clay content, 1.5 - 3% organic content, <500ppm soluble salts. • pH: 5.5 - 6.5	1.2 m	–	–
New Jersey Dept. of Environmental Protection, 2003	–	46 cm	3 days	• Native plant material when possible • Perimeter: trees • Inner saturated areas: shrubs and herbaceous specie • Density: 1000 stems per acre	• 5-10 cm shredded hardwood or chips	sufficient to fully drain the stormwater quality design storm runoff volume within 72 hours	• 10-15% clays, 65% sands, 20-25% silt • pH: 5.5 - 6.6	0.9 m	• Thickness: 30 cm • Medium aggregate concrete sand • 2x permeability of design permeability rate of planting soil	>0.3 m to seasonal high water table
Metropolitan Council, 2003	• 5 - 10% of impervious drainage area	15 - 23 cm	–	• Should replicate a forested or grassland ecosystem and withstand stresses (i.e. frequent inundation and inter-event drying	–	–	–	1.2 m	• Thickness: 30 cm	0.9 m
Prince George's County Dept. of Environmental Resources, 2002	• Calculated on a site-specific basis	15 cm	2 days	• Hardy, perennial, native plant specie • Site-specific - must be determined based on the need for tolerance of various stressors (i.e. fluctuations in soil moisture, ponding, contaminant loads)	• shredded hardwood aged at least one year	1.27 cm/hr	• 50-60% sand, 20-30% leaf compost, 2-30% topsoil • pH: 5.5 - 6.5 • 1.5-3% organic content	0.8 - 1.2 m	• Thickness: 30 cm • sand with grain size of 0.05 - 0.10 cm	0.6 m

Over the long-term it may also become necessary to address soil contamination concerns that are common to stormwater infiltration practices by, for instance, excavating and replacing the soil. There are several studies that address the migration of contaminants in soils below a stormwater infiltration installation. Some of this research is discussed in section 2.1.2.3. While accumulation of contaminants should be expected in swales or beneath permeable pavements, the eventual disposal of soils would not likely be subject to special requirements. In California, Barrett *et al*. (2005) sampled soils in vegetated road side ditches along highways that had been infiltrating road runoff over many years. Results showed that even maximum leachate concentrations of 7 heavy metals were between 2 and 3 orders of magnitude less than the threshold designation level for hazardous waste.

2.2.4 Cost Considerations

The cost of installing a bioswale will depend on various factors including the bioswale size, vegetation types used and whether or not the construction will be a retrofit or a new installation (USEPA, 1999). Retrofitting will increase the construction costs due to the need for demolition of existing structures and pavements (USEPA, 1999). Implementing bioretention near the source of stormwater runoff has the potential to significantly minimize the amount of storm drainage infrastructure needed. Several case studies from Prince George's County, Maryland have found that integrating bioretention facilities at a site may ultimately reduce development costs by 15-20% in comparison with costs associated with more traditional stormwater BMPs (Prince George's County Dept. of Environmental Resources, 2002).

3.0 STUDY SITES

The permeable interlocking concrete pavement (PICP) and bioretention swale evaluated in this study were installed on a parking lot at Seneca College's King Campus. Surveys of several older permeable pavement and bioswale sites in the Greater Golden Horseshoe were also conducted to assess the effect that age may have on various aspects of the two infiltration practices.

3.1 Seneca College Site

The campus is located at the north-west corner of Dufferin Street and 15th Sideroad in the Township of King, within the Oak Ridges Moraine (ORM) complex (Figures 3.1 and 3.2). The area drains to a tributary of the East Humber River.

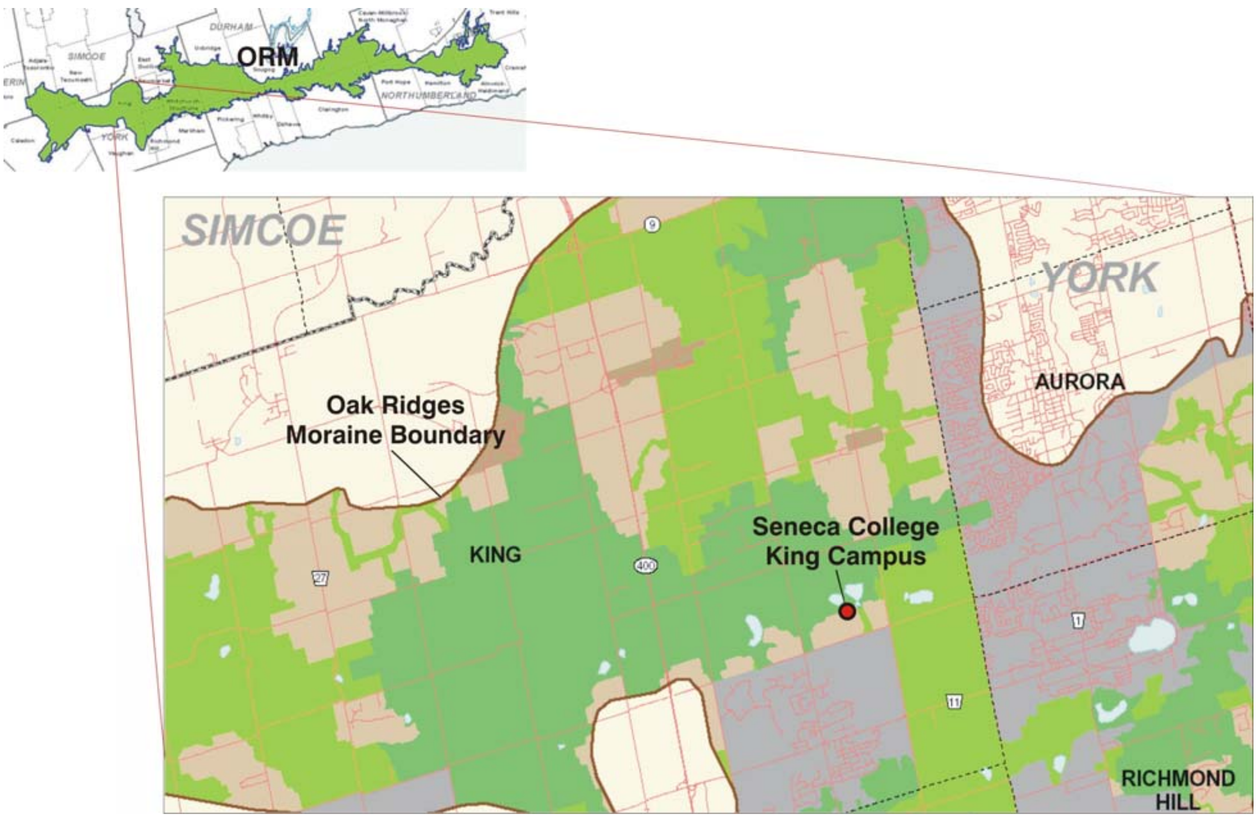


Figure 3.1: Seneca College's King Campus in the Township of King within the Oak Ridges Moraine complex

Figure 3.2: Study site at Seneca College, King Campus

The parking lot at Seneca College was considered to be suitable for the study of these infiltration practices for the following reasons:

(i) The existing parking lot at Seneca College was constructed without a storm sewer network. Instead, runoff drains as sheet flow to the perimeter of the parking lot, and then across a large vegetated area between the parking lot and the receiving water body. Permeable parking lots and bioretention swales are ideally suited to such drainage systems.

(ii) The soils beneath the parking lot have infiltration rates comparable to those of many other areas of the GTA, and the local groundwater table is more than 3 m below the ground surface. Permeameter testing in July 2004, prior to reconstruction of the parking lot, indicated that the field saturated hydraulic conductivity (K_{fs}) of clay loam soils was in the order of 10^{-4} to 10^{-5} cm/s. This is at the low end of the recommended range for these types of infiltration practices (OMOE, 2003). Demonstrating the practices on less permeable soils allows for assessment of the technologies at the limit of their potential effectiveness. It also permits evaluation of whether or not the existing soil permeability guideline for these practices is too conservative.

(iii) As the parking area is associated with Seneca College, there is the potential for the site to be used for educational purposes in environmental science and engineering courses.

3.2 Other Permeable Pavement and Swale Sites

In addition to the Seneca site, a number of older permeable pavement and swales were also surveyed to assess the effect that age may have on various aspects of the two infiltration practices. A description of each of the sites and the date of installation is provided in Table 3.1. Pictures of the sites are shown in Figures 3.3 and 3.4. The permeable pavement sites were surveyed for structural integrity, infiltration capacity and soil quality. The bioswale and road side ditch surveys were limited to visual assessments of plant condition and soil quality sampling. Sampling methodologies at the older sites are described in chapter 4.

Table 3.1: Older PICP and swale site installation dates and locations

Name	Type	Installation Date	City or Town	Location
Earth Rangers, Kortright Centre for Conservation	PICP	2003	Vaughan	Pine Valley Drive and Rutherford Road
Belfountain Conservation Area	PICP	1990	Belfountain	Mississauga Road and Forks of the Credit Rd
Sunset Beach	PICP	1999	Richmond Hill	New Bayview Avenue and Bethesda Sideroad
Humber College[1]	PICP	2003	Toronto	Highway 27 and Finch Avenue
Humberwood Centre	PICP	1995	Toronto	Highway 427 and Finch Avenue
Jerrett's Funeral Home	PICP	1997	Vaughan	Yonge Street and Highway 7
University of Guelph	PICP	1994	Guelph	Gordon Street and Stone Road East
Royal York Road Area[2]	Roadside Ditch	before 1990	Toronto	Royal York Road and Dundas Street
DeVere Gardens Area	Roadside Ditch	before 1990	Toronto	De Vere Gardens near Yonge Street and Wilson Avenue
TRCA Head Office	Swale/wetland	1997	Toronto	Jane Street and Steeles Avenue West
York University	Bioswale	2002	Toronto	Keele Street and Steeles Avenue West
University of Toronto, Scarborough Campus	Bioswale	2006	Toronto	Morningside Avenue and Ellesmere Road

1. The Humber College interlocking concrete pavers appeared to have open joints but may not have been designed to be permeable. 2. The DeVere Gardens ditch was replaced with a curb and gutter style street 3 months after the site was surveyed.

Belfountain Conservation Area (17 years)

Earth Rangers, Kortright Conservation (4 years)

Jerrett's Funeral Home (10 years)

Guelph University (13 years)

Sunset Beach (8 years)

Humberwood (12 years)

Humber College (4 years)

Figure 3.3: Older PICP sites and age at time of sampling

York University (6 years)

University of Toronto (2 years)

TRCA Head Office (11 years)

Royal York Road area (>18 years)

DeVere Gardens area (>18 years)

Figure 3.4: Older swale/road side ditch sites and age at time of sampling

4.0 STUDY APPROACH

4.1 Site Design and Construction

For the purposes of research, the parking lot was divided into three equal areas. On one area, the asphalt was removed and resurfaced using PICP (Unilock® interlocking pavers). On a second area, a bio-retention swale was constructed at the drainage edge of the asphalt to treat runoff from the existing pavement. The middle area remained unaltered and served as a control area for the study (Figure 4.1).

In order to evaluate the performance of the PICP and bioswale, a comprehensive monitoring program and collection system for both surface and subsurface flow was required. The overall study design is presented in plan view and cross section in Figure 4.1 and 4.2, respectively. Detailed descriptions of the experimental set-up are provided in the following sections.

4.1.1 Permeable Pavement

The PICP portion of the study area was excavated to a depth of more than 1.5 m with a 1.5% grade towards the sampling vault. The excavation was lined with an impermeable geotextile. Three rows of weeping tile, wrapped in filter socks, were placed on top of the liner, and covered with granular material for structural stability (Figure 4.3). The entire excavation was subsequently backfilled to an average depth of 1 m using the native soil. The weeping tile was connected to a porous tank collection system manufactured by Atlantis® (Figure 4.3), which in turn directs the infiltrated water to a sampling vault for quantity and quality monitoring. A similar collection trough (modified Atlantis® tank) was constructed at the edge of the parking area to collect surface runoff from the PICP area during heavy rainfall. This trough also drained to the sampling vault (Figures 4.2 and 4.3).

The backfilled native soil (hereafter referred to as the subgrade) was compacted to approximately 100 % Standard Proctor Maximum Dry Density (SPMDD) in order to provide adequate structural foundation for the parking lot. A geoweb material was then placed over the compacted subgrade soil and covered with 45 cm sub-base course of granular ‘A’, which was also compacted to 97 % SPMDD. The granular ‘A’ material consisted of crushed gravel with particles ranging in size up to 20 mm. A 15 cm bedding course layer composed of finer clear stone was graded and the permeable pavers were installed. The voids between the pavers were subsequently filled with the same bedding material to allow rapid infiltration and for public safety. In addition to providing structural support, the base course (bedding and base granular material) provides active storage of runoff for storms up to the 50 year design storm.

Small paved speed bumps were constructed along the perimeter of each catchment (*i.e.* PICP, bioswale, control) in order to prevent intermixing of runoff. A trough on the conventional asphalt was also installed to assist with drainage into the trough (Figure 4.4).

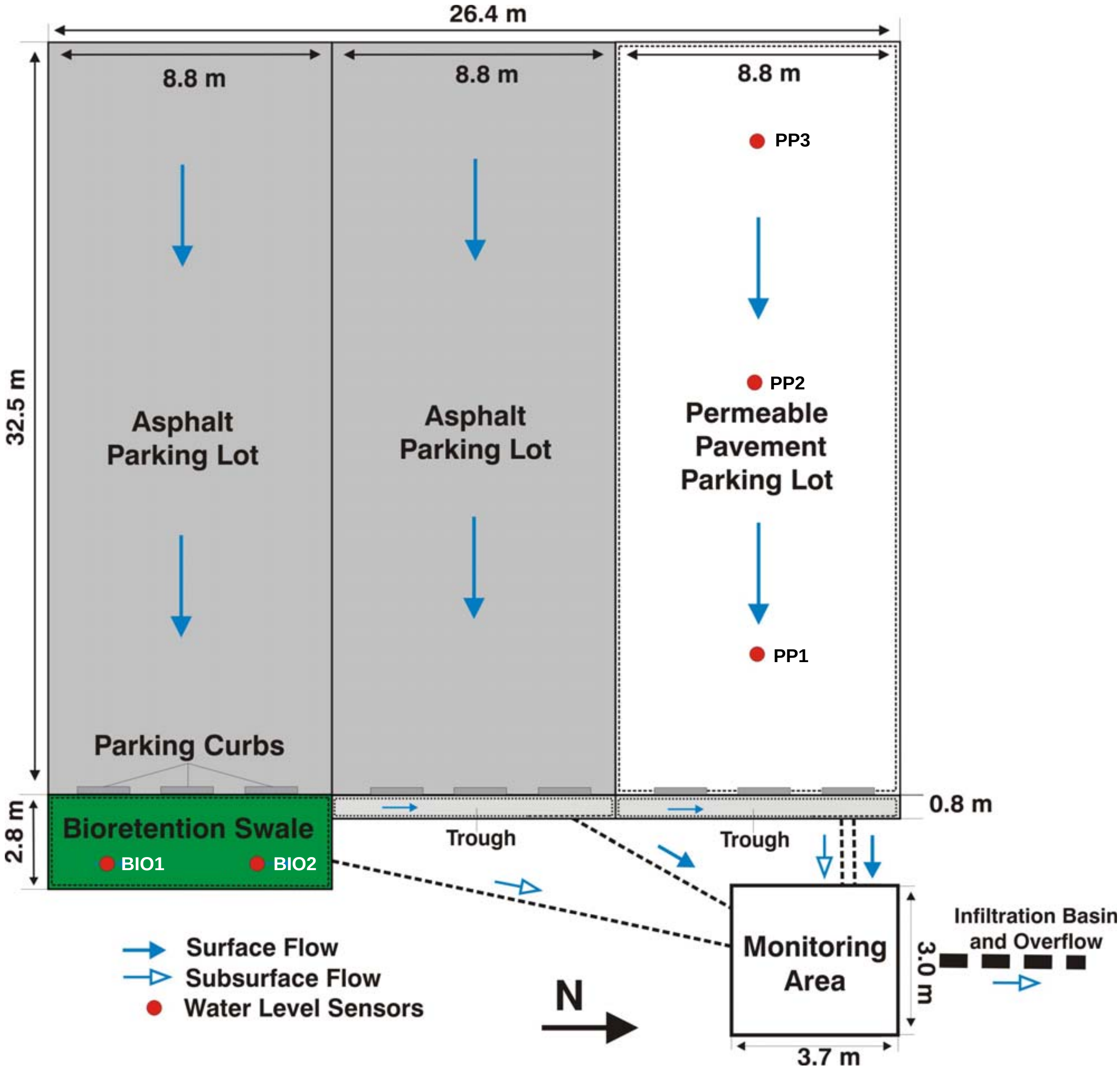


Figure 4.1: Parking lot design, plan view

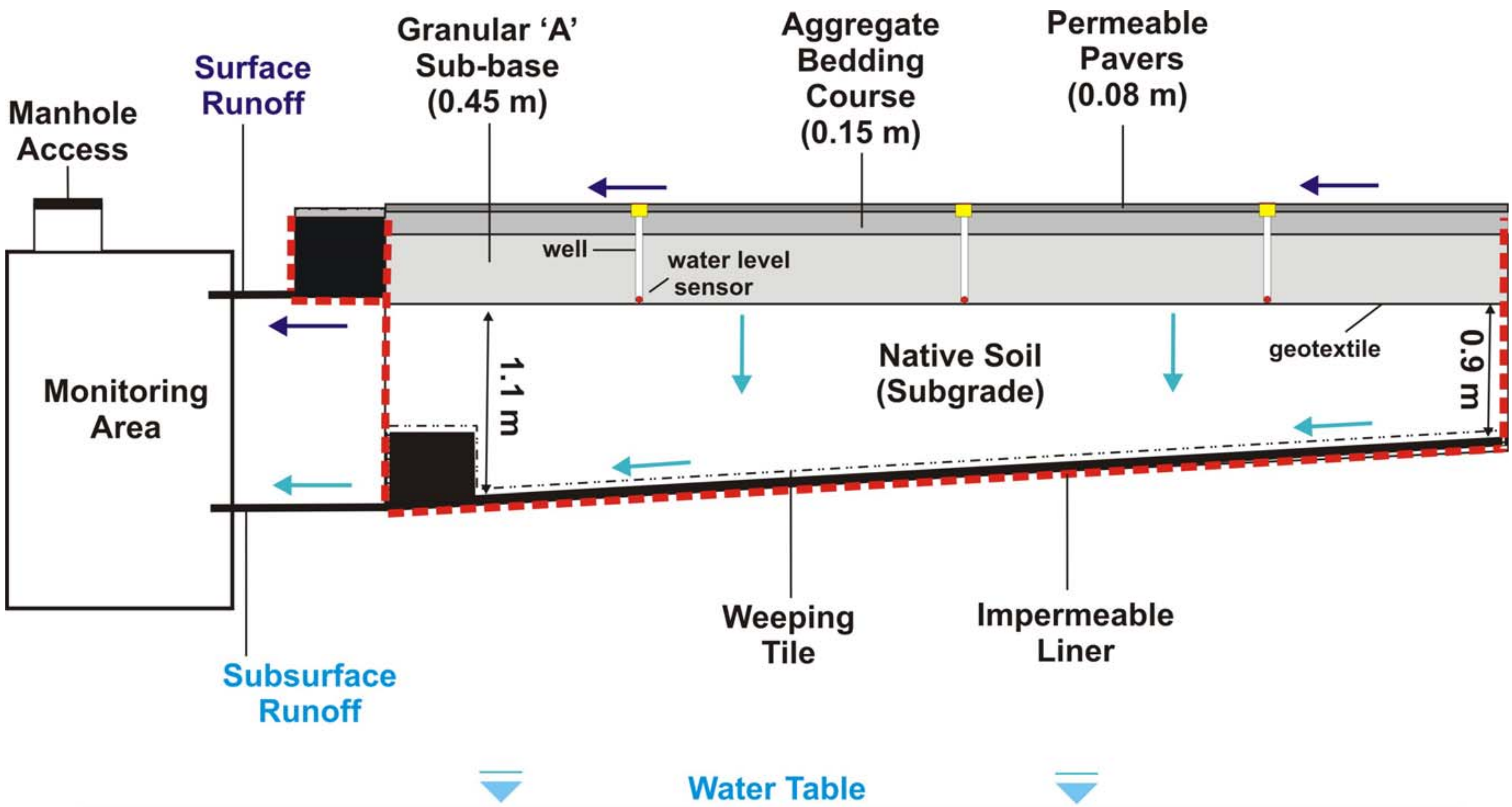


Figure 4.2: PICP design, cross section

Figure 4.3: Installation of the PICP drainage collection system

Figure 4.4: Catchment flow and drainage controls

4.1.2 Bioretention Swale

An area (25 m^2) adjacent to the down-gradient edge of the parking lot (286 m^2) was excavated to approximately 1 m and graded towards the sampling vault. For monitoring purposes, the entire excavation was lined with an impermeable plastic liner and a weeping tile underdrain wrapped with a filter sock was installed at the bottom, and covered with granular (as under the PICP soil). The native soil was replaced with screened 3:1 garden soil, consisting of 42% sand, 50 % silt and 8% clay. A more permeable sandy soil was specified for the layers below the topsoil but a contractor misunderstanding resulted in the omission of this important design element during construction. The bioswale surface was lightly compacted, graded to form a shallow depression for storage, and layered with cedar mulch. The swale was planted with plants that were tolerant of drought and periodic inundation (Figure 4.5). Species included but were not limited to *Andropogan gerardii, Aster puniceus, Aster laevis, Penstemon digitalis, Liatric spicata, Cornus sericea.*

The swale was originally sized to accommodate a ponding volume equivalent to runoff from an 11 mm storm. The depression area is overtopped during events with rainfall greater than the combined ponding volume, soil storage volume and infiltration capacity of the swale. Excess runoff flows towards grass swales by way of pre-construction flow paths and ultimately infiltrates into the ground.

Figure 4.5: Bioswale during dry weather (left) and wet weather (right)

4.1.3 Sampling Vault and Power Supply

The monitoring vault is a 3.0 m x 3.6 m x 1.8 m cement chamber located underground in the north east corner of the study area (Figure 4.6). The vault prevents the automated monitoring equipment from freezing during the winter and protects against vandalism.

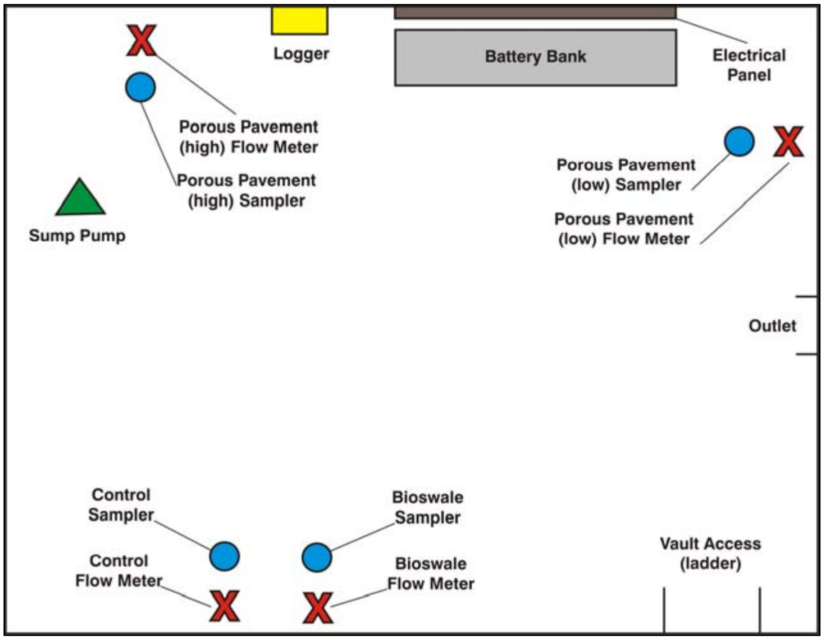


Figure 4.6: Monitoring vault floor plan

Figure 4.7: Power supply system: a) wind turbine and solar panels, b) power supply panel, c) solar panel controller, and d) battery bank.

Power to operate the monitoring equipment is supplied by one 300w Southwest Windpower H40 wind turbine and 3 Sharp solar panels (1 x 165w and 2 x 170w). Designed and built by John Meulendyks of Northpoint Power Center and Seneca College, the wind turbine and solar panels are regulated using two controllers (one for the solar panels and one for the turbine) and an inverter to generate 12, 24, and 120 VDC. A battery bank consisting of 24 VDC is used to store generated energy and has a capacity of 1000 Ah which would provide just over 9 days of system operation with no energy input (Figure 4.7).

4.2. Methods

4.2.1 Water Quantity

4.2.1.1 Rainfall

Rainfall was measured using a 0.2 mm TB3 Hydrological Services tipping bucket raingauge and recorded with an Onset Microstation logger set to record at 5 minute intervals (Figure 4.8). The station was located approximately 4 km away on top of a York Region pump station at Bathurst Street and Jefferson Sideroad in 2005. A tipping bucket raingauge was installed immediately adjacent to the study site in 2006. A second manual gauge installed on site provided back-up measurements in case of sensor malfunction.

Figure 4.8: Rain gauge and logger

4.2.1.2 Flow

Flow rates from surface runoff and infiltrated water were measured using four Endress and Hauser Promag 53W electromagnetic flow metres located in the underground sampling vault. Electromagnetic flow metres operate according to Faraday's principle of electromagnetic induction which states that a conductor (water) moving through an electromagnetic field generates a voltage proportional to its velocity. Proper function of the metres requires that they be continuously submerged in water. This was achieved by installing the meters within reverse slope pipes (Figure 4.9). The sensor was positioned away form the lowest point in the drain and a sediment cleaning valve was installed to avoid risk associated with solids accumulation.

All four flow metres were connected to a single Endress and Hauser Memograph logger. Data were logged continuously and recorded at a 1 minute interval. All flow was directed to a single 12" outlet and into a combined infiltration trench and overflow structure, as discussed above. The meters were checked, cleaned, and calibrated at the beginning of each year.

4.2.1.3 <u>Surface Water Level and Storage</u>

Ponding depths on the bioswale and water level changes in the PICP base course were monitored continuously with five pressure transducers. Two were located in the bioswale and three were located in the PICP base course, as shown in Figure 4.1. These sensors allow for an accurate determination of surface storage during rain events and indicate the time at which surface overflow occurs. The sensors were also equipped with temperature monitors, which indicated when water at the measurement point was above or below freezing in the winter. Monitoring of surface and base course water levels began in the spring of 2006.

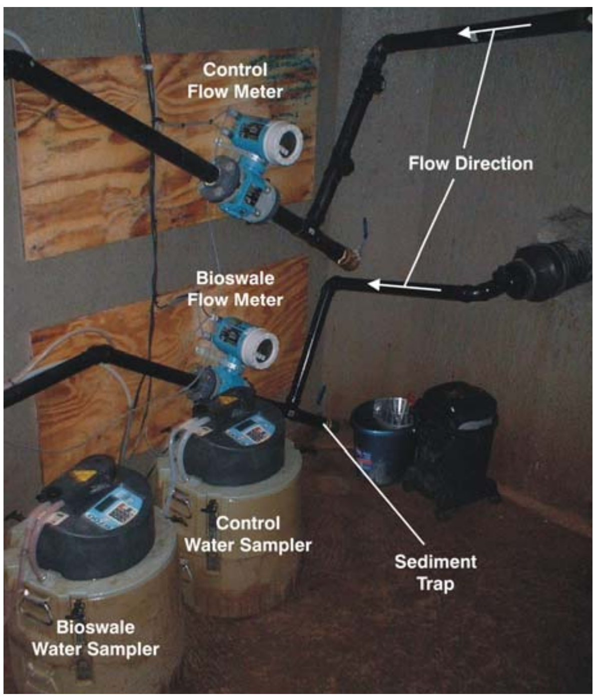


Figure 4.9: Flow meter and reverse slope pipe setup. Both PICP flow meters (high and low) and samplers are not depicted.

4.2.2 Water Quality

Water quality was collected using four ISCO 6700 automated water samplers, each containing 24 1L Teflon bottles. The samplers were connected directly to the Promag 53W flow meters via the relay output on the meters. The flow meter relays trigger the samplers at a flow threshold of 0.005 L/s and the 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 (asphalt and PICP) were set at 2 min intervals with 2 aliquots per bottle. The bioswale and PICP underdrain samplers also collected two aliquots per bottle, but in this case samples were 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. To achieve this, flow data were downloaded when the samples were collected and data were copied into a pre-prepared template spreadsheet that automatically identifies the appropriate volume to be extracted from each sample bottle. Composite samples were subsequently prepared and delivered to the Ontario Ministry of the Environment (OMOE) Laboratory in Etobicoke for analysis following OMOE lab preparation and submission protocols. The major variable groups analyzed include general chemistry (*e.g.* alkalinity), oil and grease, nutrients, metals and polycyclic aromatic hydrocarbons (PAHs). The list of variables was selected based on typical stormwater runoff contaminants in runoff from both parking lots and urban centres. A list of the variables and analytical methods are provided in Table 4.1 below.

Table 4.1: Analytical methods for major water quality groups

Variable	MOE Method	Description
chloride	E3016A	Colourimetry following two-stage reaction with mercuric thiocyanate and ferric iron
total, dissolved and suspended solids	E3188B	Gravimetry
organic Solvent Extractable	E3201B	Liquid-liquid extraction using dichloromethane
conductivity, pH and alkalinity	E3218A	Potentiometry
turbidity	E3311A	Nephelometry under robotic control, calibrated to Formazin turbidity standards
hardness, sodium, potassium	E3171A	Atomic absorption spectrophotometry (AAS)
particle Size	E3328A	Optical- laser light diffraction (Coulter analyzer)
total phosphorus, TKN	E3367A	Colourimetry
phosphate, nitrite, ammonia + ammonia, nitrate + nitrite	E3364A	Colourimetry
dissolved inorganic and organic carbon, silicon	E3370A	Colourimetry
metals	E3386A	Inductively coupled plasma atomic emission spectroscopy (ICP/AES)
mercury	E3060B	Cold vapour flameless atomic adsorption spectrophotometry (CV-FAAS)
polycyclic aromatic hydrocarbons	E3399A	Liquid-liquid micro-extraction (LLME), and gas chromatography – mass spectrometry (GC-MS)

4.2.3 Soil Sampling

Soil sampling and chemical analyses were undertaken at the Seneca college site, 7 older PCIP sites, and 5 older sites with bioswales or grassed roadside ditches in the GTA. The intent of the sampling was to assess the extent and rate at which road runoff contaminants accumulate in the PICP subgrade soils and bioswale surface soils over time.

During the summer of 2006, three cores were extracted from each site to a depth of between 25 and 38 cm using a 'zero contamination' soil corer. At the PICP sites the three sites were selected from the front, middle and back of a representative parking stall. At the bioswale site, the three sites were selected at representative sites in the deepest part of the swale where ponding occurred. The cores were subsequently cut into 7.6 cm (3 inch) segments. The depth segments from the three cores were then combined to form a single depth profile from each site. Thus, each 7.6 cm depth segment represents a composite of three samples taken at the same depth from three different locations. At two of the PICP sites (Sunset Beach and Belfountain), the granular layer beneath the pavers was too dense to penetrate. At these sites, three sediment cores were extracted from the sub-base and combined into a single sample for chemical analysis.

For comparative purposes, a core was also taken from a nearby reference site unimpacted by surface runoff. Although unimpacted by runoff, these sites would have been subject to similar levels of atmospherically deposited contaminants, including salt spray. The reference site cores were taken beneath the grassed topsoil layer to ensure that a comparative native soil was being sampled. The reference samples consisted of single cores and were not divided into segments.

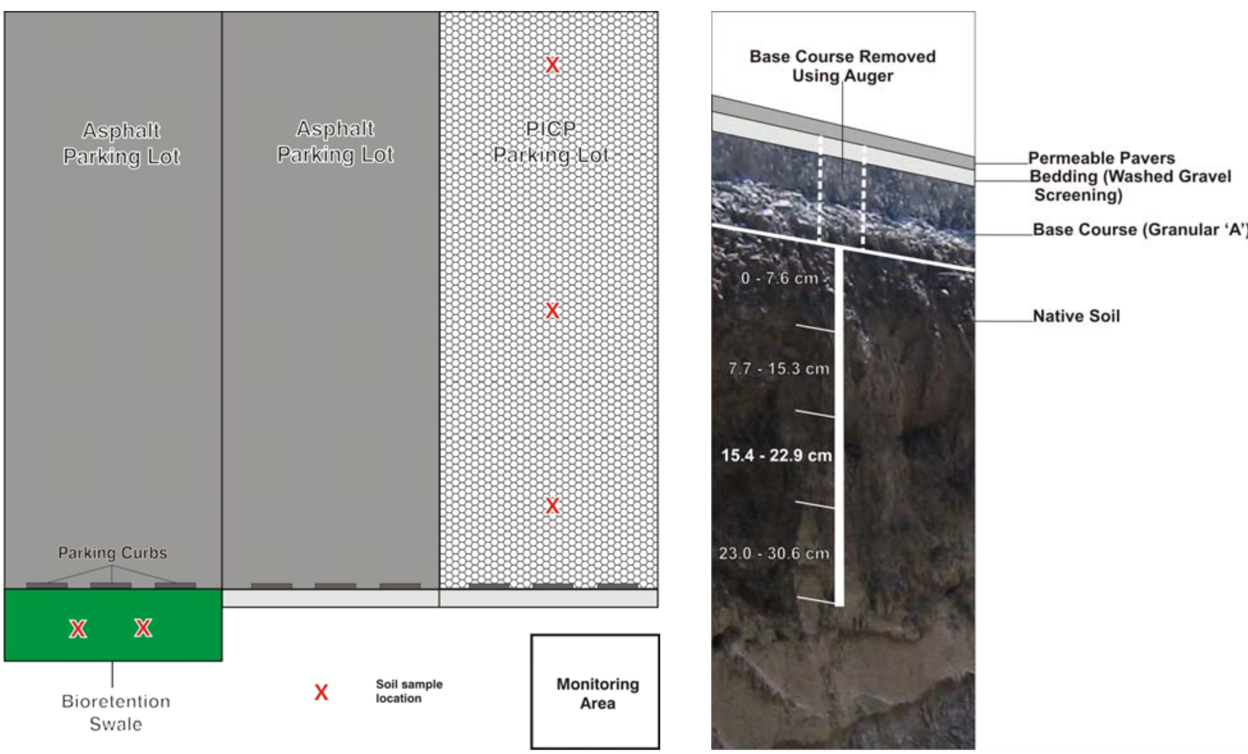


Figure 4.10: Soil sample locations and sample profile

4.2.4 Parking Lot Activity Survey

Parking lot activities were surveyed and documented throughout the study. A simple map and summary sheet are used during each sight visit to record observations. Items recorded include parking capacities, campus maintenance (*e.g.* snow plow and salting), and general observations. The site is typically visited at least once a week.

4.2.5 Infiltration Rates

Surface pavement permeability was determined qualitatively at all eight sites (including Seneca College) by pouring a 500 ml bottle of water on the surface. The permeability was rated as poor, good, or excellent depending the distance the water traveled over the surface. While this test is subjective in nature, it provides a good relative measure of surface permeability and clogging when the same operator performs the test at all locations, as was the case in this study.

Quantitative tests of surface permeability were conducted at three sites using a double ring infiltrometer (DRI) following the method described by Bean *et al.* (2007). The three sites represent different pavement ages and bedding materials. Belfountain Conservation Area is the oldest, at 17 years, followed by Jerrett's Funeral Home (10 years) and Seneca College (3 years). Sand was used as the pavement bedding and joint material at the Belfountain and Funeral Home sites, whereas the Seneca bedding layer was constructed with 3 to 5 mm stone (or high performance bedding).

At each site, three tests were performed in areas that visually represented different levels of clogging. The average of the three tests does not necessarily represent the average condition of the pavement, but rather a range of infiltration conditions at each of the sites. At two sites (Belfountain Conservation Area and Jerrett's Funeral Home) a fourth test was performed in which pavement maintenance was simulated following a method similar to that performed by Bean *et al.* (2007) and Gerrits (2001). This method entailed removing the top 15 mm of material from the surface joints or drainage cells and conducting the DRI test on an area visually similar to the location where the lowest surface infiltration rate was observed. Maintenance was not simulated at Seneca College as the site is relatively young and void spaces remain unclogged.

The rings in this study were made of aluminum with inner and outer ring diameters of 14 and 28 cm, respectively (Figure 4.11). Rings were sealed to the pavement surface using a clay putty and water was poured into each of the rings separately to test for leaks. Once all leaks were repaired, the rings were refilled to a depth of 100-170 mm, and the initial values were recorded for time zero. Depending on the speed of infiltration subsequent depth measurements were taken every 30 seconds to every 5 minutes, until the rings were dry, or 45 minutes had passed.

In addition to testing for surface permeability, a falling head permeameter was used to measure the infiltration capacity of native soils below the base course. Measurements were taken at most of the older sites and compared to similar tests at a nearby reference site.

Figure 4.11: Double ring infiltrometer and Guelph permeameter

4.2.6 Temperature

Temperature sensors were installed on the PICP and bioswale late in 2006 to assess freeze-thaw cycles and surface and subsurface air and water temperatures year round. The sensors were embedded: (i) inside the pavers and conventional asphalt 1 cm below the surface, (ii) in the granular filled paver drainage cells 1 cm below the surface, (iii) 1 cm below the pavers in the bedding course (iv) 50 cm below the soil surface of the bioswale, and (v) within the base course approximately 5 cm above the interface between the base course and native soil (or 55 cm depth). Measurements were continuous throughout the summer and winter.

4.2.7 Structural Integrity

The load bearing capacity or structural integrity of the PICPs was assessed through a partnership between the TRCA and the Centre of Pavement and Transportation Technology (CPATT) at the University of Waterloo in Ontario. A detailed report on the evaluation was prepared by Koeth et al., 2008. The following summary of the sites and test method is based on this report.

The Seneca College site in King City and the Earth Rangers facility in Vaughan were selected for evaluation. The Earth Rangers PICP was constructed in 2003, roughly 2 years before the Seneca site, but has a similar base depth (55 to 75 cm) and was constructed with similar materials (dense graded granular 'A' with high performance bedding). At both sites a portable falling weight deflectometer (PFWD) supplied by CPATT was used to evaluate the stiffness of the pavement structure and compacted layers (Figure 4.12). Tests were conducted in accordance with the established operating procedure for the make and model of the PFWD (Dynatest LWD 3031). The PFWD generates a force to create a deflection in the pavement equivalent to a rolling vehicle with an axle load of 4000 lbs (or 16 to 17 kN).

Figure 4.12: University of Waterloo staff operating the PFWD at the Seneca site

Tests were conducted on October 5, 2007, March 6, 2008 and June 12, 2008 representing dry, cold or partially frozen and wet states. The number of test locations on the Seneca PICP, Seneca asphalt and Earth Rangers PICP was 12, 6, and 32. At each location, six measurements were taken. Following standard procedures, the first measurement was considered a trial and not included in the overall average. Pavement deflection (in microns) and modulus of elasticity (in MPa) were calculated for each site and date of testing.

In addition to formal PFWD testing, structural integrity was also evaluated by TRCA qualitatively at the Seneca and 7 older PICP sites discussed in section 4.2.3. General observations of slumping, heaving and the condition of the pavers were noted to determine how well these pavements faired over time and whether or not they continued to meet the expectations of users.

5.0 MONITORING RESULTS AND ANALYSIS

5.1 Runoff and Infiltration

A total of 71 runoff events with precipitation depths greater than 5 mm were monitored between September 2005 and April 2008. Twenty six of these occurred during the winter (December to April). A ‘runoff event’ was defined as the period between the start and end of surface and subsurface flow. Since the PICP drained over several days, an ‘event’ could include more than one discrete period of rainfall.

5.1.1 Warm season

Among the warm season runoff events monitored, only one produced surface flow from the PICP. This storm was the largest event monitored, producing 72 mm of rain over a period of 5.5 hours. Rainfall events of this size and intensity occur at frequency of approximately once every 25 years in the Greater Toronto Area (Toronto AES, 1950 – 2003). Surface and subsurface runoff from the three surfaces during this event are presented in Figure 5.1. Hydrographs and hyetographs for other events are provided in Appendix A.

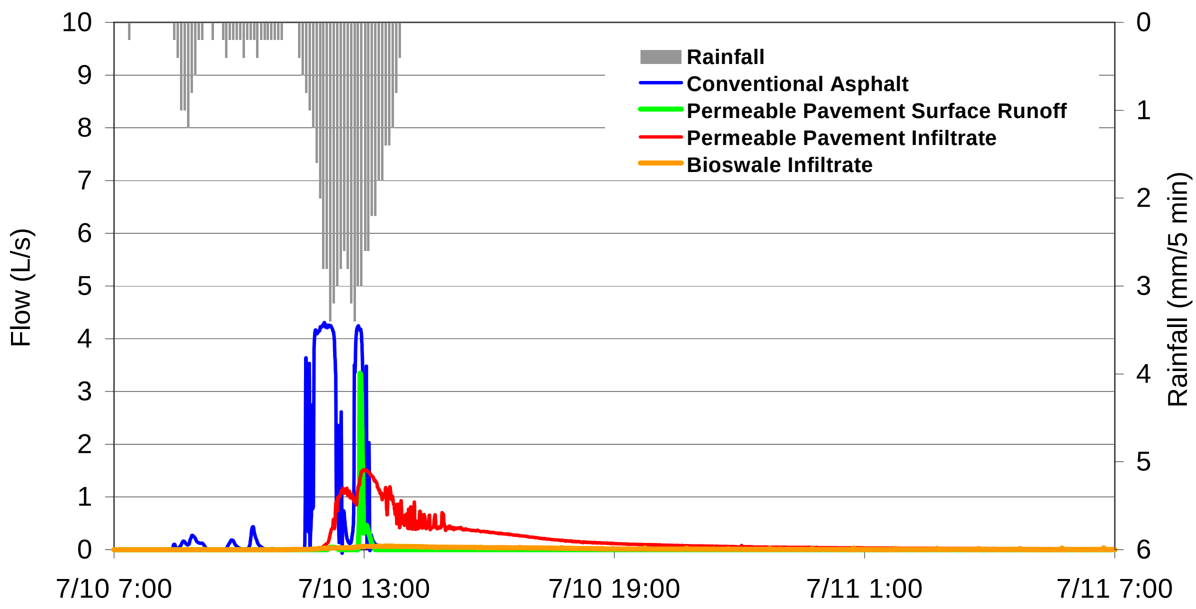


Figure 5.1: Runoff event on July 10th, 2006. Rainfall = 72 mm.

Flow rates from the conventional asphalt closely paralleled precipitation rates over the course of the event. A small amount of water was lost through leaks in the distribution system near the beginning of the event (this problem was rectified in December 2007). During the most intense part of the storm, runoff from conventional asphalt peaked after 15 minutes, followed by the peak from the PICP underdrain 75 minutes later. The majority of water infiltrated over a 10 hour period after the end of rainfall, with very slow drainage thereafter. Surface runoff from the PICP during this event measured less than 10 percent of total measured runoff, and it 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 contributing drainage area. Flow rates from the bioswale underdrain were substantially lower than either the asphalt or PICP.

Monitoring of water level fluctuations in the PICP base reservoir and on top of the bioswale was initiated in September 2006. Rainfall, water level changes, and surface and subsurface flows for a sample rainfall event on November 15th, 2006 are presented in Figure 5.2. 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. The event started with water in the PICP base course from a previous event. Initially, water levels increased slowly, as the pavement was wetted and water permeated into the base course. With additional rain, pore spaces filled quickly to saturation, causing a rapid rise in water levels. The time delay between the rainfall and water level peaks was roughly 30 minutes.

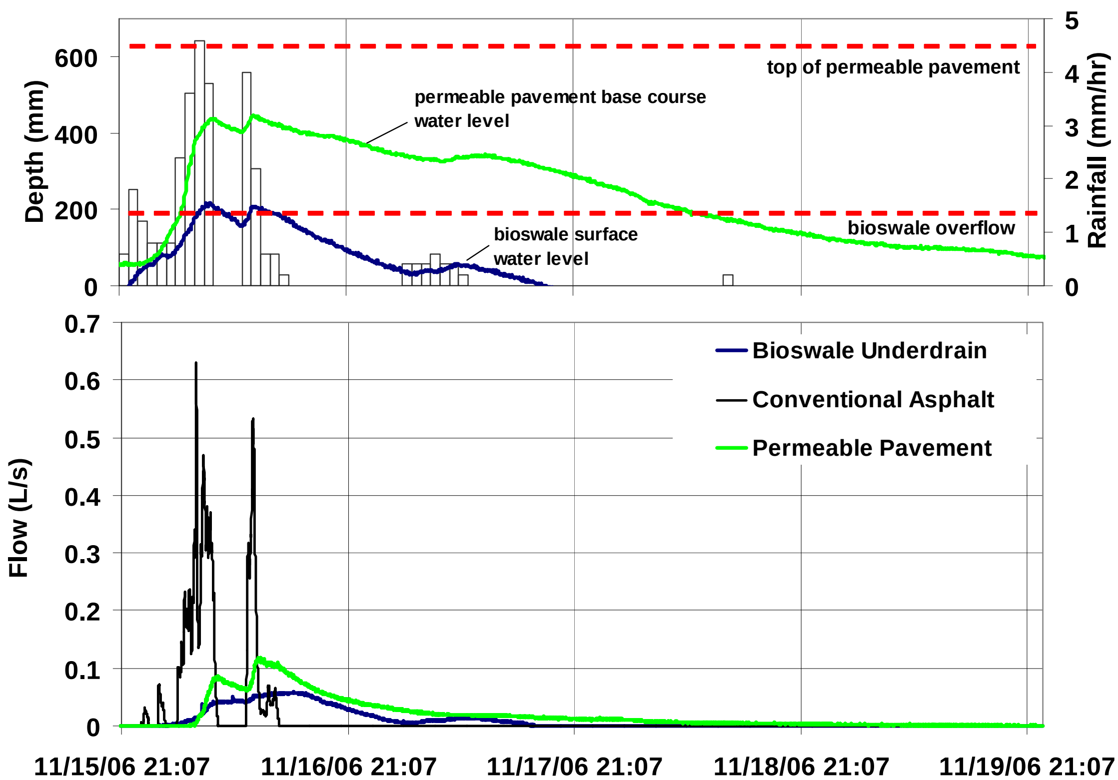


Figure 5.2: Storm hydrographs and hyetograph on November 15th, 2006. Total rainfall: 31 mm.

Bioswale water levels responded more quickly than the PICP because runoff enters the swale from a drainage area approximately 11 times its size. Water levels increased to the overflow point and then declined once rainfall had ceased. A small amount of water was lost through the overflow channel, as reflected by the lack of well defined peaks in the underdrain hydrograph (lower graph in Figure 5.2). The higher permeability of the bioswale soils is evident from the difference in the rate and duration of drawdown. Whereas the ponded water on the swale drained over less than two days, the PICP base reservoir drained over a period of approximately 3.5 days. This long drawdown period caused the base reservoir to remain partially saturated through successive rain events, fully draining only during prolonged dry or cold periods. Typical installations of PICP on low permeability soils would include a perforated underdrain at the bottom of the base course to allow water to drain more quickly.

The lower of the two graphs in Figure 5.2 shows the flow response at the asphalt surface and within the two underdrains. As noted previously, runoff from the asphalt closely parallels rainfall. Flow appears first in the swale underdrain as water ponds on the surface, infiltrates and then drains through the relatively permeable organic soils. Measurable flow in the PICP underdrain starts approximately 6 hours after the initial increase in base course water levels as soil pore spaces filled and saturated conditions formed around the underdrain. Very low flows were either below the level that could be measured by the flow instruments, or lost through tears in the impermeable liner. The inability to capture these low flow volumes prevented accurate quantification of losses to evapotranspiration.

Storage capacity within the PICP base reservoir was not uniformly distributed over the full depth of the granular layers. Figure 5.3 presents the relationship between rainfall on the rising limb of the hydrograph and the extent of water level rise in the PICP base reservoir. The graph shows a declining rate of water level rise as rainfall increases. These declining rates can be attributed to several factors. The decline at the top end of the curve (water level rises between 350 and 400 mm) is largely influenced by the movement of water from the lower porosity sub-base (granular ‘A’) into the higher porosity bedding layer (15 cm depth). As hydraulic head increases, so too does infiltration, which slows the rise in water levels. Nearer the bottom of the base course (represented by the lower portion of the curve), where finer particles predominate, the available void space is limited by the presence of capillary water. Hence, water levels rise quickly with the addition of even a small amount of rainfall.

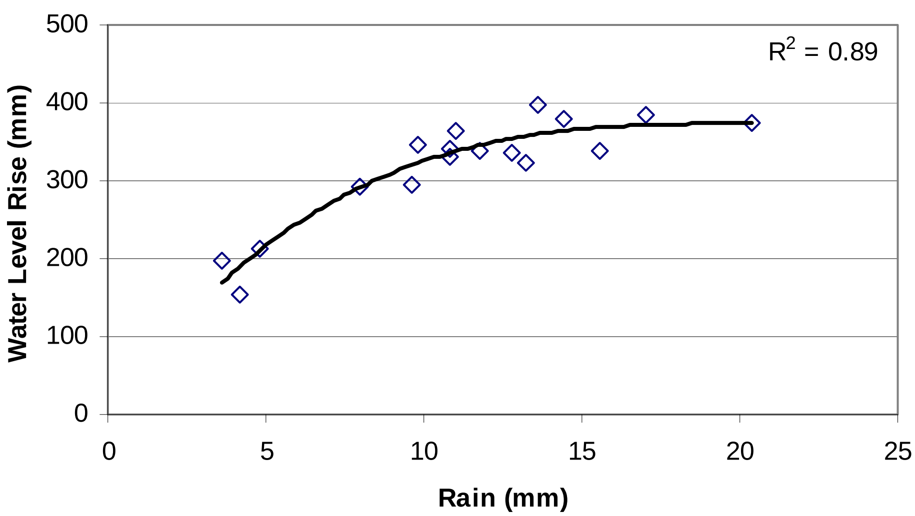


Figure 5.3: Relationship between rainfall and the extent of water level rise in the PICP base course

Based on measurements of water level rise, the effective porosity of the sub-base media was calculated to be less than 5%. This is much lower than the dry porosity value of 25 to 40% for gravels (Freeze and

Cherry, 1979). Limiting the inclusion of fines through the use of open graded granular materials (*i.e.* clear washed stone) would likely increase base storage capacities.

While the hydrologic data presented in this section suggest that PICPs can significantly reduce surface runoff on low permeability soils, the unique design of this installation calls into question the transferability of results to other similar sites. It is likely, for instance, that the perforated drain 1 m below the base enhanced the rate of infiltration, particularly near the end of the drawdown period when, in the absence of a drain and impermeable liner, soils may have become saturated. There was also the distinct possibility for preferential flow along the liner, allowing water to infiltrate slightly more quickly than otherwise would have been the case. A baffle installed within the base of the PICPs prevented contact with the liner along the downstream edge, but preferential flow may still have been possible elsewhere. Further investigation of typical installations on different types of clay based soils is needed to determine the runoff reduction potential of PICPs where subgrade soils are characterized by low permeability.

5.1.2 Cold season

Figures 5.4 and 5.5 show the precipitation, air temperature, surface temperature (in the pavement base course and bioswale surface soil), surface water level fluctuations and surface/subsurface flows for the periods from January to April, 2007 and November 2007 to April 2008.

In 2007, the January period was unusually mild, with several periods of rain (Figure 5.4). Temperatures began to drop for a prolonged period in mid January accompanied by snow (note that the small amount of rain on January 27th was measured at the nearest airport 5 km from the site; the lack of any flow response on the control surface suggests that all of the precipitation at the study site was in the form of snow). The base course drained shortly thereafter as the snow was plowed to the eastern edge of the parking lot. It is assumed that the water in the base course drained rather than froze because temperatures near the bottom of the base course did not fall below O°C until 9 days later. The slow decline in base course temperatures in the early winter, and the accumulation of road salts, likely helped prevent the formation of ice and the potential for heaving. Even when base course temperatures were as low as -4°C, water levels in the granular reservoir continued to fluctuate (water was observed to be slushy during these times). There was only one period from the 7th to the 10th of March when a rapid decline in air temperature to -25°C may have led to frozen water in the base course.

In 2008 there was nearly twice as much precipitation and more frequent snowmelt events compared to the previous winter (Figure 5.5). Temperatures from January to April were on average 1°C warmer. The PICP base course temperatures fell to a minimum of -2°C, which is 3 degrees warmer than the minimum observed in 2007. The PICP base course was empty (water levels below 50 mm) or partially frozen only twice: once in February and for a brief period in March; infiltration continued throughout the winter. As in 2007, the potential for heaving was greatest in early March when base course temperatures were below zero and periods of snow melt were punctuated with rapid declines in temperature.

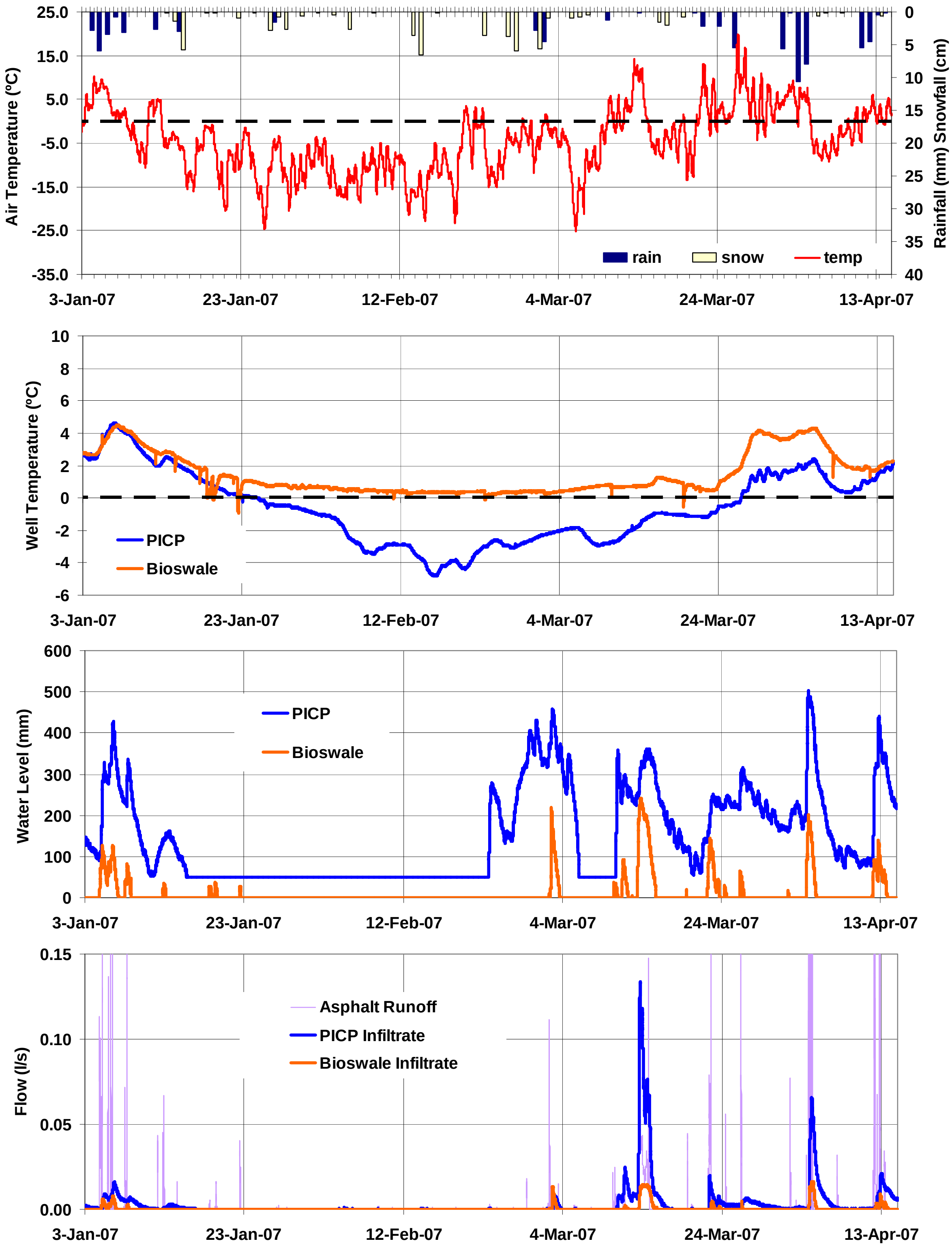


Figure 5.4: Precipitation, air temperature, surface temperature, water levels and flows during the winter from January 3rd to April 14th, 2007. Note that the base course water level sensor was located 50 mm above the subgrade.

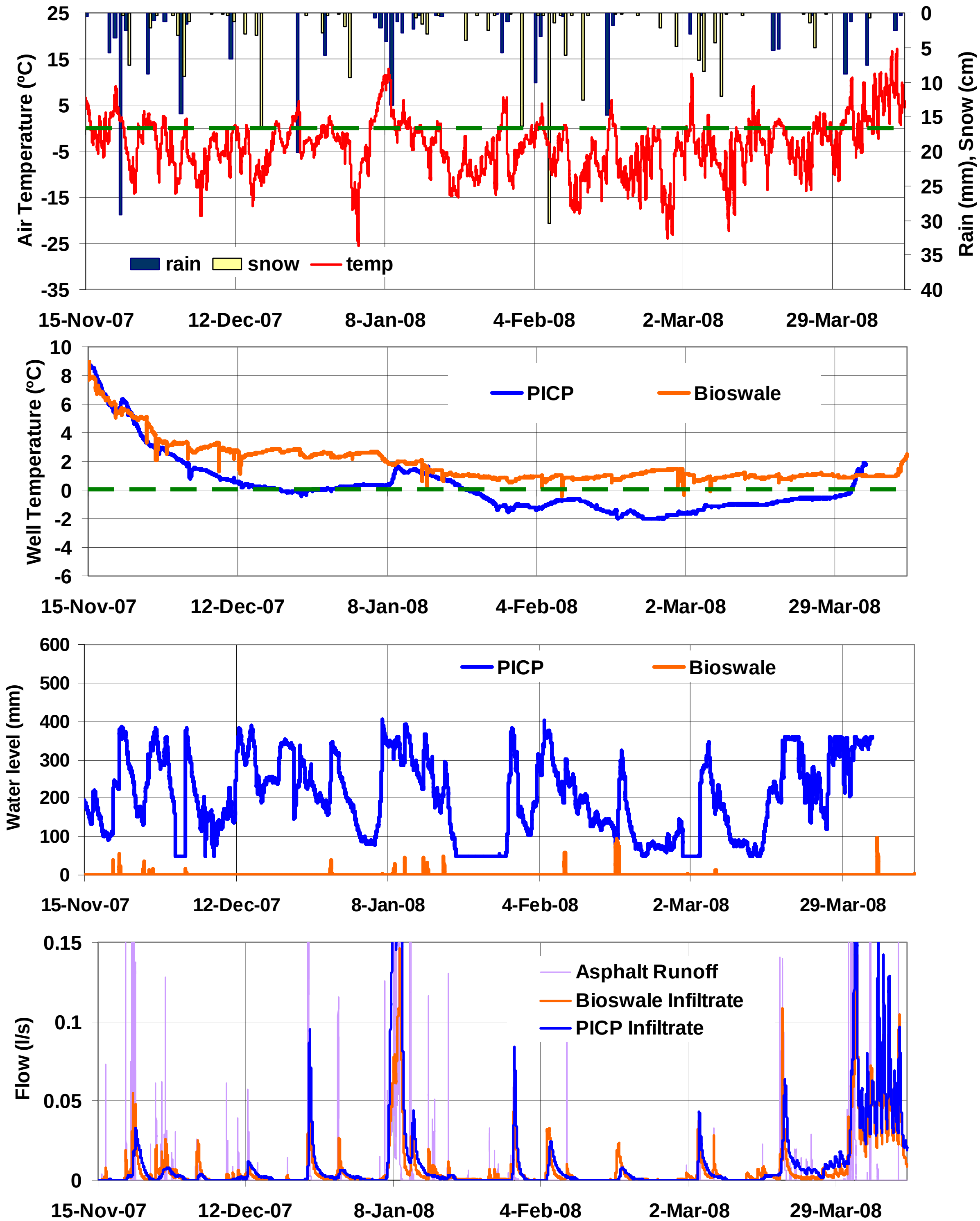


Figure 5.5: Precipitation, air temperature, surface temperature, water levels and flows during the winter from November 15th, 2007 to April 10th, 2008. Note that the base course water level sensor was located 50 mm above the subgrade.

Figure 5.6: The PICP and bioswale during the winter of 2007

When the study was initiated, there was some concern that ice formation within the PICP base course layer would inhibit or delay infiltration when the first rain occurred after an extended cold spell, potentially causing excessive buildup of water in the base course, which in turn would cause some runoff to flow across the surface. This did not occur. The PICP continued to function normally during winter rain events, with infiltrate flow measured even during very cold periods. Major runoff events observed on the asphalt surface resulted in subsurface flow responses similar to those occurring during the summer. After a period of very cold temperatures in 2007, the base course water levels started to become active roughly 6 hours following the end of a two day warming period from February 20 to 22 (Figure 5.5). Much of this water consisted of melt from surrounding snow banks, which typically occurs slowly after air temperatures rise above freezing. A similar pattern was noted after cold periods in 2008. Since the permeable pavement was located along two edges, it received much more snowmelt from the banks than the asphalt or bioswale.

During both winters, the bioswale surface soils remained above zero, likely due to the insulating layer of soil and snow above the swale, and microbial activity in the organic rich soils (Figure 5.5 and 5.6). Despite the warm soil temperatures, however, there appeared to be very little snowmelt or infiltration in 2007, possibly due to ice formation on top and around the perimeter of the swale, which blocked the flow of melt waters from the pavement and surrounding areas. In 2008, infiltration was greater, suggesting that a similar blockage at the entry points of the swale was not present, or that reconstruction of the berm around the swale in the spring of 2007 allowed for more melt waters to be directed into the swale. There was no ponding or back up of water onto the parking lot, indicating that the swale was an effective means of draining melt water.

5.1.3 Surface Infiltration

Seven older PICP sites ranging in age from 3 to 17 years were surveyed in 2006. The age, surface permeability, and physical characteristics of the Seneca parking lot and the 7 older sites are presented in Table 5.1. Infiltration measurements at 3 sites using a double ring infiltrometer indicated average surface infiltration rates (n = 3) ranging from 3 cm/hr at the oldest site (Belfountain) to 122 cm/hr at the newest one (Seneca College). A year earlier, qualitative tests of surface infiltration were also conducted by pouring a bottle of water on the surface and observing the distance that water spread across the surface.

These tests showed a similar range at the three sites where infiltrometer tests were performed, and a ranking of good to poor at the other sites. Several of the sites showed visual evidence of surface clogging and vegetation growth in the joints between the pavers.

Table 5.1: Character and condition of permeable interlocking concrete pavements surveyed in 2006 and 2007

Site Name	Age (yrs)	Structural Condition	Surface Infiltration		Base Course[3]			Subgrade Soil Texture[4]
			Qualitative Test[1]	Double Ring Infiltrometer (mm/hr)[2]	Bedding Depth (cm)	Sub-base Depth (cm)	Total Depth (cm)	
Earth Rangers	4	Excellent	Good	n/a	10 (gravel)	51 - 66 (coarse granular)	61 - 76	Loam
Belfountain Conservation Area	17	Excellent	Poor	34 (23 - 47)	5 (sand)	>25 (coarse granular)	depth unknown	Sandy Loam
Sunset Beach	8	Excellent	Poor	n/a	1.3 (sand/gravel)	unknown depth (coarse granular)	depth unknown	Sandy Loam
Humber College[5]	4	Good, a few broken bricks	Poor	n/a	5 (sand)	20 - 25 (coarse granular)	25 - 30	Loam
Humberwood Community Centre	12	Generally good, some slumping	Good	n/a	5 (sand)	36 - 66 (sand & coarse granular)	41 - 61	Sandy Loam
Jerrett's Funeral Home	10	Excellent	Good	96 (83 - 113)	5 (sand)	43 - 64 (coarse granular)	49-69	Silty Clay
University of Guelph	13	Generally good, some slumping	Good	n/a	10 (sand)	68 - 94 (coarse granular)	78 - 104	Sand
Senca College	2	Excellent	Excellent	1222 (790 - 1641)	15 (gravel)	38 (coarse granular)	53	Clay Loam

1. Determined qualitatively by pouring water on the surface and observing the degree of infiltration
2. Double Ring Infiltrometer tests were completed in one year later than all other tests
3. Base course depths vary across the pavement surface. Bedding and sub-base layers typically consisted of pea gravel and granular 'A', respectively.
4. Determined through grain size analysis
5. The Humber College interlocking concrete pavement may not have been designed to be permeable. The ratio of surface voids to pavement was less than at the other sites surveyed.

Surface infiltration rates increased by 121% at Jerrett's and by 221% at Belfountain when paver maintenance was simulated by removing 1.5 cm of material from the surface drainage cells. This method of simulating pavement maintenance was adapted from Gerrits (2001) and Bean *et al.* (2007), who found similar improvements in infiltration at study sites in University of Guelph, Ontario and in Maryland and North Carolina, respectively. These results indicate that the permeability of older PICPs where clogging has resulted in reduced infiltration can be substantially improved by vacuum sweeping the upper veneer of granular material and debris from the drainage cells or joints and replacing it with new gravel.

The use of sand within the bedding layer (Table 5.1) or as a winter maintenance practice (at Belfountain, Sunset Beach, Earth Rangers) likely contributed to premature clogging at several of the sites surveyed. Since sand clogs more quickly than granular bedding materials (*e.g.* Gerrits, 2001), most PICPs installed after the late 1990s use a 2 to 5 mm clear stone as the bedding and joint filler. The use of sand for winter maintenance on PICPs is strongly discouraged by most manufacturers of PICPs.

The infiltration capacity of the subgrade soils was determined by augering through the base course and measuring soil permeability. The Sunset Beach and Belfountain sites were not tested because augering through the base course proved too difficult. All sites tested showed zero infiltration or inconclusive results (n = 5) due to hydrologic discontinuities (n =2). The absence of water in the base indicated that water was infiltrating, but the very small area selected for testing clearly did not capture this broader infiltration effect. Cracks and sand lens in the soil matrix may have been responsible for a considerable portion of the infiltration that was occurring. Uncompacted reference site hydraulic conductivities ranged from 2×10^{-4} to 4×10^{-5} cm/s (n = 4). These results underscore the importance of considering the effects of scale on the values derived from pre and post construction tests of soil permeability.

5.2 Water Quality

Water samples were collected during 56 runoff events between September, 2005 and December, 2007. The samples were analyzed for general chemistry (e.g. pH, alkalinity), nutrients, metals, bacteria and polycyclic aromatic hyrdrocarbons (PAHs). Fewer samples were analyzed for some variables (e.g. TSS, nutrients) because of a temporary shutdown of some laboratory departments during the spring of 2006. Box plots of concentrations for selected variables are presented in section 5.2.1 and graphs showing temporal variations in water quality are presented in section 5.2.2. Water quality statistics for the full list of variables analyzed are provided in Appendix B.

5.2.1 Box Plots

Figure 5.7 presents box plots and 95% confidence limits (nonparametric) for general chemistry (*e.g.* total suspended solids, hardness (as $CaCO_3$)), nutrients (N and P), oil and grease (solvent extractable), three heavy metals, and three polycyclic aromatic hydrocarbons (PAH). Median concentrations of the plots are significantly different (α=0.05) when the lower and upper confidence limits do not overlap. Box plots and summary statistics for other variables are presented in Appendix B. Confidence intervals are not shown for dissolved solids because these variables exhibit strong seasonal trends and were unduly influenced by snow plowed from other parts of the parking lot onto the PICPs, and to a lesser extent, the bioswale.[1]

Suspended solids entering through the pavement or bioswale surface are trapped in void spaces as they migrate vertically through subsurface media. Hence, observed TSS levels largely reflect the capacity of the geotextile wrapped perforated pipe to filter out solid particles within the vicinity of the drain. The

[1] An interruption in lab services during the winter and spring of 2007 affected seasonal weightings of some of the general chemistry variables, particularly dissolved solids, conductivity, sodium and chloride. Nutrients were less affected because the nutrients laboratory was down for a shorter time period. The metals lab, which includes calcium and magnesium, continued to function throughout this period.

elevated concentrations in the bioswale infiltrate are likely due to a tear in the filter cloth and much higher levels of algae, which were clearly present in the pipe draining the swale.

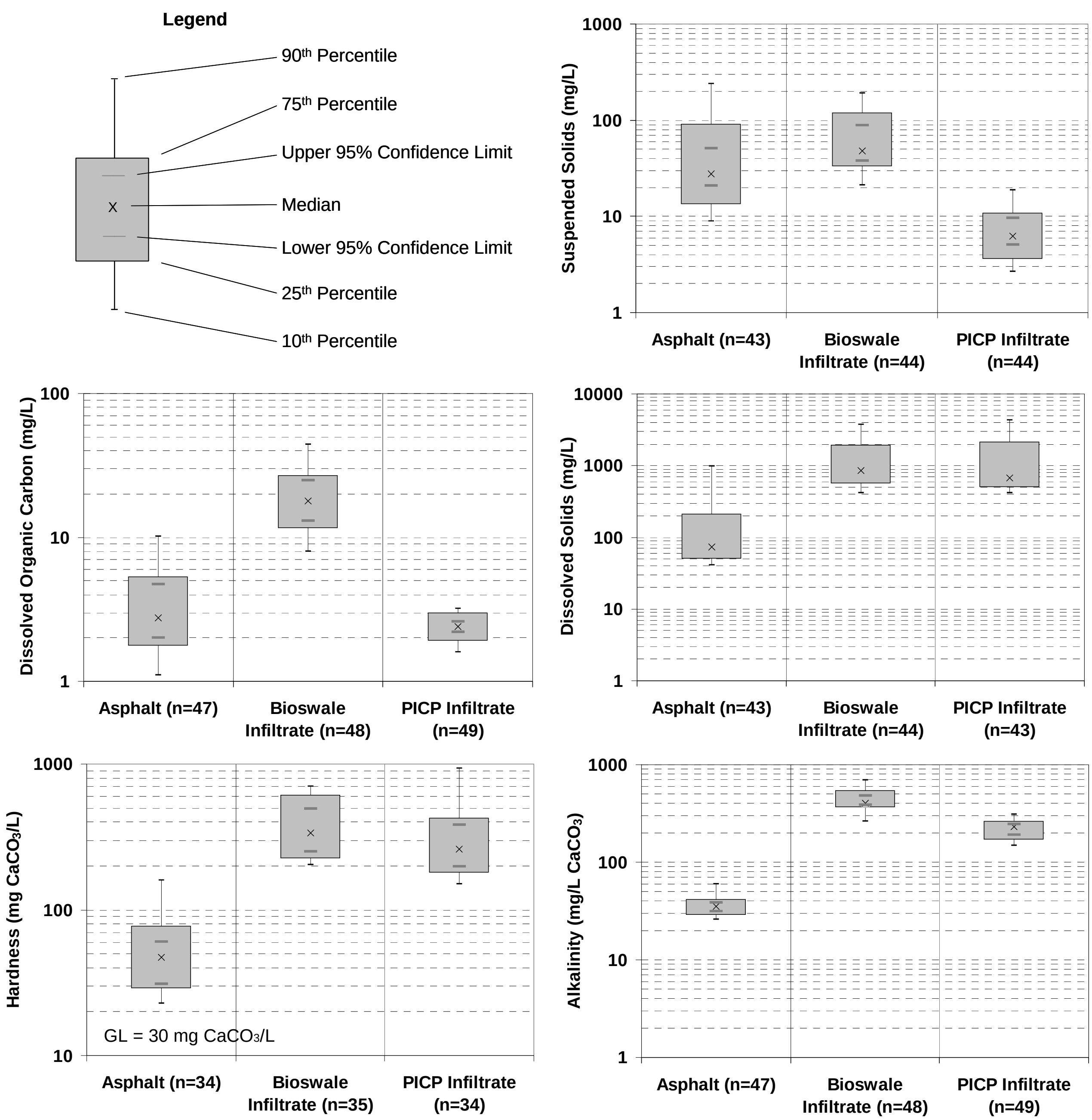
Hardness (as $CaCO_3$) and dissolved organic carbon (DOC) influences the mobility and bioavailability of some metals. Metals such as lead, cadmium, and beryllium are more toxic to aquatic organisms at hardness concentrations below 75 to 100 mg/L. While the bioswale and PICP infiltrate were consistently above these levels, the asphalt runoff was not (Figure 5.7). Fifty percent of asphalt samples had hardness levels less than 50 mg/L. The bioswale infiltrated contained higher DOC concentrations (Figure 5.7), which is generally associated with lower metal bioavailability. The pH of all outlets fell within acceptable ranges (6.5 to 8.5). The median pH of asphalt runoff was 7.6, compared to bioswale and PICP infiltrate medians of 7.9 and 8.2, respectively.

Concentrations of copper were not significantly different across the three study areas. Median zinc concentrations in infiltrate samples were significantly lower (α=0.05) than the median concentration in asphalt runoff. Copper and zinc are natural soil micronutrients; hence low concentrations would be expected even in infiltrate samples from relatively undisturbed soils. Lead was detected in less than 10% of infiltrate samples, and in 39% of asphalt samples. Fluoranthene, phenanthrene and pyrene were also detected much less frequently in the PICP and bioswale infiltrate samples. None of the other 12 PAHs analyzed were detected in infiltrate samples, but six were detected in asphalt runoff between 2 and 6% of the time. Concentrations of most PAHs could not be evaluated against Ontario surface water guidelines because, with the exception of phenanthrene, the guidelines were below detection levels. Benzo (a) pyrene was the only PAH with a drinking water guideline, and this variable was not detected in infiltrate samples.

Pavements are not a primary source of phosphorus and nitrogen compounds. These nutrients are largely transported onto pavements as drainage from pervious areas containing fertilizers and nutrient rich organic matter. Other sources include atmospheric deposition and dirt and dust from vehicles. The median concentration of phosphorus in PICP infiltrate was significantly lower (α=0.05) than that of the asphalt and bioswale. The compost rich bioswale soils provided a ready source of phosphorus. The concentration of phosphorus in PICP native soils was less than half that of the bioswale soils (see section 5.4). The asphalt runoff contained considerably lower concentrations than the bioswale infiltrate, but concentrations still exceeded the provincial receiving water standard of 0.03 mg/L most of the time.

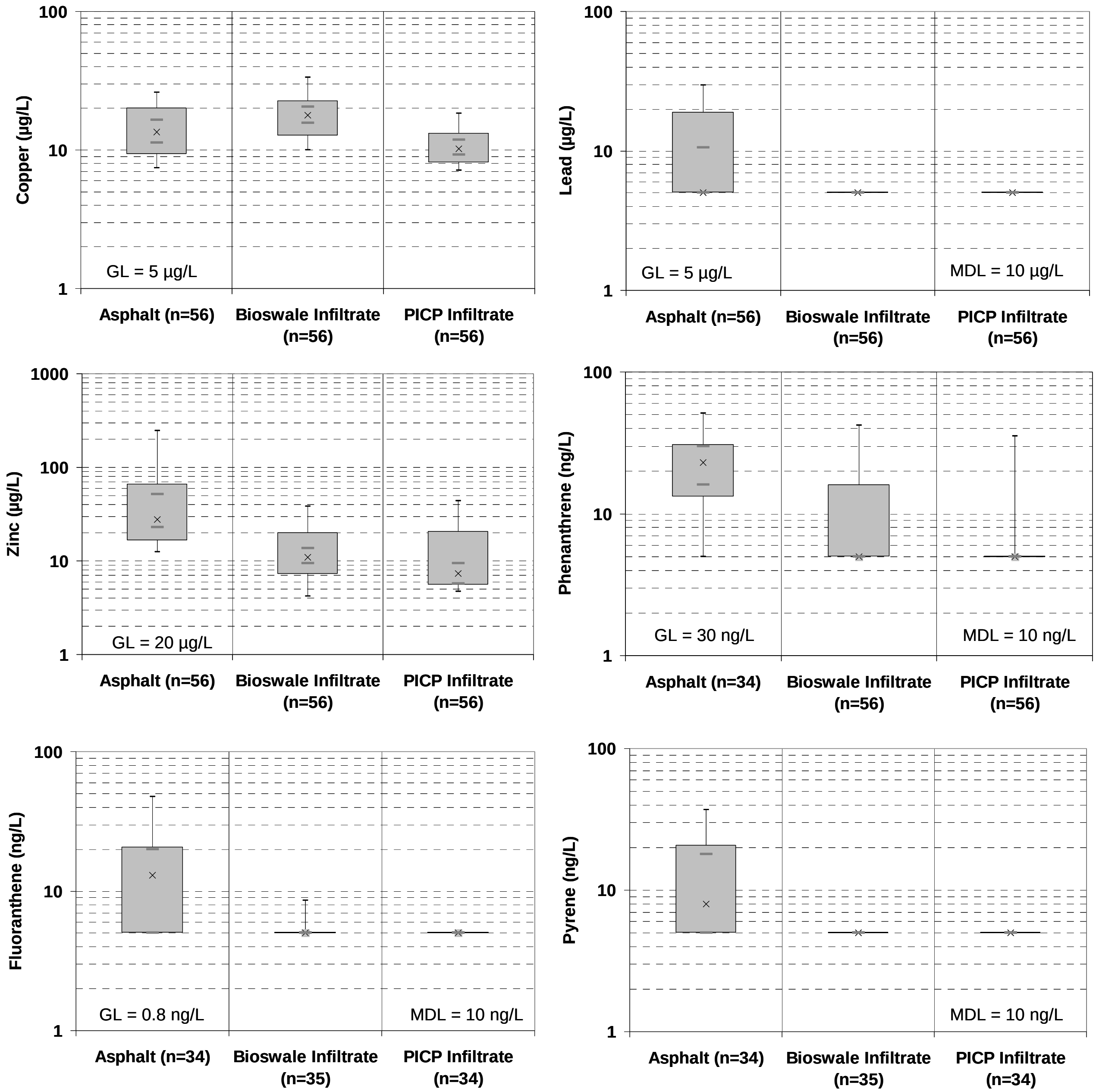
The PICP infiltrate contained higher nitrate concentrations than both the bioswale infiltrate and asphalt runoff. However, overall concentrations of nitrate were relatively low and would not pose a threat either to surface or groundwater. The Ontario drinking water standard for nitrate is roughly 10 times the level observed in subsurface runoff samples. PICP infiltrate concentrations of TKN and ammonia were significantly lower than in asphalt runoff. The highest concentrations of organic nitrogen and ammonia were observed in bioswale infiltrate, where the organic soils acted as a source of these constituents.

PICP infiltrate concentrations of oil and grease (solvent extractable) were below laboratory method detection limits (1.0 mg/L) in 72% of samples, and median concentrations were significantly lower than median concentrations in asphalt runoff. Bioswale infiltrate concentrations were lower than in asphalt runoff, but not statistically different. The elevated levels of oil and grease in the bioswale infiltrate likely originate from natural oils in the manure and compost rich garden soils as oils are relatively insoluble and tend to be readily adsorbed by soil particles, particularly those with high organic content (Pitt *et al*., 1996). By contrast, engine fluids and oils deposited by vehicles would have accounted for most of the oil and grease found in asphalt runoff.



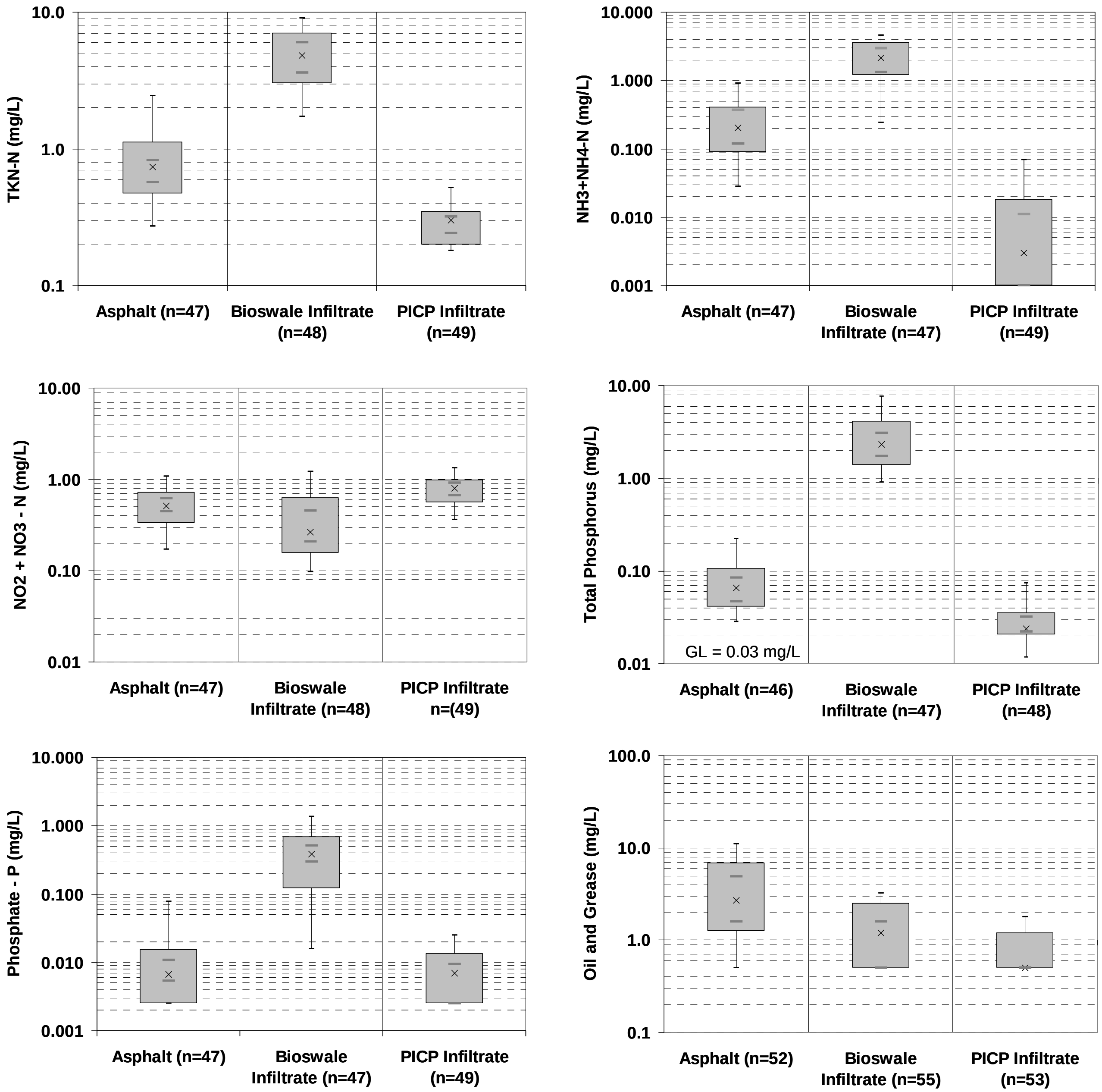
Notes: Surface water guidelines (GL) are provided where available; The laboratory method detection limit (MDL) is indicated where more than 25% of observations were below the MDL.

Figure 5.7: Concentrations of TSS and general chemistry variables with nonparametric 95% confidence limits



Notes: Surface water guidelines (GL) are provided where available; The laboratory method detection limit (MDL) is indicated where more than 25% of observations were below the MDL.

Figure 5.7 (continued): Concentrations of selected metals and PAHs with non-parametric 95% confidence limits



Notes: Surface water guidelines (GL) are provided where available.

Figure 5.7 (continued): Concentrations of nitrogen, phosphorus and oil/grease (solvent extractable) with non parametric 95% confidence limits

5.2.2 Temporal variations

Time series plots of selected variables are shown in Figure 5.8. Plots for additional variables are presented in Appendix B. Total suspended solids (TSS) data were not available during part of the 2006 winter due to an interruption in lab services, but the following winter and spring showed generally higher concentrations from the asphalt surface. Wash off of accumulated sand and dirt in the snow pack may have contributed to higher TSS levels in asphalt runoff during the winter and spring of 2007. The infiltrate concentrations of TSS from the bioswale and PICP plots were less variable.

Concentrations of chloride and sodium increased dramatically during the winter when road salts (NaCl) were applied to the parking lot (Figure 5.8). These were washed off the surface during the winter, reaching peaks in asphalt runoff of 36,400 and 22,700 mg/L, respectively. Infiltrate concentrations showed more gradual changes, with an accumulation of sodium chloride in the winter, and gradual release during subsequent seasons. Chloride and sodium are highly mobile in soils and several studies have demonstrated their potential to accumulate in groundwater to levels that exceed drinking water standards (*e.g.* Howard and Beck, 1993; Jones and Sroka, 1997; Granato *et al.*, 1995). Although shallow aquifers are most at risk, deeper aquifers may also suffer adverse effects depending on the geologic and groundwater flow conditions.

In addition to direct effects on groundwater, road salts have also been shown to increase the mobilization of heavy metals in soils. The distinct rise in underdrain concentrations of several heavy metals during the winter and spring of 2007 may be related to this effect (Figure 5.8 and Appendix B). The influence of sodium chloride on metal mobility in soils is well documented. Norrstrom (2005) identified colloid assisted transport as the primary mechanism for increased lead release from soils in a roadside ditch in Sweden. The formation of chloride complexes and potentially ion exchange were thought to be important in the release of zinc and cadmium. In an examination of pore water chemistry of roadside soils in Sweden, Backstrom *et al.* (2004) identified the primary mechanisms for metal mobilization as ion exchange, lowered pH, the formation of chloride complexes and potentially colloid dispersion. The presence of high concentrations of exchangeable calcium was thought to be an important factor in the enhanced release of cadmium.

While chloride may have helped to increase the mobility of metals, the observed rise in metal concentrations during the winter and spring of 2007 also appears to be a response to higher loading rates. Asphalt runoff concentrations of several metals increased in January and February, and were either paralleled or followed by a rise in infiltrate concentrations (*e.g.* zinc, cadmium). As mentioned earlier, the PICPs and bioswale received snow plowed from other parts of the parking lot, which would have further enhanced contaminant loading to these surfaces. Preferential drainage along the liner may have been another factor influencing the vertical transport of trace metals and other contaminants. Boving *et al.* (2006) noted a similar increase in metals during the late winter and early spring in water drained through a porous asphalt pavement structure in Rhode Island (without a liner). The authors attributed the increase to enhanced corrosion of automobile parts during this period.

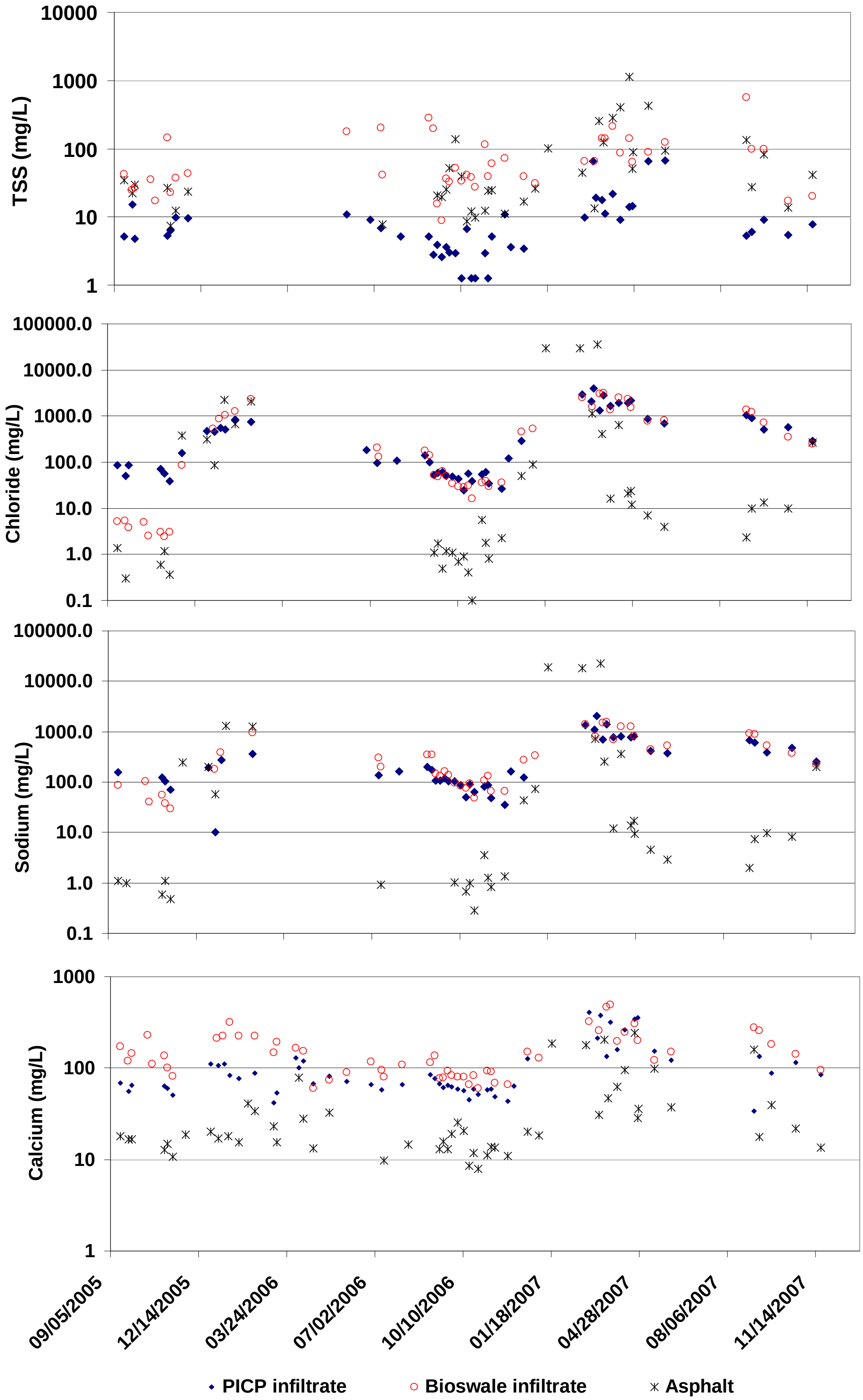


Figure 5.8: Time series plots for TSS, chloride, sodium and calcium

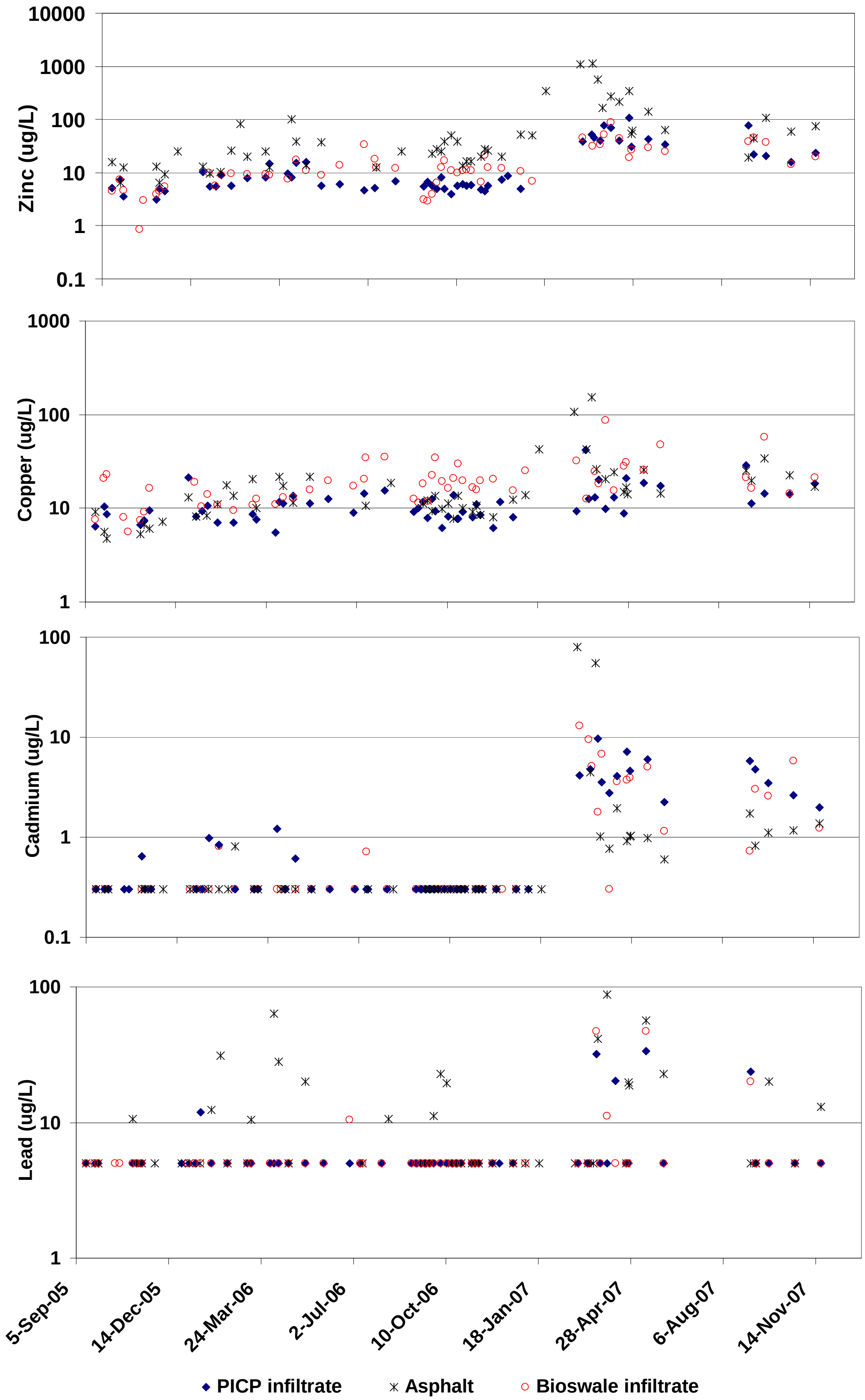


Figure 5.8 (continued): Time series plots for selected trace metals

At observed concentrations, zinc and copper were not a concern as groundwater contaminants, but may be a concern in surface waters if dilution capacity is not sufficient to reduce concentrations. Cadmium was detected in 30% of PICP infiltrate samples and 36% of bioswale infiltrate samples. Concentrations were above the drinking water guideline of 5 ug/L in 11% and 7% of PICP and bioswale infiltrate samples, respectively. Cadmium tends to be more mobile than most other trace metals because it is highly soluble in water. By contrast, lead is relatively immobile and was rarely detected in infiltrate samples. In the few instances when it was detected, concentrations were above both the surface and drinking water standards of 5 and 10 ug/L, respectively.

The conditions under which metals may contaminate underlying aquifers is a topic requiring further investigation. Howard and Beck (1993) found that Toronto groundwaters contaminated with sodium chloride contained concentrations of trace metals close to background levels. Granato *et al.* (1995) analyzed groundwater samples up and down gradient of a highway in Massachusetts to determine the effect that deicing chemicals may have on groundwater quality. Their results suggested that deicing chemicals in highway runoff temporarily increased the mobilization of heavy metals into shallow groundwaters (5 to 17 meters), although metals were below national drinking water standards. Deep wells at 27 m below the surface were unaffected.

There was little seasonal variation in the concentrations of nutrients and PAHs. The PAHs were rarely detected in infiltrate samples throughout the study period and sodium chloride did not appear to increase the mobility of these constituents. Infiltrate concentrations of soluble phosphorus from the PICP plot increased briefly during the late winter and spring. Elevated phosphate concentrations in asphalt runoff at the same time suggest that the increase may have been related to higher surface loading rates.

5.3 Temperature

Surface and subsurface temperatures were monitored from January 24, 2007 to January 23, 2008, with a 66.5 day gap from May 9th to May 19th, July 13th to August 27th, and September 12 to September 24th. As described in section 4.2.6, temperatures were measured continuously near the surface of the pavers, within the gravel filled void space, 3 cm beneath the pavers at the top of the bedding layer, 55 cm below the surface in the base course and 50 cm below the surface in the bioswale.

The temperature of the air and PICP surfaces are presented as hourly durations in Figure 5.9 and as cumulative frequencies in Figure 5.10. There was little difference between the temperature of the pavers and that of the void spaces. Both surfaces were warmer than the air during the winter and summer. During the summer, the daily peak void temperatures were approximately 2°C cooler than the daily peak paver temperatures. The bedding layer displayed a narrower temperature range than the pavers, despite the sensor being located only 3 centimeters below the bottom of the pavers. Deeper, near the bottom of the base course, temperatures were buffered from air temperatures to a much greater extent. Unlike the other surfaces, the base course was not subject to diurnal fluctuations due to the insulating effect of overlying layers and water stored in the base reservoir.

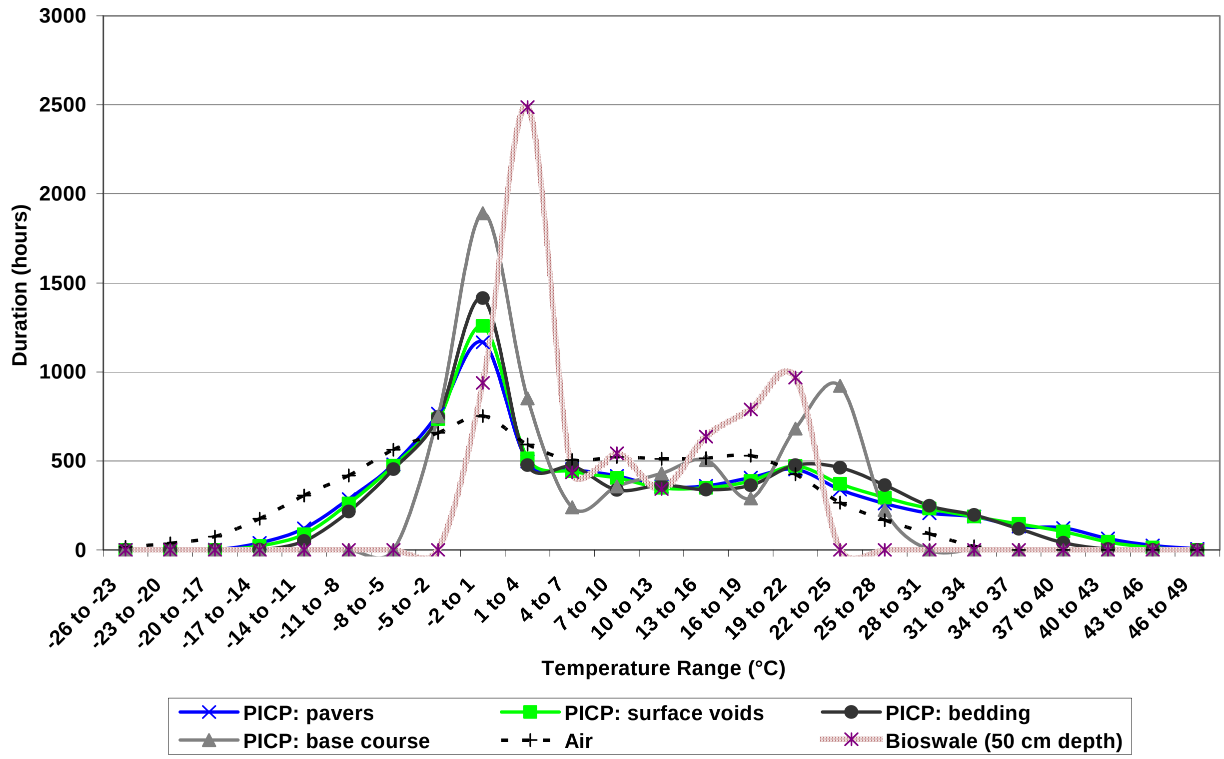


Figure 5.9: PICP and air temperature durations - January 24, 2007 to January 23, 2008

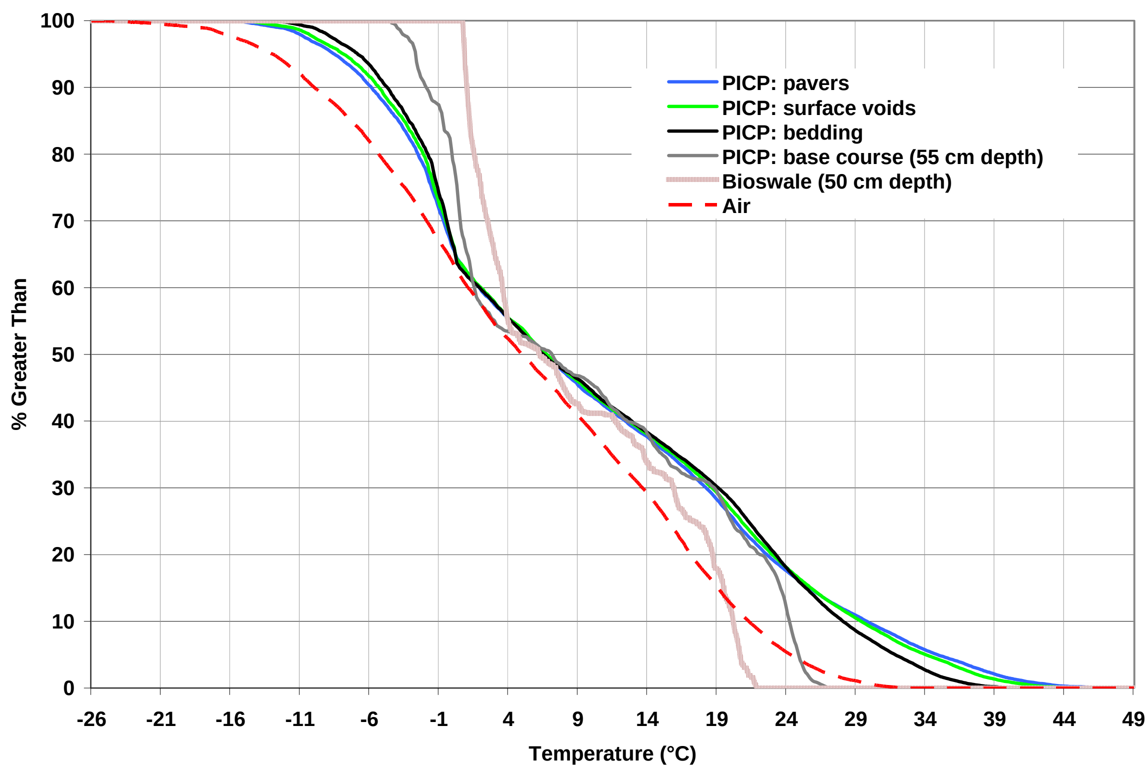


Figure 5.10: PICP and air temperature cumulative frequencies – January 24, 2007 to January 23, 2008

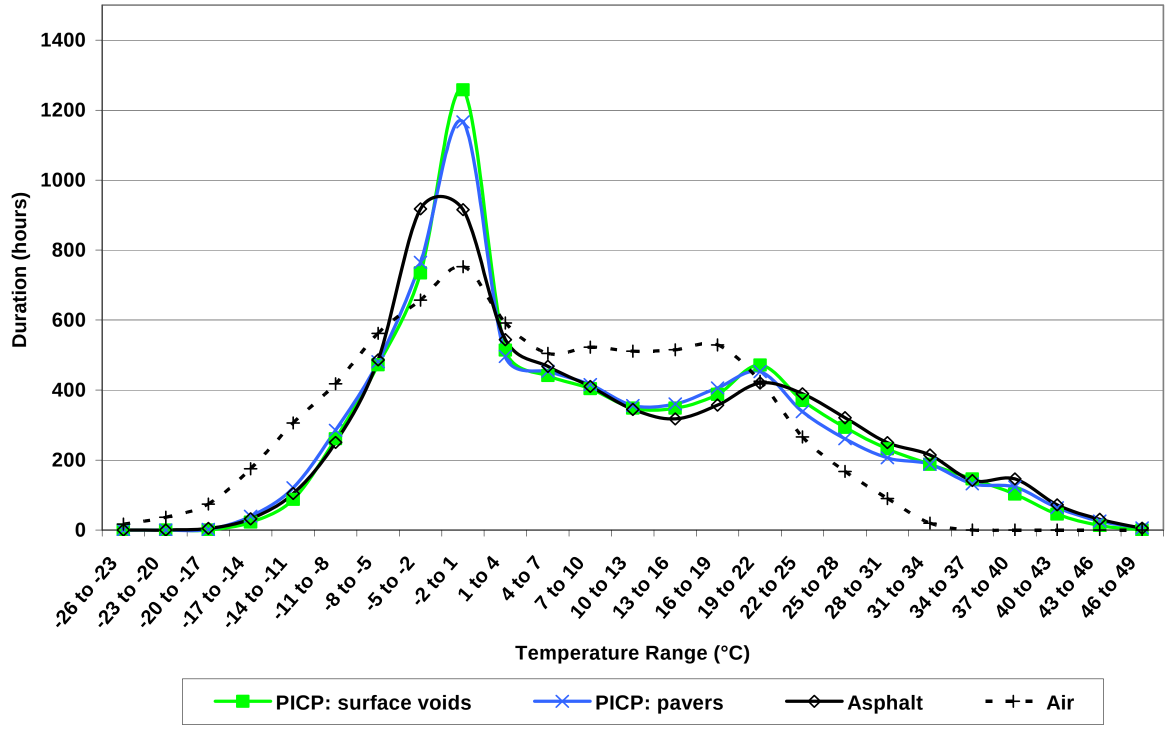


Figure 5.11: PICP, asphalt and air temperature durations - January 24, 2007 to January 23, 2008

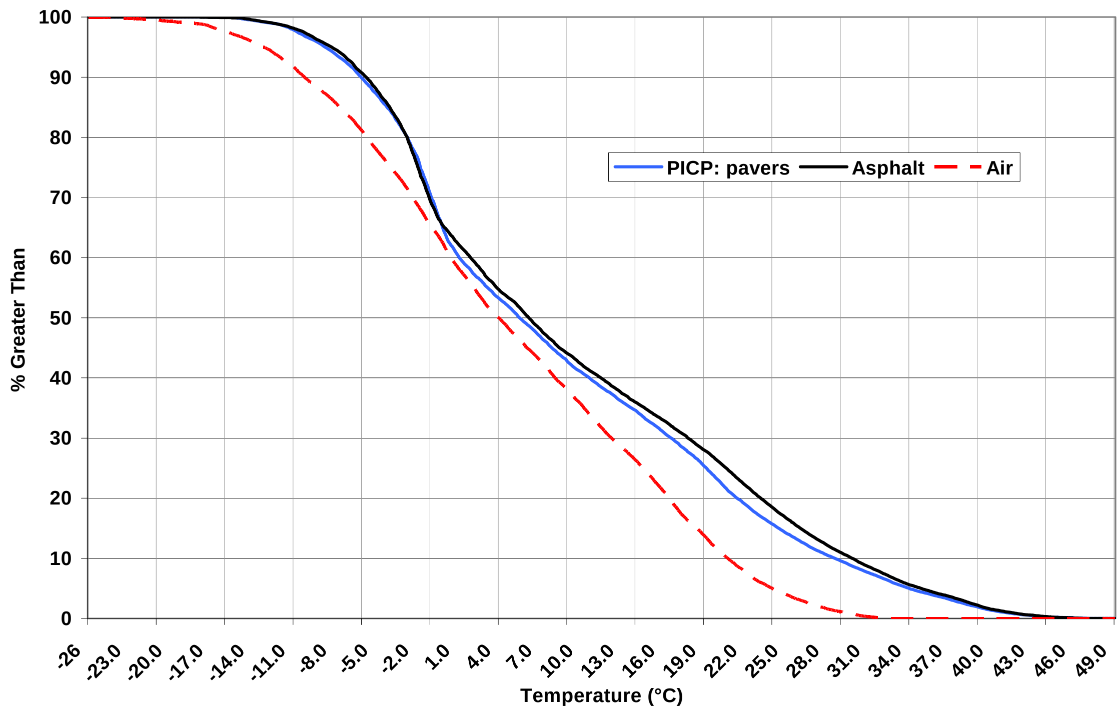


Figure 5.12: PICP, asphalt and air temperature cumulative frequencies – January 24, 2007 to January 23, 2008

The bioswale soils (at 50 cm depth) remained above 0°C over the entire year, and exhibited a much narrow range of temperature fluctuations than the pavements. The warmer temperatures reflect the good insulating properties of the soil, plant shading during the summer, and the active processing of organic material by soil microbes. The irregular shapes of the base course and bioswale cumulative frequency curves reflect the alternating effects of water and air on the temperature sensors as water is temporarily stored and then drains.

The asphalt and PICP surface temperatures are compared in Figures 5.11 and 5.12. The two pavement surfaces exhibited similar temperature fluctuations over all seasons, with minor differences at temperatures ranging from 0 to 38°C. Paver temperatures were observed above 20°C approximately 12% less often than the asphalt. The slightly cooler paver temperatures may be attributed to their lighter colour (*i.e.* higher reflectivity) and ability to dissipate heat through open joints between the pavers. While the differences are small, this finding suggests that this type of PICP may hold some benefit in mitigating against heat induced smog and other undesirable effects associated with the urban heat island.

During the winter, the temperature differences between PICP and asphalt were relatively small. The pavers were observed below 0°C approximately 3% more often than the asphalt. The main benefit of pavers during the winter relates to their capacity to prevent ponding and subsequent ice build-up by infiltrating surface water or snowmelt.

5.4 Soil Quality

5.4.1 Permeable pavements

Sediment samples were extracted from the upper bedding layer, the subgrade soils (or in two cases the lower base course) and nearby reference sites to assess the degree of soil contamination caused by infiltration of road runoff contaminants (see section 4.2.3 for a detailed description of methods). At the Seneca site, a sample was also collected from the subgrade and analyzed for soil quality prior to construction. Results of the analysis are presented in Figure 5.14 in relation to typical background soil concentrations in Ontario for agriculture and other land uses (OMOEE, 1997). In the following discussion of soil chemistry, the bedding, subgrade and reference site soil samples are discussed separately.

5.4.1.1 Bedding

The samples nearest the surface were coarse textured soils or granular media collected from the joints and the bedding layer immediately below the pavers. The quality of these samples was expected to be poorer than that of deeper subgrade or base course samples because they were closer to the source of contamination. However, analyses show most of these samples to be of comparable quality to deeper soils (Figure 5.13). While some metals (*e.g.* cadmium and zinc) were elevated in the bedding layers at the University of Guelph and Humber College sites, nutrients at all sites were lower than in subgrade soils, and PAH concentrations were similar. The quality of bedding samples rarely exceeded background concentrations for non-agricultural uses.

These results are in contrast to those reported by Legret *et al.* (1996) for a porous asphalt in France. They found much higher concentrations of lead, zinc, copper and cadmium in the surface pores of the asphalt than at the bottom of the base reservoir, 60 cm below the surface. Their samples were collected with a vacuum sweeper, and represent the upper most layer of fine particulate matter. In the Seneca study, the bedding samples were taken just below the surface drainage cells, where the fine particulate matter may be less concentrated. PICPs also have coarser granular materials at the surface than porous asphalt, allowing for dust and fine sediment to wash through the surface and distribute themselves more evenly throughout the base layers.

5.4.1.2 Subgrade

At most sites, the quality of PICP subgrade soils was similar to or better than Ontario background concentrations for non-agricultural land uses. In several instances, subgrade soil concentrations were also lower than agricultural background concentrations (Figure 5.13). Exceptions include zinc at the University of Guelph site and chloride at the Humberwood site, both of which were elevated relative to background concentrations, but still well below the levels where the soil would be considered to be contaminated (OMOEE, 1997).

The subgrade depth profiles showed some variations with depth but most of these could be attributed to natural variations in soil chemistry, rather than to influences associated with contaminant build-up. Together, the absence of a distinct depth profile, and the uncontaminated nature of most soils suggest that parking lot contaminants are being trapped primarily in the base course, rather than the underlying soils. Legret *et al.* (1996) reported a similar finding in their investigations of a porous asphalt in France

Seneca College was the only site for which soil samples were collected when the pavement was installed in the fall of 2005 (SG2005 in Figure 5.13) and after two years of operation in late 2007 (SG 2007). The results show very little change in most variables, which is consistent with the generally low level of contamination observed at all sites.

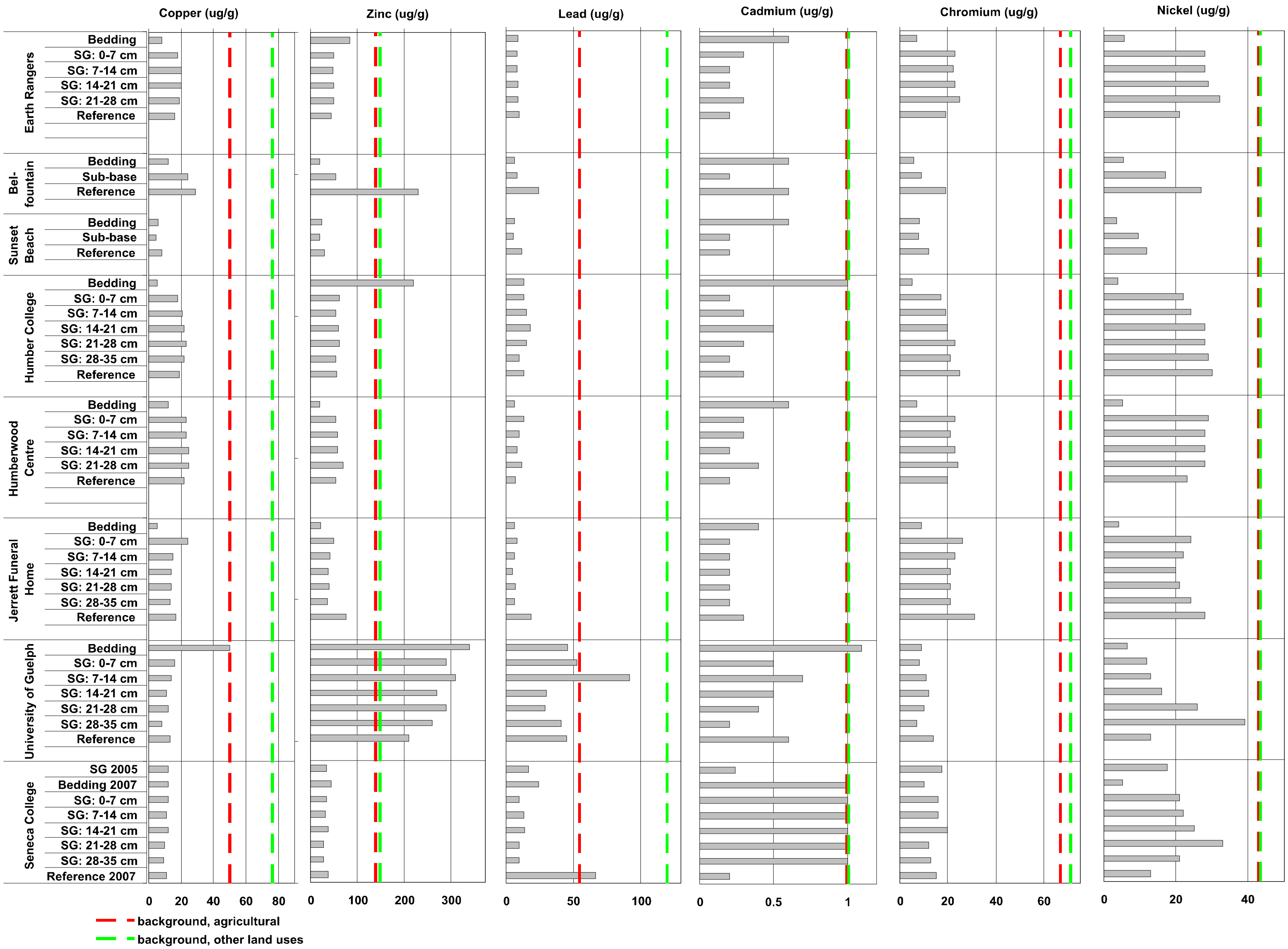


Figure 5.13: PICP, bedding, subgrade (SG) and reference site soil concentrations

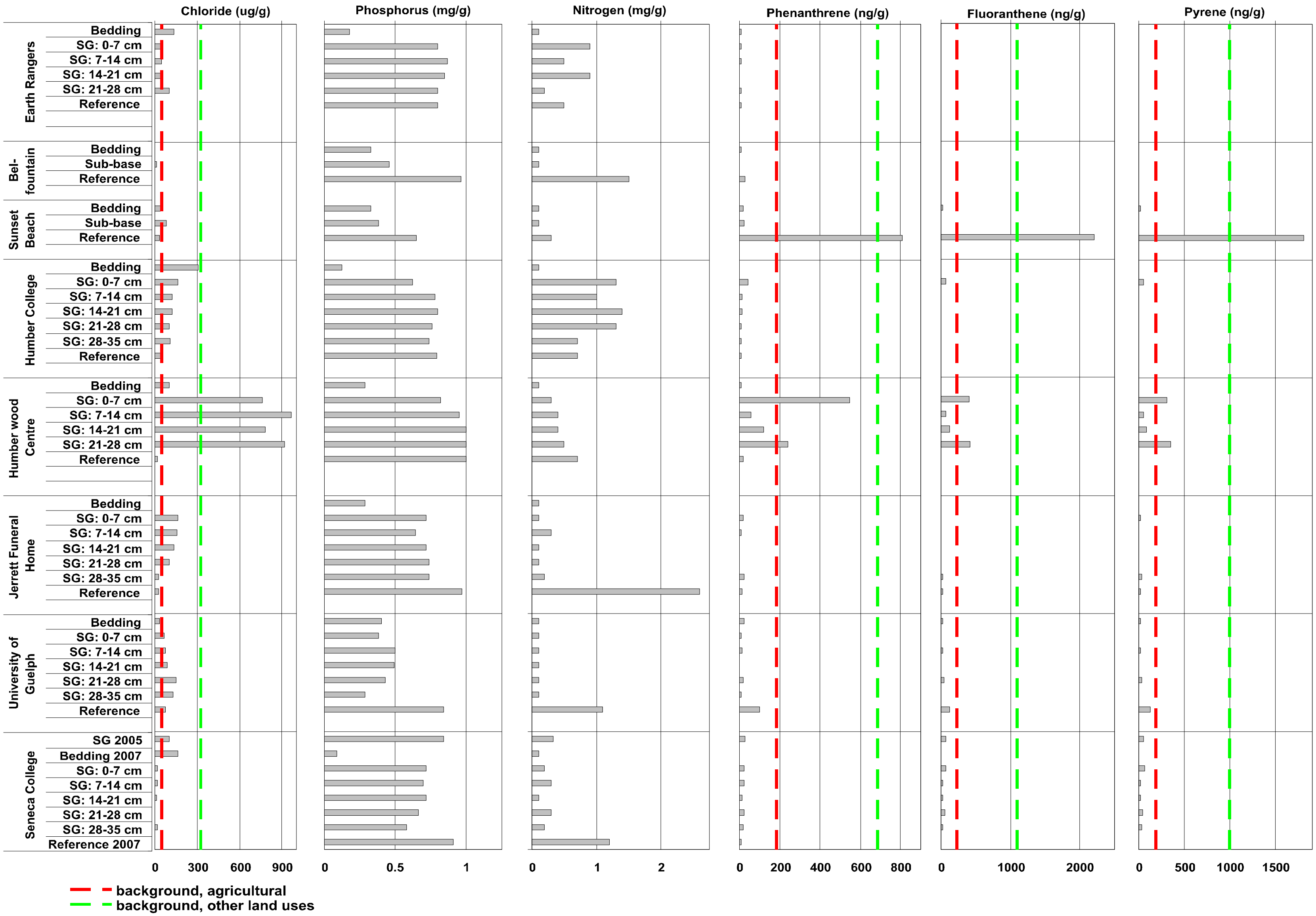


Figure 5.13 (continued): PICP, bedding, subgrade (SG) and reference site soil concentrations

5.4.1.3 PICP Reference sites

Figure 5.14 compares PICP and reference site soils. PICP soil concentrations of metals were similar to or lower than reference site soil concentrations. Chloride levels in reference soils were lower than PICP sites, as they were not subject to direct applications of road salt. Chloride accumulates in the subgrade over time, but in the absence of additional inputs, would be expected to eventually leach from the soil into the shallow groundwater system, eventually discharging to surface waters. PAH concentrations in the Humberwood and Seneca PICP soils were higher than those of the reference sites, but PAH levels at both PICP sites were below Ontario background concentrations (Figure 5.13). The Sunset Beach reference site had anomalously high PAH levels, which explains the very low ratio for PAHs at this site. A larger number of reference samples and more information on land use history at each of the sites may have helped to better explain inter-site differences in soil chemistry.

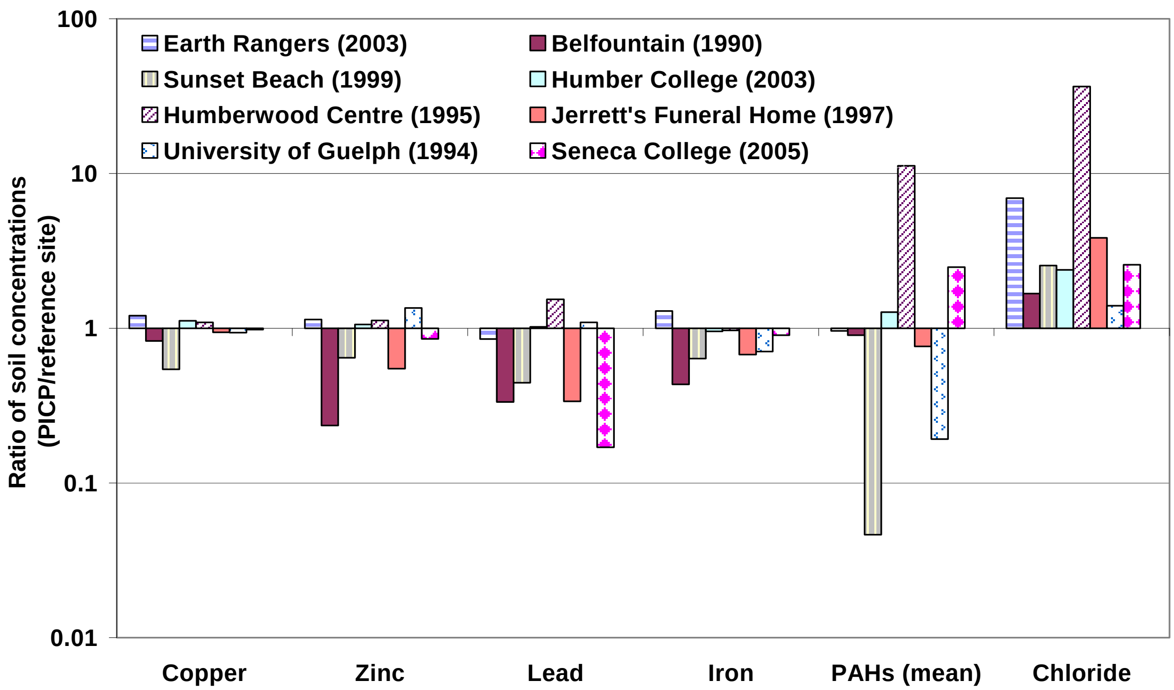


Figure 5.14: PICP soil concentration ratios. Values greater than 1 indicate that PICP concentrations were greater than the reference site, and vice versa.

5.4.2 Bioretention Swales and Ditches

Soil quality was assessed at the Seneca site and five other sites with bioretention swales or roadside ditches/swales to determine the extent to which road runoff contaminants build up in soils over time. Table 5.2 presents the name, age, condition and soil texture at all of the sites. The Royal York and DeVere gardens sites were road side ditches with culverts below the driveways. These were intentionally preserved by the residents to give the streets a more rural, country appearance. While the exact age of these ditches is unknown, they are probably at least a few decades old. These swales were intended to convey rather than infiltrate water. The other sites had swales or bioretention areas that were constructed between 1997 and 2006.

Soil cores were extracted to a depth of between 30 and 38 cm from the swale and a nearby reference site unimpacted by runoff. Figure 5.15 compares soil concentrations from these sites to 'typical background concentrations' for agricultural and other land uses in Ontario (OMOE, 1997). The concentrations of metals in the bioswale cores were below background concentrations for agricultural soils, and showed no consistent variation with depth. Metal concentrations in soils at the Seneca College site in 2005 and 2007 were similar, indicating little if any accumulation of metals in surface soils over a two year period.

Table 5.2: Character and condition of bioswales surveyed in 2006 and 2007

Site Name	Description	Constructed	Condition	Soil Type[1]
Royal York Road area	Roadside swales	Before 1990	Vegetated with natural grass	Loamy Sand
DeVere gardens area	Roadside swales	Before 1990	Vegetated with natural grass	Loam
TRCA Head Office	Wetland/bioswale	1997	Bare soil in ponding area; vegetated around the periphery	Silty Clay
York University	Bioswale	2002	Landscaped with rock swales, wood chips and liners	Silt Loam
University of Toronto Scarborough Campus	Bioswale	2006	Landscaped with rock swales, wood chips and liners	Sandy Loam
Seneca College	Bioswale	2005	Landscaped with mulch but not maintenaned	Loam

1. Soil type determined through grain size analysis

Chloride concentrations were typically above background concentrations for agricultural land use but below those for other land uses (Figure 5.16). There were no background concentrations for nitrogen and phosphorus. Concentrations of these nutrients were clearly much higher at Seneca than at other sites because of the nutrient rich garden soils used to construct the swale. Concentrations of PAHs varied substantially from site to site, but were mostly below background concentrations for 'other land uses'. The two roadside ditches at Royal York and DeVere gardens showed the highest levels of PAHs. The imported Seneca soils also contained relatively high levels of PAHs, even in 2005, soon after they were installed. However, infiltrate sampling suggests that these PAHs are not being leached from the media. In 2007, the depth profile at Seneca was the reverse of that observed in 2005, with higher concentrations deeper in the soil profile. The other three sites had very low levels of PAHs. Two of these were relatively new, whereas the TRCA site was 10 years old at the time of sampling. These results suggest that age and volume of runoff may not be the most important factors governing PAH buildup in bioswale soils.

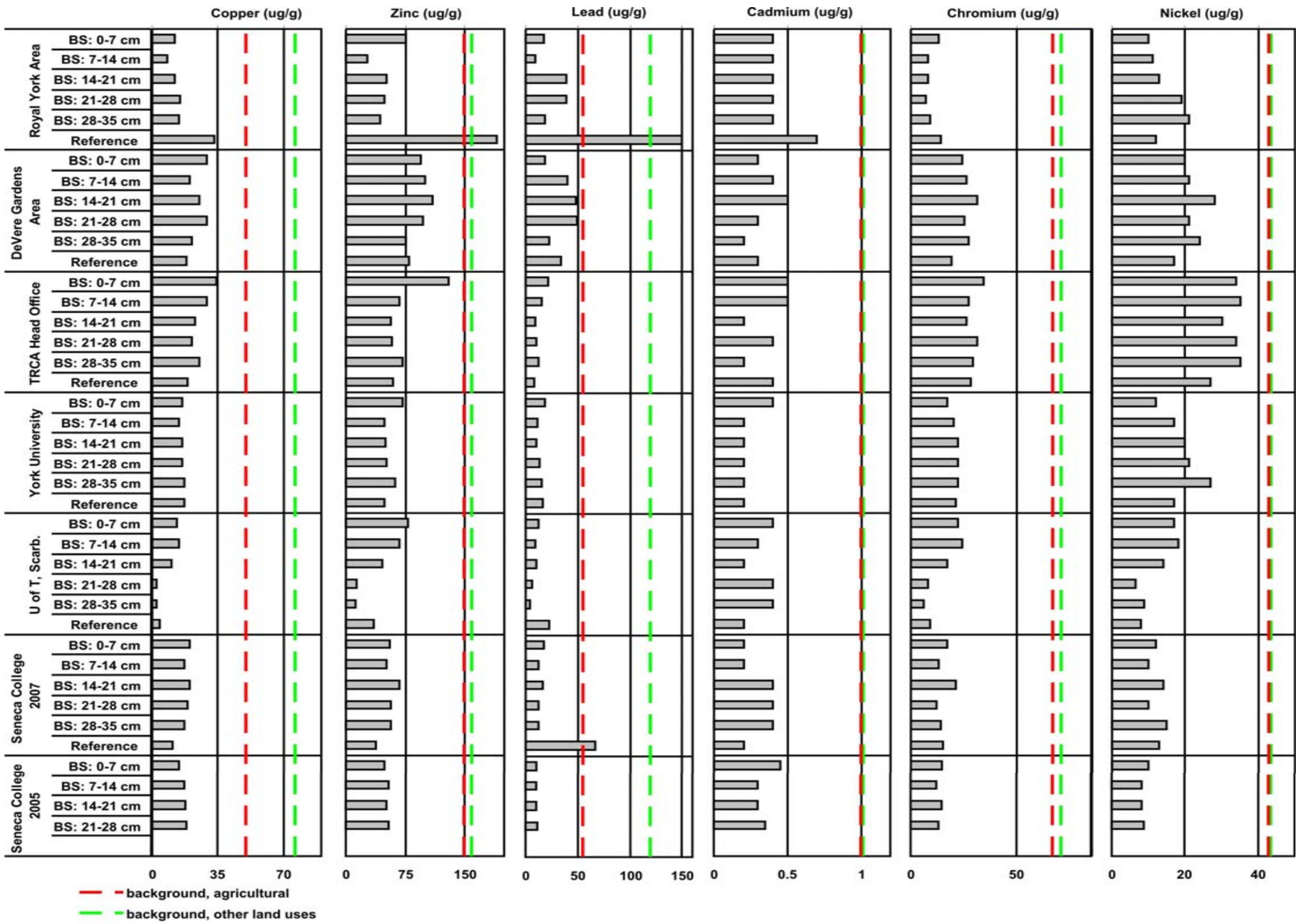


Figure 5.15: Bioswale (BS) and reference site soil concentrations

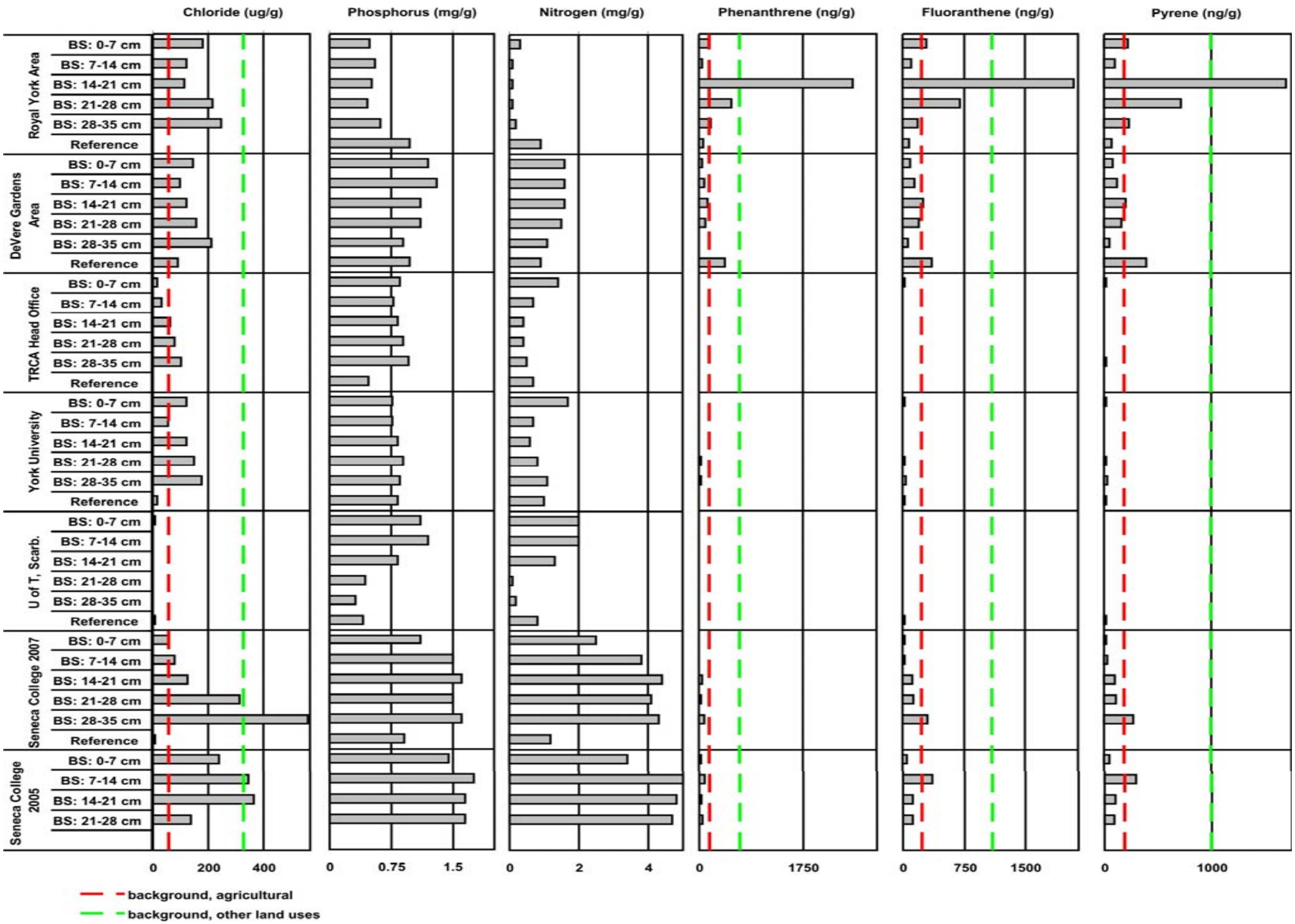


Figure 5.15 (continued): Bioswale (BS) and reference site soil concentrations

5.4.2.1 Bioswale Reference Sites

The bioswale and reference site soils are compared in Figure 5.16. The pattern is similar to that observed at the PICP sites (Figure 5.14), with mixed results for PAHs and metals, and generally higher bioswale concentrations of chloride. Chloride and sodium levels in soils would vary throughout the year as deicing chemicals are added and subsequently leached down to lower soil layers. Plants and grasses were thriving on the swales despite chloride accumulations well above reference site levels. The newest site, at the University of Toronto, was the only swale with chloride concentrations lower than the reference. Sand rather than salt may have been used in this area for winter road maintenance. The Seneca site had much higher PAHs than the reference site but, as noted earlier, these PAHs were part of the original soil imported to construct the swale, and had little to do with accumulations occurring over the course of the study.

Overall, the bioswale soils would not be considered contaminated as soil concentrations for all variables tested are generally below background concentrations, and well below OMOE (1997) soil remediation criteria for potable and non-potable groundwater conditions.

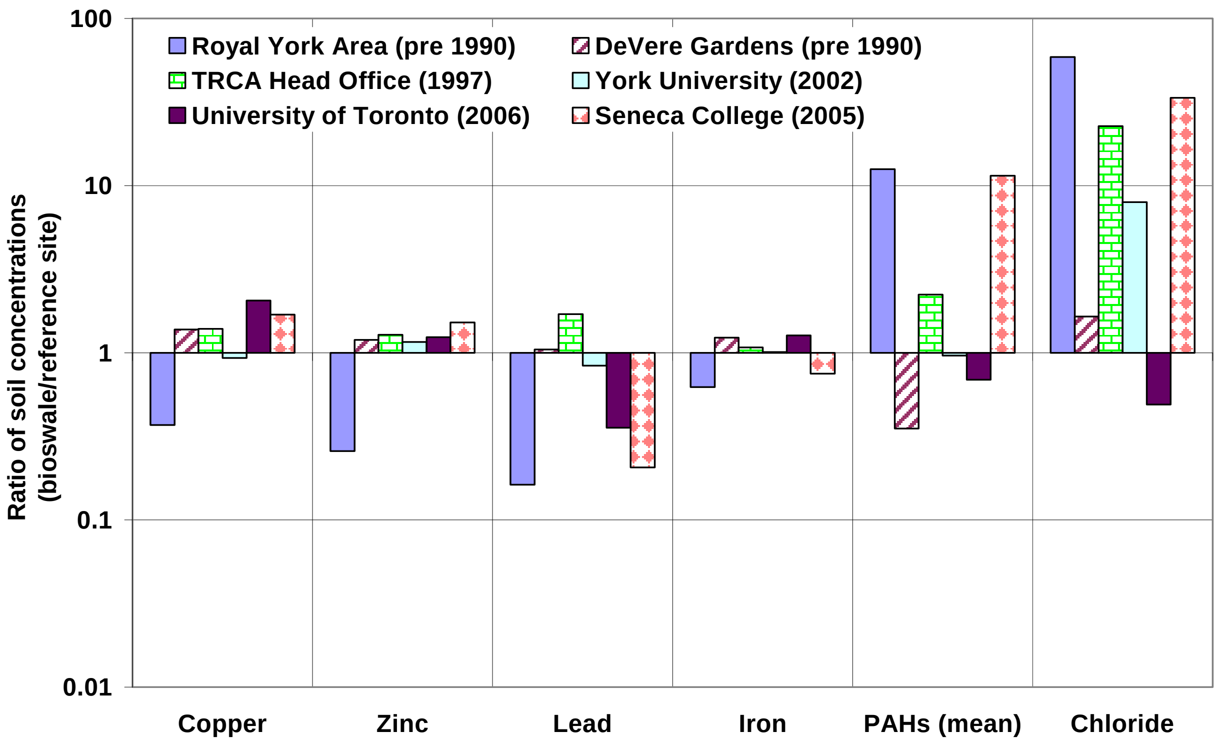


Figure 5.16: Bioswale soil concentration ratios. Values greater than 1 indicate that PICP concentrations were greater than the reference site, and vice versa.

5.5 Structural Integrity

Visual surveys of the older PICPs indicated that the pavements were holding up well from a structural point of view. There were very few signs of slumping or heaving due to freeze-thaw conditions (Table 5.1). The Humber College site had a few broken pavers and the Humberwood and Guelph sites showed some signs of slumping, but they continued to provide a suitable surface for parking. The Guelph site had been subject to heavy construction traffic during the construction of a nearby building a few years earlier, which likely contributed to surface displacement observed at that site. Minor surface undulations are normal for interlocking paving and should be expected when using these products.

Researchers from the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo conducted tests of load bearing capacity at the Seneca and Earth Rangers sites using a portable falling weight deflectometer (PFWD). Results presented here are based on a detailed report prepared by the study team (Koeth *et al.*, 2008). The two PICP sites were constructed with the same type of pavers and had similar base materials. The PFWD is designed to impart a load to the pavement equivalent to a rolling vehicle with an axle load of approximately 1800 kg (or 4000 lbs). The PFWD tests were conducted on October 5, 2007, March 6, 2008 and June 12, 2008 representing dry, cold or partially frozen and wet states. A total of 12, 6 and 32 test locations were selected for testing on the Seneca PICP, Seneca asphalt and Earth Rangers PICP, respectively. The pavement moisture and temperature conditions were determined by TRCA.

Table 5.3 presents the weather and base course conditions at the Seneca site during and before the three test dates in the fall, winter and spring. Similar measurements were not available at the Earth Rangers site. The temperatures on October 5 and June 12 were much warmer than on March 6^{th}. On all dates there was some water in the base. Water levels were greatest on June 12^{th}, when the base was almost half full of rainwater from an event the day before.

Figure 5.17 shows the deflection and elastic modulus results obtained from the PFWD tests (Koeth *et al*., 2008). All of the pavements exhibited seasonal changes in strength. Elastic modulus values were highest and deflection values were lowest during the winter (March 6, 2008), indicating that the pavements are stiff and structurally sound during the winter when the upper base layers are frozen. Although the temperature of water in the Seneca PICP base was below 0°C on March 6^{th}, the water levels continued to fluctuate, suggesting that the ponded water remained in a liquid or semi liquid state. Frozen water or ice crystals trapped in the pores of the bedding and upper base layers likely contributed to the increased strength and stiffness of the pavements during the winter.

Table 5.3: Average temperatures and water levels on the test dates

Test Date	Air Temperature (°C)	Temperature of Seneca PICP Base Course	Surface Temperature		Seneca PICP Base Course Water Level (mm)
			Seneca PICP	Seneca Asphalt	
Oct. 5, 2007	19	19	29	n/a	144
Mar. 6, 2008	-1	-1	1	-2	220
Jun. 12, 2008	17	22	27	26	290

Although the October test date was intended to represent a dry day, as it had not rained for several days, water level measurements at the Seneca PICP site showed some water ponded in the base. The presence of water in the base may account for the similarity in elastic modulus and, to a lesser extent, deflection results on the June and October test dates. The asphalt would have had less water entering the base, and may have been significantly drier in October than on the wet day in June. If correct, this hypothesized difference in moisture content may partly account for the differences in asphalt deflection values on these two dates.

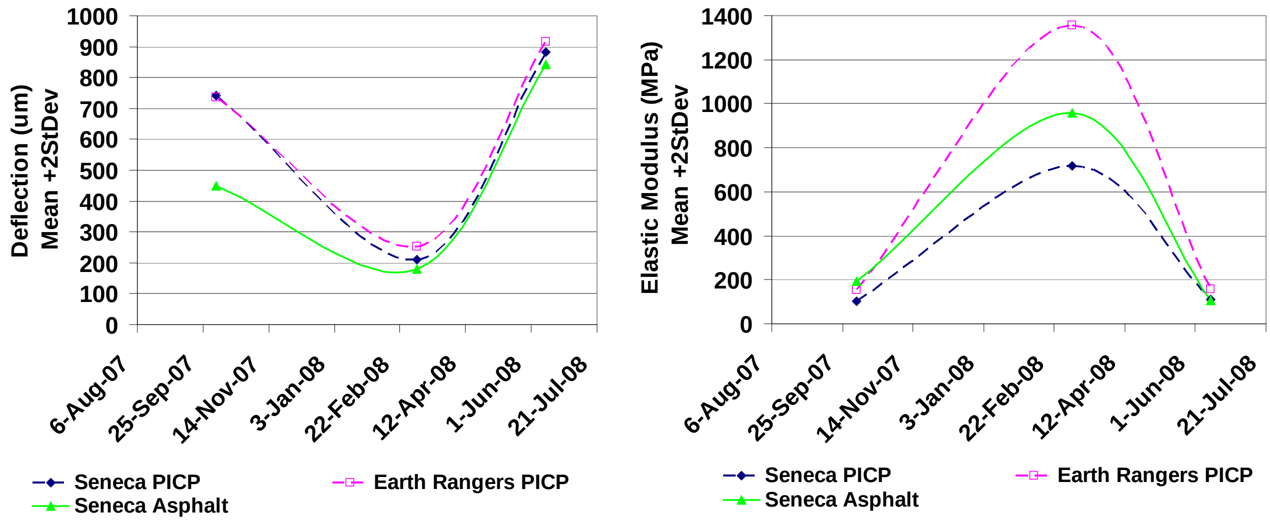


Figure 5.17: Deflection and elastic modulus results (adapted from Koeth *et al.*, 2008)

Overall, these results do not show a dramatic difference in strength between the asphalt and PICP pavements. The lower asphalt deflection values on the dry day may be due to differences in moisture content. The strong seasonal change in pavement strength suggests that the pavements are weaker during warm weather, and that they may be more susceptible to damage from heavy truck loading during this time.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Runoff and infiltration

Results of this study show that permeable interlocking pavers and bioretention swales offer significant stormwater management advantages over conventional impervious pavement drainage systems. Chief among these is the capacity to reduce surface runoff volumes. Over a 32 month period, only one very large rain event produced surface runoff from the PICP. The overflow volume during this event was less than 10% of total runoff from the asphalt pavement. The bioswale overflowed more frequently, but still met its design objective of storing and infiltrating runoff from storms with at least 15 mm of rain. While the reduction in runoff in both cases was likely enhanced to some degree by the presence of a liner and underdrain, the results nevertheless suggest that these technologies can contribute significantly to restoring or maintaining natural infiltration functions in an urban landscape, even on low permeability clay based soils.

In addition to reducing surface runoff volumes, the two infiltration practices also helped to delay and reduce peak flows by storing runoff and releasing it slowly through the underdrains over a period of several days after a storm event. Peak infiltrate flows were less than 5% of asphalt peak flows. The slower and more controlled flows help protect downstream watercourses and infrastructure by reducing flood risk and preventing stream erosion caused by post-development changes to the flow regime.

Base course water level monitoring of the PICP since September 2006 indicated that the 60 cm granular base reservoir was rarely filled to more than two thirds of its capacity. This finding suggests that a reduction in base thickness by one third (*i.e.* to 40 cm) would not have significantly affected its capacity to store and infiltrate runoff. In typical applications on low permeability soils, the underdrain would be located in the base course, which would further reduce the potential for surface overflows.

Winter data show the PICP functioning well during cold weather with air temperatures as low as -25°C. Minimum base course temperatures (at 55 cm depth) in 2007 and 2008 were -5°C and -2°C, respectively. Even at these temperatures, water levels in the base continued to fluctuate. Accumulation of sodium chloride in the base reservoir may have helped to ensure water remained in a liquid or semi-liquid state. The probability of ice formation in the base course tended to increase during the late winter period when snow melt or rain was followed by a sudden drop in temperatures. A similar phenomenon was not evident in the early winter period because higher base course temperatures provided a good buffer against sudden changes in air temperature.

The bio-retention swale also performed well during the winter. Soil temperatures (at 50 cm depth) remained consistently at or above 0°C and infiltration occurred throughout cold weather. The presence of an insulating layer of snow and microbial activity associated with the organic soils were suggested as important factors explaining the higher temperatures. During spring thaw, there was no evidence of melt waters backing up onto the parking lot as a result of ice and snow buildup around the perimeter of the swale.

6.1.2 Surface infiltration

Older PICP sites tended to have lower surface infiltration rates than newer ones. The oldest site (17 years) had a surface infiltration rate of 36 mm/h, which is similar to an uncompacted sandy soil. The infiltration rate (1200 mm/h) at the newer Seneca site was more typical of course gravel. Use of sand instead of gravel as a bedding layer and joint filler at many of the older sites likely enhanced the potential for clogging. Current guidelines from most jurisdictions recommend using open graded granular media in the base and surface joints of permeable interlocking concrete pavements.

6.1.3 Water quality

Sampling of stormwater quality after infiltration through 1 m of soil provided a measure of the potential for infiltrated water to contaminate groundwater. Chloride and sodium from de-icing salts were the biggest concern as both constituents are relatively mobile in soils. Concentrations of these constituents were well above drinking water standards. The road salts may also have increased the mobility of metals as there was a distinct rise in the concentrations of several trace metals mid way through the second winter of monitoring. Several studies have shown relationships between deicing chemicals and increased mobility of metals, particularly cadmium and zinc (*e.g.* Norrstrom, 2005; Backstrom *et al*., 2004). Other factors potentially influencing the rise in metal concentrations include an increase in surface loading and preferential pathways through cracks in the soil matrix or along the liner. In this study, cadmium and lead were of greatest concern as both were occasionally observed in infiltrate samples above drinking water standards. The processes governing the transport of metals through soils under permeable pavements and bioswales where road salts are applied is a topic that requires further investigation.

Over the monitoring period, median concentrations of several variables in PICP infiltrate were significantly (α=0.05) lower than median concentrations in asphalt runoff, including oil and grease (solvent extractable), total phosphorus, total suspended solids and zinc. The PICP structure leached environmentally beneficial constituents, such as calcium and alkalinity. Median concentrations of nitrate in infiltrate were higher than asphalt runoff (α=0.05) but overall concentrations were relatively low. Statistical differences could not be determined for lead, cadmium, chromium and PAHs because of low detection frequencies (<50%) from all outlets. Detection frequencies for lead and PAHs were considerably greater in asphalt runoff.

Median concentrations of zinc in bioswale infiltrate were significantly lower than in asphalt surface runoff, and other contaminants such as lead and PAHs were detected much less frequently. Nutrients such as phosphorus, ammonia and TKN were leached from the organic bioswale soils resulting in significantly higher infiltrate concentrations relative to asphalt runoff (α=0.05). Median concentrations of nitrate, oil and grease, and copper in bioswale infiltrate were not significantly different from asphalt runoff. Most of the oil and grease in the bioswale was probably from natural sources (*e.g.* manures, compost).

6.1.4 Temperature

The surface temperatures of the asphalt and PICP were similar throughout the year. During the summer, asphalt was slightly warmer, with temperatures above 20°C roughly 12% more often than the pavers. This difference was attributed to the lighter colour (*i.e.* higher reflectivity) of the pavers and their ability to dissipate heat through open joints. While the temperature differences are small, this finding suggests that PICPs may hold some benefit in mitigating against heat induced smog and other undesirable effects associated with the urban heat island. During the winter, temperature differences between the PICP and asphalt were negligible. The main benefit of the PICP during cold weather lay in its ability to reduce ponding and ice-buildup by infiltrating snow melt.

6.1.5 Soil Quality

Soil sampling of 7 older PICP parking lots and 5 older swales or ditches indicated contaminant levels below Ontario soil 'background' concentrations for nonagricultural land uses. Exceptions on the PICP sites include zinc at the University of Guelph site and chloride at the Humberwood site. On the bioswales, PAHs were above background concentrations for nonagricultural land uses at one of the oldest sites (Royal York). However, soil concentrations of these variables were still well below Ontario soil remediation criteria (OMOEE, 1997), which are used in Ontario to determine whether remediation or landfilling of soils is necessary.

At the Seneca site, soil cores were extracted for analysis from the swale and PICP subgrade in 2005, and again in late 2007. Although more samples would be needed to establish a statistical difference, the absence of an apparent change in swale or PICP subgrade soil chemistry over this time period is consistent with generally low soil contamination observed at other older sites.

6.1.6 Structural Integrity

Visual observations from older PICP sites showed that, from a structural point of view, the pavements continued to meet the expectations of users, with few signs of slumping or heaving. A Portable Falling Weight Deflectometer was used to evaluate pavement strength at the Seneca and Earth Rangers sites during the fall, winter and spring. These tests indicated that the asphalt and PICPs were comparable in strength. Both pavement types were weaker during the summer, rendering them more susceptible to damage from heavy truck loading during this time.

6.2 Recommendations

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

6.2.1 Design

- Measurements of water level fluctuations in the PICP base course indicated that, at this particular site, a base course depth of 40 cm would have provided sufficient storage capacity for most rainfall events.
- Applications of PICPs and bioswales on low permeability soils with underdrains in the base reservoir should include a flow restrictor on the drainage pipe to maximize infiltration by allowing water to slowly drain and seep into the ground after an event. Water levels in the base reservoir

should be monitored to ensure that the drawdown period is well suited to the particular soil and climate conditions for a given area.

- The potential for de-icing salts to mobilize heavy metals may warrant an increase in the current allowable depth to the seasonally high ground water table from one meter to two or more meters below the base of the PICP or bioswale installation.
- Effective porosity of the granular 'A' sub-base materials was very low, limiting the capacity of the reservoir to detain stormwater runoff. Use of clear washed stone would help improve the storage capacity of the base reservoir.
- Surface infiltration tests in this and other studies confirm that using sand as a bedding layer or applying sand on pavements during the winter slows surface infiltration and significantly increases the risk of premature clogging.
- In bioswales, garden soils with high organic content should be limited to the upper 20 cm and underlain with a sandy soil mix to reduce the export of nutrients through underdrains while maintaining good permeability.

6.2.2 Operation and Maintenance

- Alternative deicing products such as calcium magnesium acetate should be considered in the winter on permeable parking lots where there are concerns that groundwater resources may be contaminated with sodium or chloride.
- Good infiltration through the pavers after 3 years of operation suggested that vacuum washing of PICPs may be needed only once every three to four years. Higher maintenance frequencies may be required in areas with greater traffic volumes.
- Base course water levels should be monitored periodically to provide early warning of potential reductions in subgrade infiltration rates.
- Soil quality results from older PICP and bioswale sites indicate that land fill disposal or remediation of the underlying soils would typically not be required when the pavers or swales need to be replaced.

6.2.3 Topics for further research

- *The quality of effluents from underdrain applications of PICPs.* This study examined water quality after infiltration through the base reservoir and one meter of native soil. In most installations on low permeability soils, the underdrain is placed within the base course to ensure sufficient storage capacity is available for subsequent storms. Monitoring of water quality should be undertaken to determine whether these types of underdrain applications provide an acceptable level of water quality control. Tests should be conducted over varying detention times (*e.g.* 12, 24, 48 hours) as contaminant loading from underdrains will be strongly influenced by residence time in the base reservoir and the volume of water that infiltrates.
- *Impact of de-icing salts on the mobility of metals beneath PICPs and bioswales.* While previous studies have shown that de-icing salts can increase the mobility of some heavy metals in stormwater runoff, few researchers have examined the specific chemical and physical processes responsible for enhanced metal mobility beneath permeable pavements and bioswales. Data

collected at the Seneca site suggest that this could be an important issue that requires further investigation.

- *Long term infiltration beneath PICPs and bioswales.* While several studies have examined surface clogging of pavements, few have evaluated the long term effects of stormwater infiltration on the infiltration capacity of subgrade soils and bioswale media. This may be particularly relevant in cold climates where de-icing salts can affect infiltration rates by altering the physical structure of soils.
- *The structural and hydrologic attributes of open and dense graded bases.* In Ontario, most PICP bases have been constructed using standard Ontario 'granular A' media, which includes a mixture of fines, sand and gravel up to 20 mm in diameter. Guidelines from Vancouver and other jurisdictions in the United States and Britain recommend using 'open graded' media (or clear stone), which have a narrower particle size range, and exclude fines. The comparative influence of clear stone and granular 'A' on PICP structural integrity, infiltration and water storage properties needs to be examined further.
- *The role of reactive media in improving water quality.* Heavy metals are a major contaminant of concern in runoff. Further research is needed on the potential for reactive media to reduce the export of heavy metals and other contaminants by retaining them within the base course or bioswale soils.
- *Microbial degradation of hydrocarbons within PICP installations.* Some European studies of permeable pavements have shown that vehicle oils and greases are degraded by microbes living on the geotextile located between the granular media and native soils. The effectiveness of these processes under local conditions, particularly during the winter, is a topic requiring more study.
- *The hydrologic characteristics of PICPs on clay based soils.* Most of the remaining buildable area in the Greater Toronto Area is located on low permeability (hydrologic group C and CD) soils. There has been little PICP research conducted on these types of soils as they are often regarded as providing limited infiltration benefits. This and other studies of infiltration systems in the GTA have demonstrated that these soils can have significant infiltration potential. More monitoring of permeable pavements is needed to quantify the flow reduction and water quality benefit of PICPs on clay based soils.
- *Structural characteristics of PICPs in cold climates.* The pavement structural tests showed greater stiffness during cold weather than in warm weather, but on all three test days, the base was partially filled with water. Further structural tests should be conducted under dry, wet, frozen and partially frozen states, as well as on bases of different depths, to determine the extent to which these different parameters affect the structural integrity of the pavement relative to a conventional asphalt surface.

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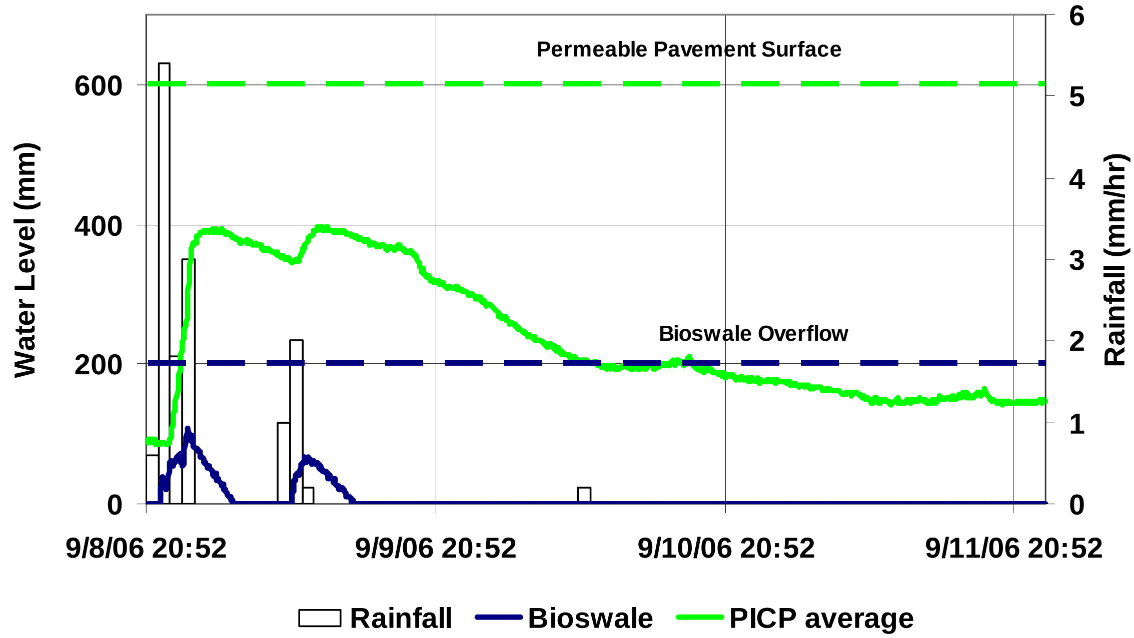
APPENDIX A:

Hydrographs, hyetographs, and water levels



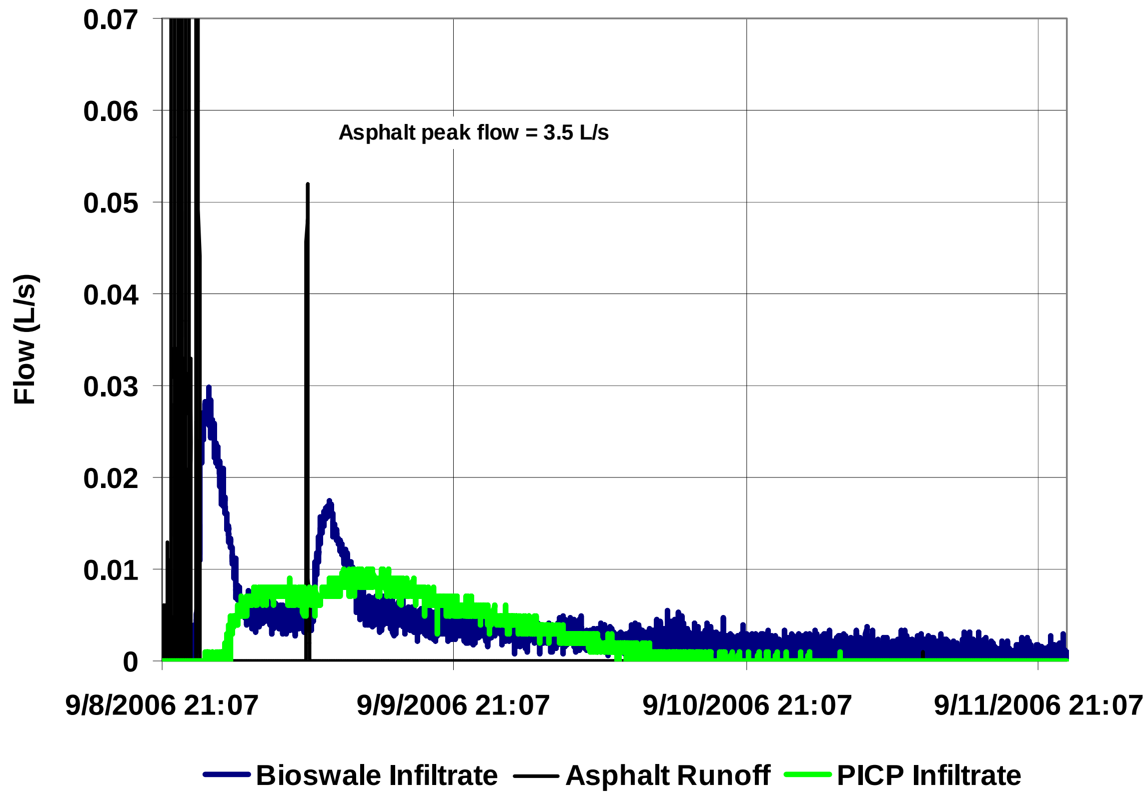
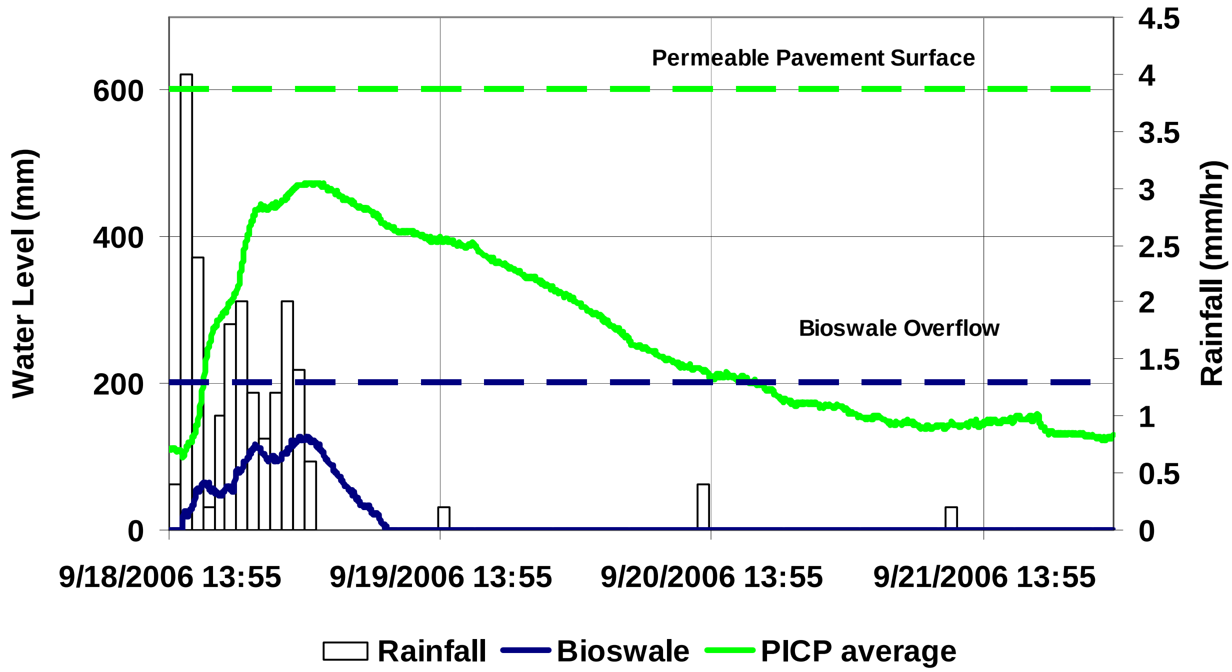


Figure A1: Hydrographs, hyetographs and water levels. Sept 8, 2006 – 14.2 mm

Note: Water levels are monitored in the PICP base and on the surface of the bioswale.



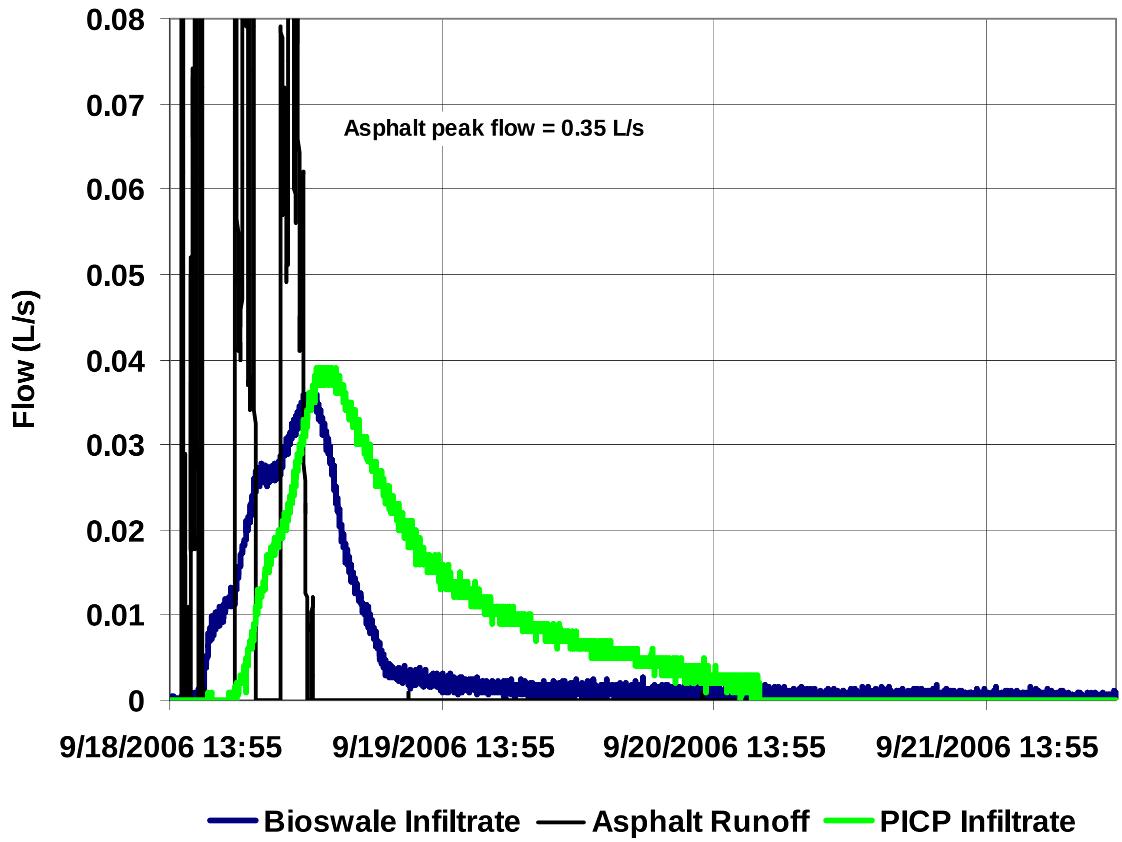


Figure A2: Hydrographs, hyetographs and water levels. Sept 18, 2006 – 19.8 mm

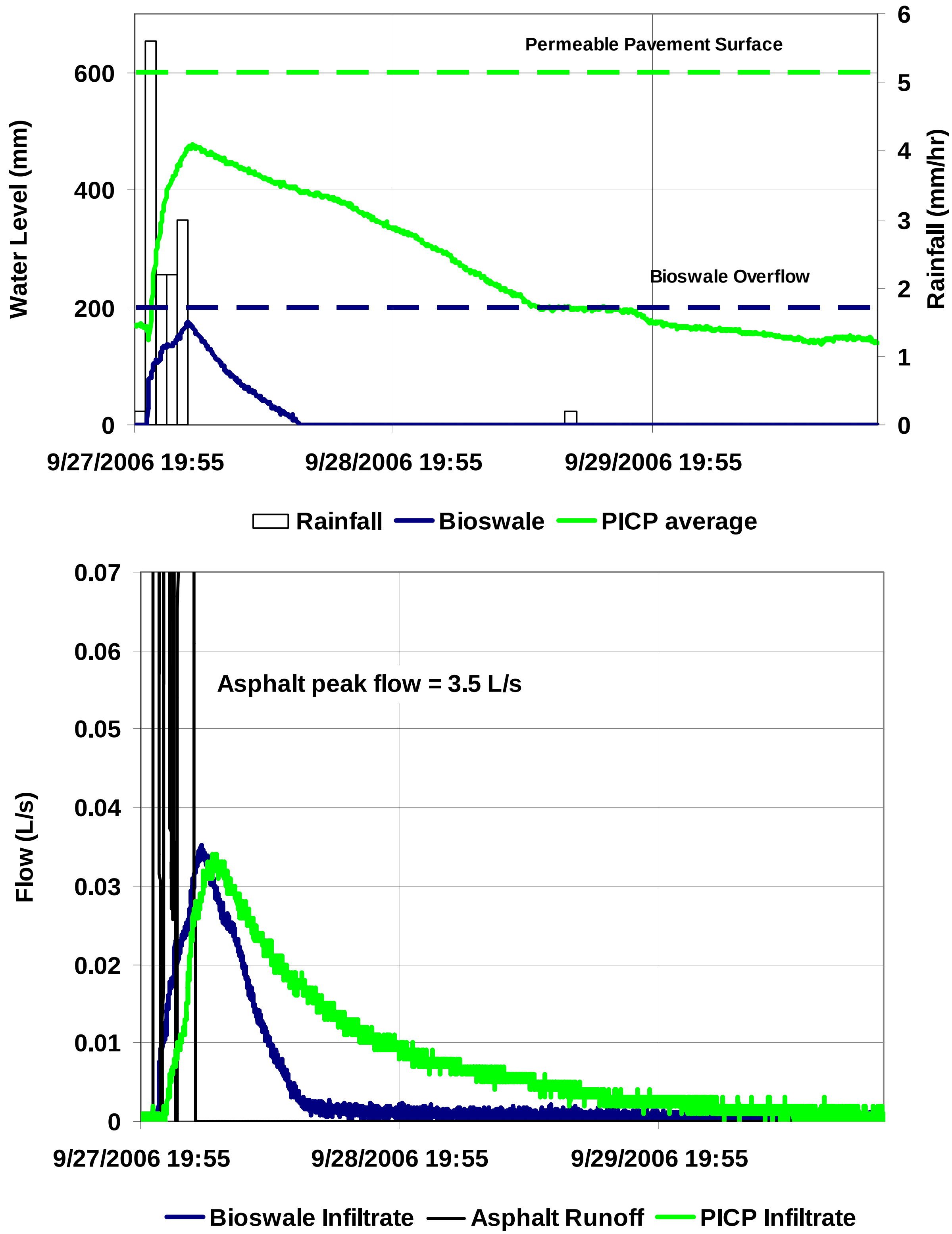


Figure A3: Hydrographs, hyetographs and water levels. Sept 27, 2006 – 13.4 mm

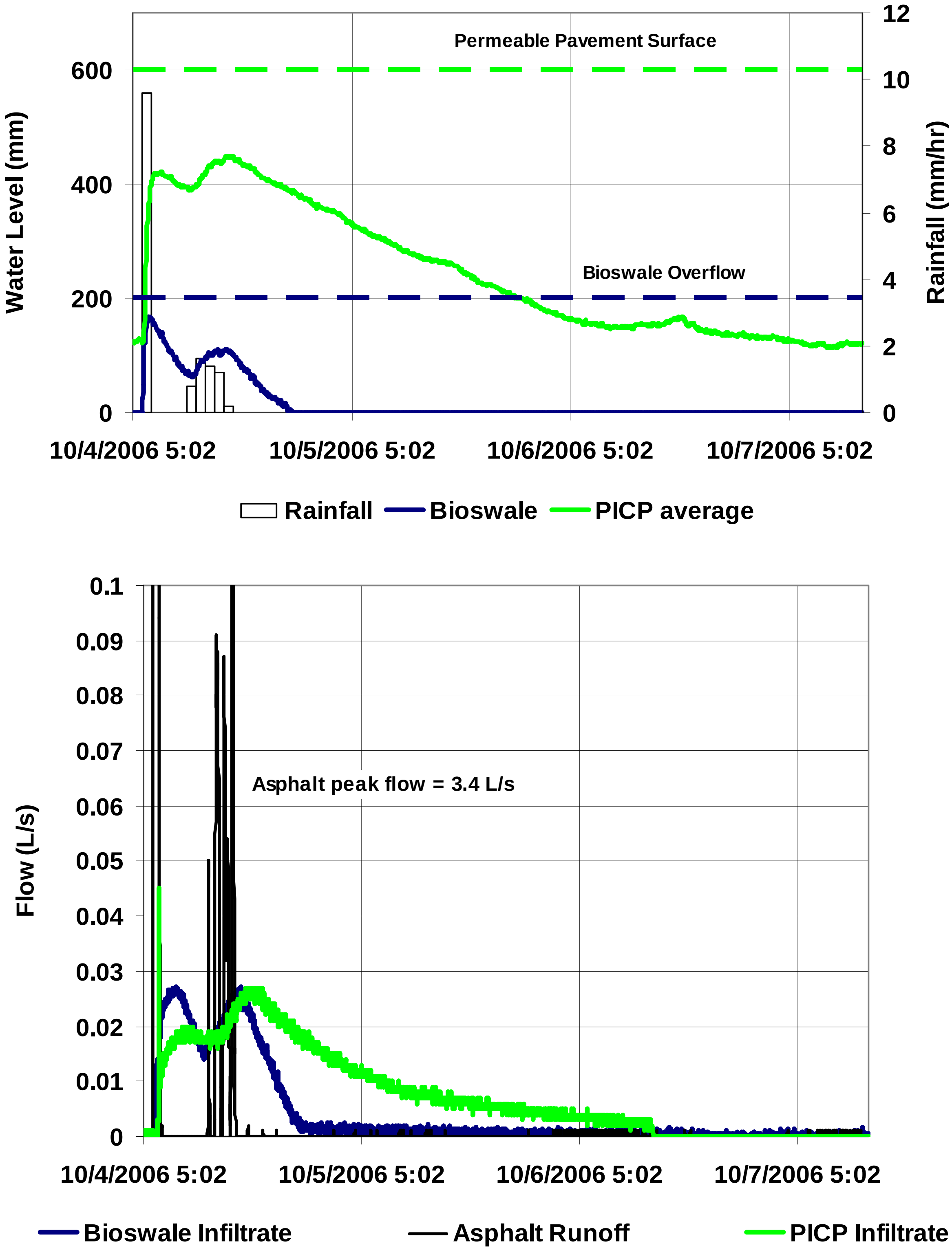


Figure A4: Hydrographs, hyetographs and base course water levels. Oct 4, 2006 – 14.8 mm

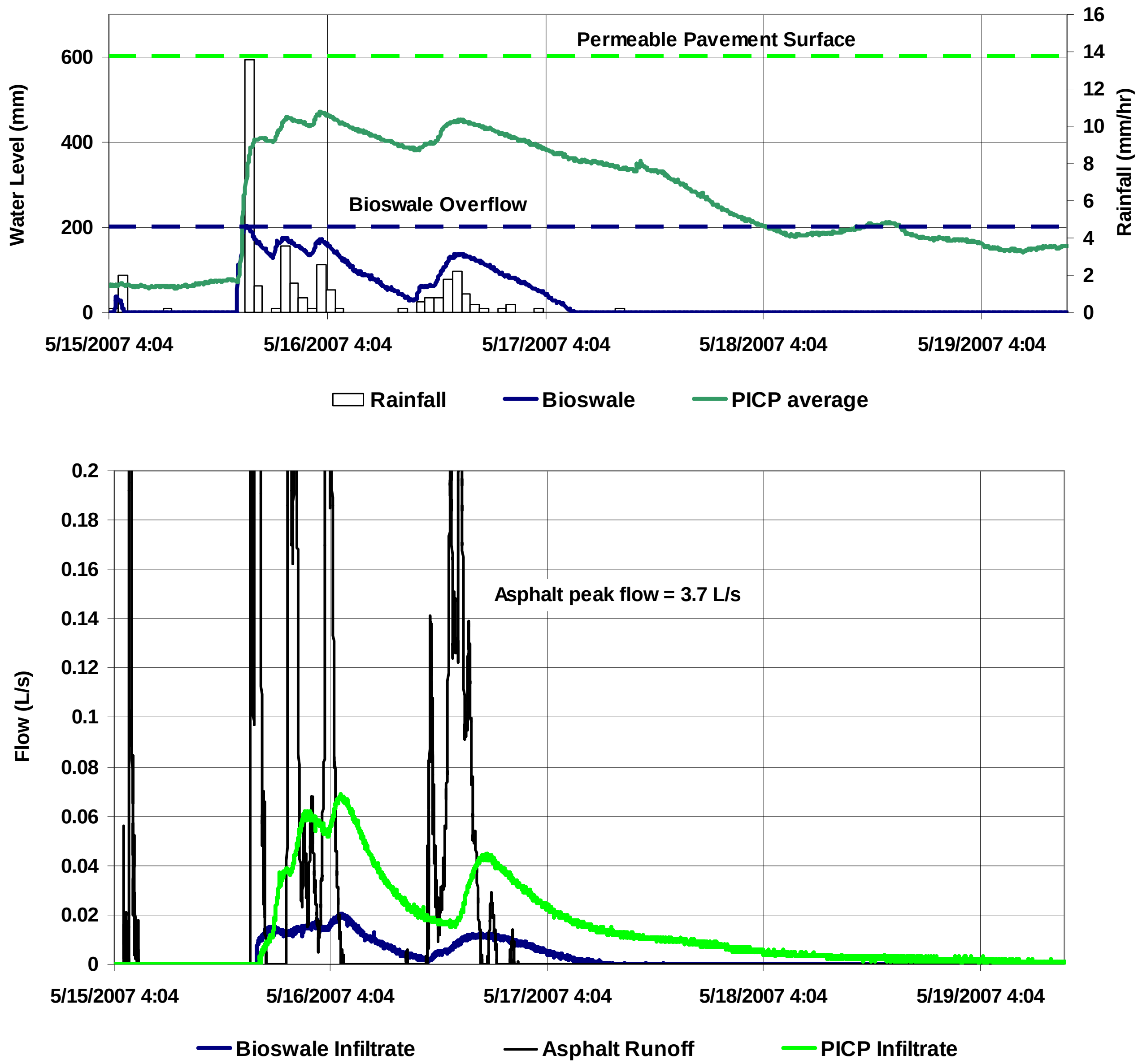
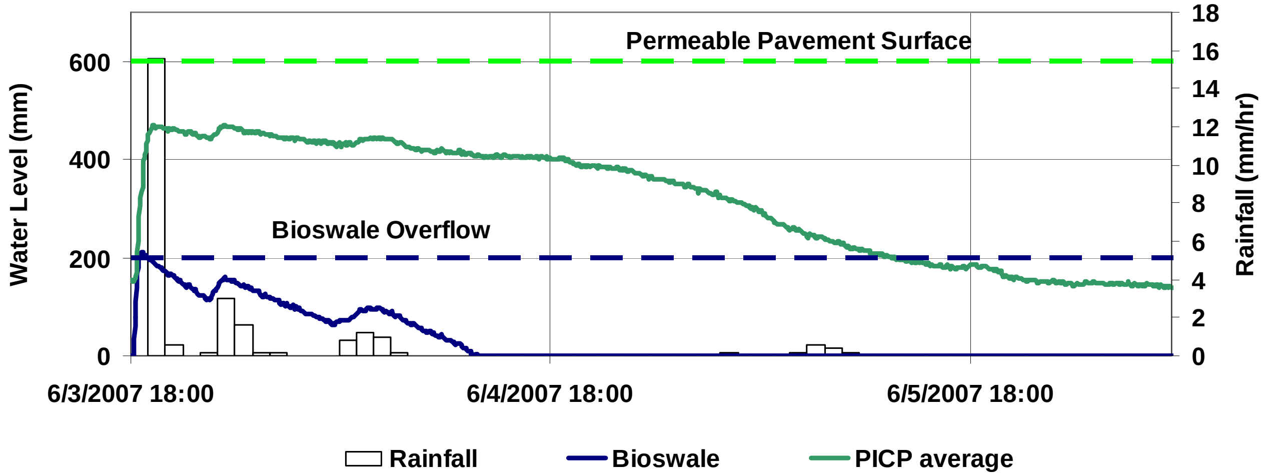


Figure A5: Hydrographs, hyetographs and base course water levels. May 15, 2007 – 34.2 mm



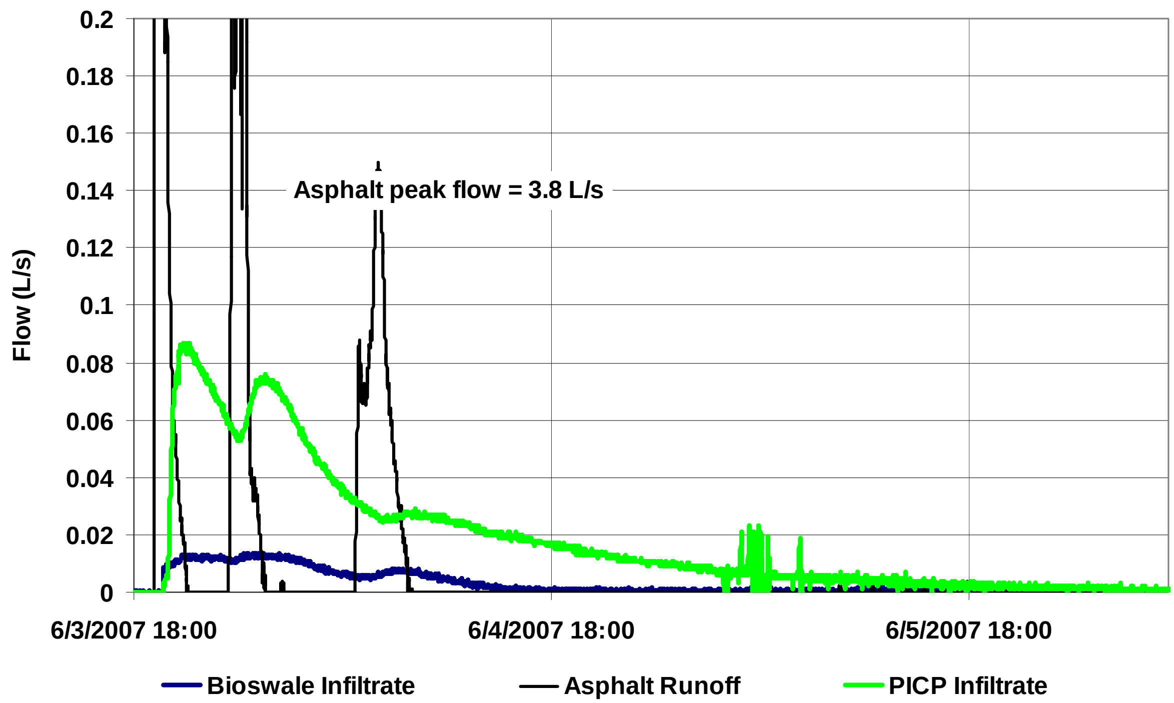
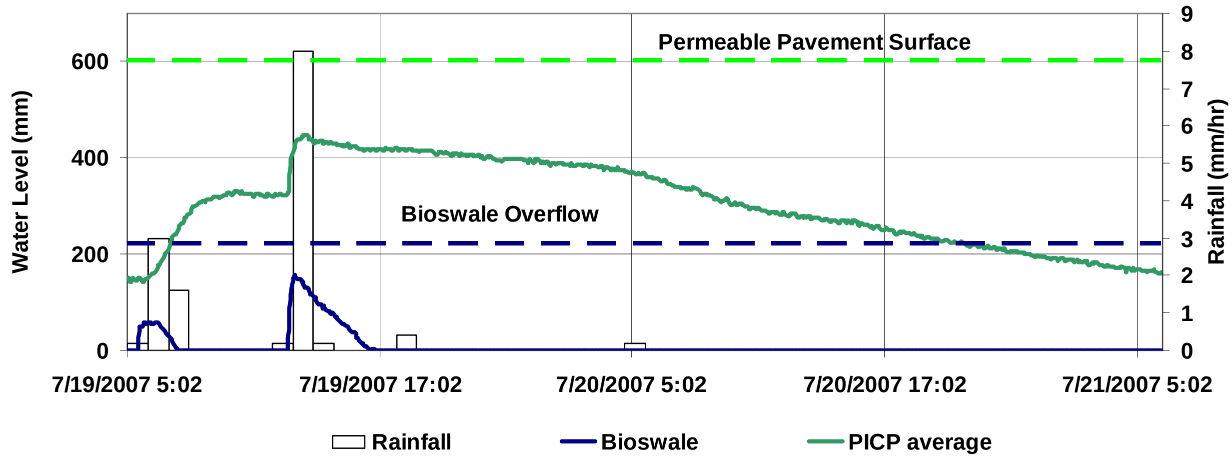


Figure A6: Hydrographs, hyetographs and base course water levels. June 3, 2007 – 26.0 mm



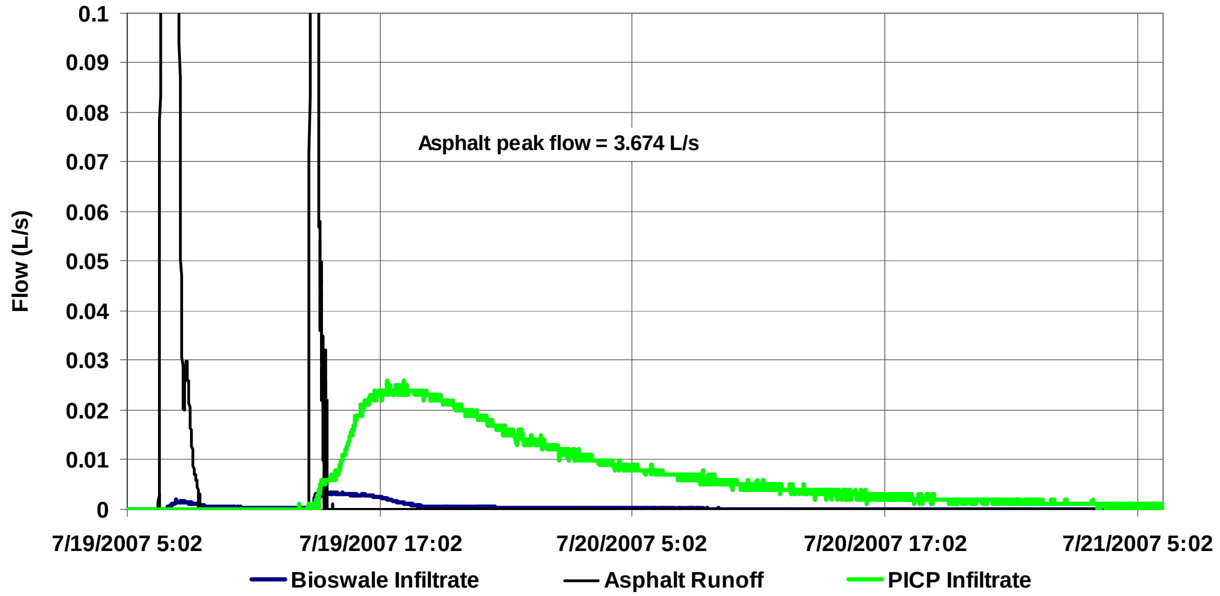


Figure A7: Hydrographs, hyetographs and base course water levels. July 19, 2007 – 13.2 mm

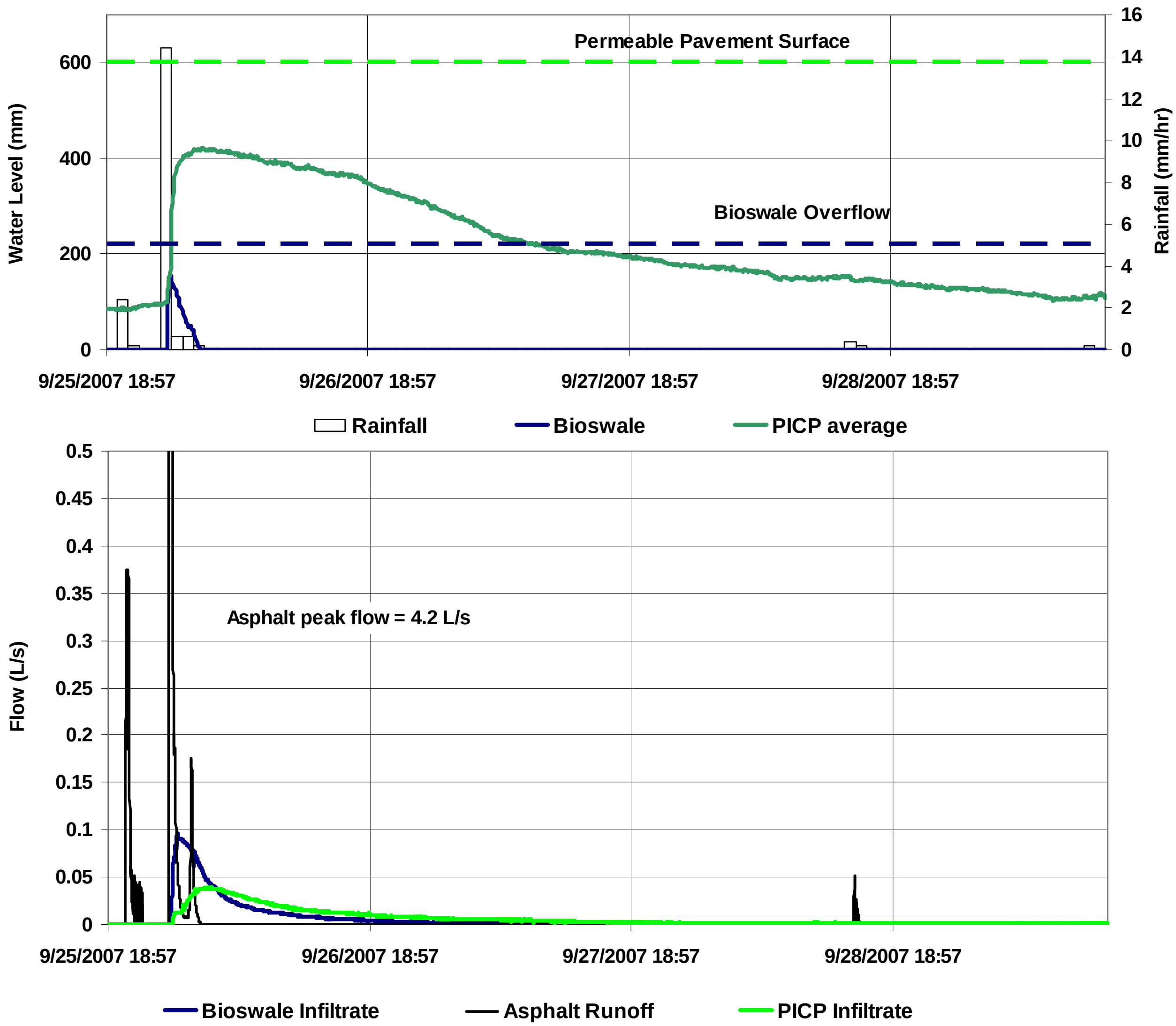
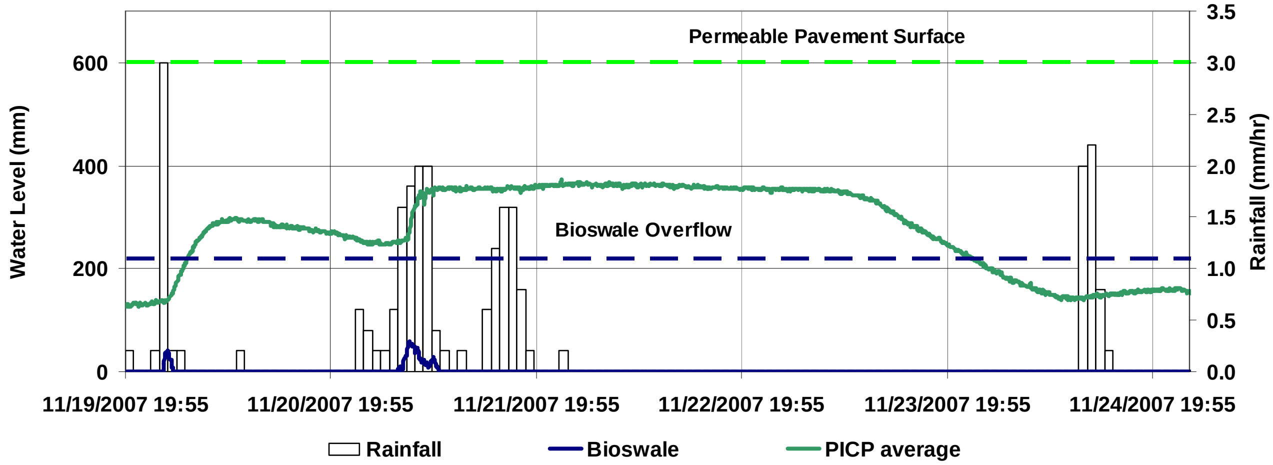


Figure A8: Hydrographs, hyetographs and water levels. Sept 25, 2007 – 19.0 mm



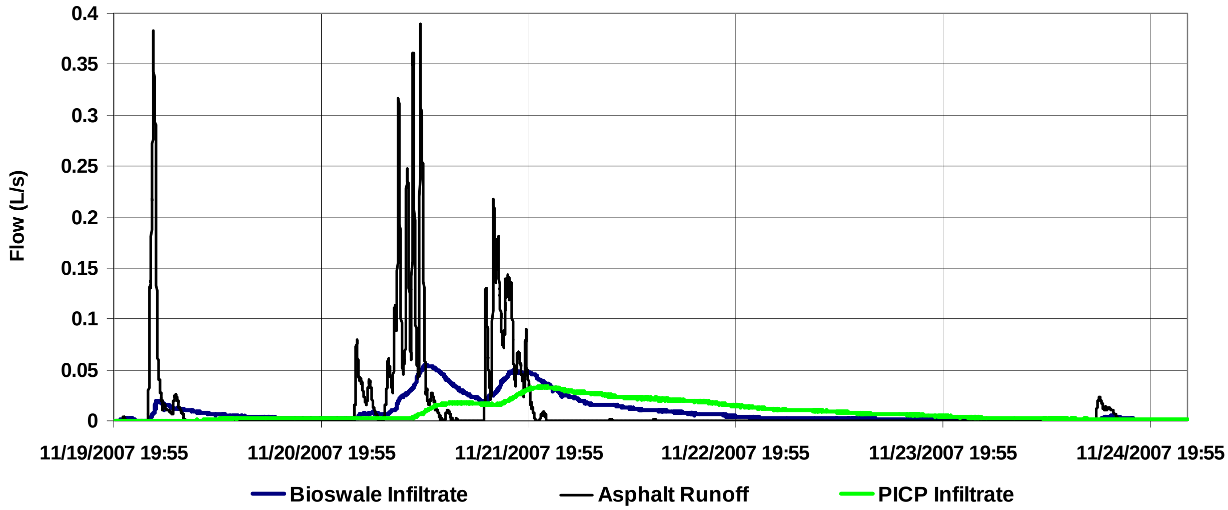


Figure A9: Hydrographs, hyetographs and water levels. Nov 19, 2007 – 25.6 mm

APPENDIX B:

Water Quality

Table B1: Summary of water quality results

					Asphalt Runoff						Bioswale Infiltrate						Permeable Pavement Infiltrate					
	Units	MDL	SWGL[1]	DWGL[2]	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median
General Chemistry																						
Chloride	mg/L	0.2	230	≤ 250[3]	97.8	46	<MDL	36400	*2266*	9	100	48	2	3210	*665*	160	100	49	25	4030	*642*	156
Sodium	mg/L	0.0		≤ 200[3]	100	39	0.28	22700	*1670.43*	9.42	100	43	30.00	1550.00	*424.46*	*225.00*	100	43	10	2080.00	*379.52*	162.00
Potassium	mg/L	0.0			100	39	0.16	2.23	0.62	0.38	100	43	1.61	21.40	6.42	5.24	100	43	1	27.10	11.36	11.20
Hardness	mg/L	0.0		80 to 100[3]	100	39	13.00	354.00	76.43	47.00	100	43	157.00	1300.00	*436.56*	*336.00*	100	43	127.00	1290.00	*383.51*	*261.00*
Sulphate	mg/L	0.0		≤ 500[3]	100	38	1.30	339.00	40.76	17.80	100	43	3.47	342.00	36.89	22.50	100	43	40.60	232.00	107.04	96.10
Fluoride	mg/L	0.0			100	40	0.01	0.09	0.02	0.02	100	45	0.01	0.07	0.03	0.04	100	45	0.01	0.37	0.21	0.25
Sulphate	mg/L	0.0			100	40	0.25	339.00	38.76	15.45	100	45	0.25	342.00	35.10	19.10	100	45	0.25	232.00	101.18	95.30
Solids; suspended	mg/L	2.5			100	43	5.9	1130.0	94.6	27.7	100	44	8.9	566.0	88.2	48.2	90.9	44	<MDL	66.7	11.3	6.3
Solids; total	mg/L	10			100	43	38	58500	3876	167	100	44	54	6440	1679	881	100	43	288	7560	1602	683
Solids; dissolved	mg/L	10			100	43	30	58300	3781	74	100	44	27	6300	1573	851	100	43	278	7540	1591	677
Solvent extractable	mg/L	1			84.6	52	1	50	5	3	52.7	55	<MDL	5	<MDL	<MDL	28.3	53	<MDL	4	<MDL	<MDL
Conductivity	uS/cm	1			100	47	42	79800	5186	162	100	48	488	9800	2647	1595	8.2	49	427	11400	2394	1250
pH	none		6.5-8.5	6.5-8.5[3]		47	7.1	8.2	7.6	7.6		48	7.2	8.5	7.9	7.9		49	7.7	8.5	8.1	8.2
Alkalinity; total fixed endpt	mg/L $CaCO_3$	2.5		30 to 500[3]	100	47	19.5	73.5	37.9	35.5	100	48	208.0	898.0	458.8	404.5	100	49	92.8	375.0	224.1	230.0
Turbidity	FTU	0.01		5	100	49	<MDL	859.00	69.50	22.00	100	50	6.03	567.00	116.33	88.55	100	50	1.20	356.00	26.89	7.41
Carbon; dissolved organic	mg/L	0.1			100	47	0.6	42.4	5.5	2.7	100	48	2.9	58.4	22.0	17.9	100	49	1.3	5.5	2.5	2.4
Carbon; dissolved inorganic	mg/L	0.2			100	47	4.1	44.4	9.0	7.9	100	48	21.4	220.0	104.7	95.7	100	49	21.3	91.9	53.0	53.5
Silicon; reactive silicate	mg/L	0.02			93.6	47	0.01	0.74	0.19	0.12	100	48	1.46	18.90	6.71	6.25	100	49	1.58	6.72	4.19	4.06

Table B1 cont'd: Summary of water quality results

					Asphalt Runoff						Bioswale Infiltrate						Permeable Pavement Infiltrate					
	Units	MDL	SWGL[1]	DWGL[2]	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median
Nutrients																						
Nitrogen; ammonia+ ammonium	mg/L	0.002	1.4		100	47	0.004	2.030	0.336	0.204	97.9	47	<MDL	7.110	2.376	2.160	53.1	49	<MDL	0.996	0.042	0.003
Nitrogen; nitrite	mg/L	0.001	0.06		100	47	0.002	0.218	0.040	0.029	97.9	48	0.001	0.258	0.070	0.052	85.7	49	<MDL	0.123	0.012	0.004
Nitrogen; nitrate+nitrite	mg/L	0.005		10	97.9	47	<MDL	2.230	0.578	0.507	97.9	48	<MDL	13.900	0.731	0.265	100	49	0.250	1.840	0.819	0.794
Phosphorus; phosphate	mg/L	0.005			70.2	47	<MDL	0.251	0.024	0.007	95.7	47	<MDL	3.080	0.568	0.383	61.2	49	<MDL	0.240	0.020	0.007
Phosphorus; total	mg/L	0.002	0.03		100	46	0.021	1.140	0.115	0.066	100	47	0.062	80.300	5.089	2.320	100	48	0.009	0.313	0.041	0.024
Nitrogen; total Kjeldahl	mg/L	0.02			100	47	0.20	5.52	1.04	0.74	100	48	0.77	20.40	5.46	4.82	100	49	0.13	0.98	0.32	0.30
Bacteria																						
Escherichia coli	c/ 100mL		100	ND		8	4	1200	302	18		11	4	260	35	10		11	4	30	7	4
Fecal streptococcus	c/ 100mL					8	4	7000	1283	155		11	4	740	182	44		11	4	540	87	32
Pseudomonas aeruginosa	c/ 100mL					8	4	240	70	8		11	4	310	58	10		11	2	230	41	10

Table B1 cont'd: Summary of water quality results

					Asphalt Runoff						Bioswale Infiltrate						Permeable Pavement Infiltrate					
	Units	MDL	SWGL[1]	DWGL[2]	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median
Metals																						
Aluminum	ug/L	11	100	≤100[3]	98.2	56	<MDL	1030	*258*	*176*	94.6	56	<MDL	355	85	61	100	56	13	2170	*259*	*131*
Barium	ug/L	0.2		1000	100	56	4.0	181.0	21.3	10.4	100	56	15.5	294.0	74.5	50.9	100	56	15.6	806.0	124.2	68.2
Beryllium	ug/L	0.2	11		1.8	55	<MDL	0.7	<MDL	<MDL	0	56	<MDL	<MDL	<MDL	<MDL	0	56	<MDL	<MDL	<MDL	<MDL
Calcium	mg/L	0.005			100	56	7.9	241.0	40.2	18.7	100	56	60.3	491.0	158.0	133.5	100	56	33.9	404.0	110.3	74.0
Cadmium	ug/L	0.6	0.1	5	30.4	56	<MDL	80.2	3.0	<MDL	35.7	56	<MDL	9.7	1.5	<MDL	30.4	56	<MDL	13.1	1.4	<MDL
Cobalt	ug/L	1.3	0.9		17.9	56	<MDL	82.9	3.6	<MDL	26.8	56	<MDL	17.4	1.9	<MDL	19.6	56	<MDL	23.3	1.9	<MDL
Chromium	ug/L	1.4	8.9	50	62.5	56	<MDL	86.4	5.2	2.3	23.2	56	<MDL	23.1	1.6	<MDL	48.2	56	<MDL	35.4	2.6	<MDL
Copper	ug/L	1.6	5	≤1000[3]	100	56	4.7	153.0	19.2	13.5	100	56	5.7	87.7	20.6	17.8	100	56	5.6	42.1	11.9	10.2
Iron	ug/L	0.8	300	≤300[3]	100	56	65.1	1860.0	410.8	241.0	100	56	325.0	26600.0	6641.3	4335.0	100	56	57.9	2480.0	366.6	198.2
Magnesium	mg/L	0.008			100	56	0.5	27.5	3.9	1.5	100	56	2.4	18.1	7.9	6.5	100	56	5.4	59.9	15.8	9.7
Manganese	ug/L	0.2		≤50[3]	100	56	8.7	415.0	62.8	30.5	100	56	169.9	4920.0	1134.7	788.0	100	56	16.1	673.0	118.6	70.6
Molybdenum	ug/L	1.6	10		12.5	56	<MDL	41.7	2.2	<MDL	23.2	56	<MDL	17.0	1.8	<MDL	64.3	56	<MDL	10.9	2.9	2.4
Nickel	ug/L	1.3	25		39.3	56	<MDL	96.7	4.2	<MDL	53.6	56	<MDL	18.7	3.0	1.6	55.4	56	<MDL	158.0	5.4	1.7
Lead	ug/L	10	5	10	39.3	56	<MDL	117	15	<MDL	8.9	56	<MDL	47	7	<MDL	8.9	56	<MDL	34	7	<MDL
Strontium	ug/L	0.1			100	56	14.4	3520.0	312.3	80.6	100	56	167.0	1500.0	495.8	411.0	100	56	103.0	3390.0	790.7	490.0
Titanium	ug/L	0.5			100	56	1.5	71.8	7.9	4.0	80.4	56	<MDL	30.5	3.2	2.6	85.7	56	<MDL	14.9	3.4	3.2
Vanadium	ug/L	1.5	7		58.9	56	<MDL	127.0	6.4	2.0	51.8	56	<MDL	19.1	2.8	1.6	28.6	56	<MDL	22.0	2.4	<MDL
Zinc	ug/L	0.6	20	≤5000[3]	100	56	6.5	1130.0	104.9	27.9	100	56	0.9	87.5	17.0	11.0	100	56	3.1	109.0	18.0	7.3
Mercury	ug/L	0.02	0.2	1	2.3	43	<MDL	0.03	<MDL	<MDL	2.2	46	<MDL	0.07	<MDL	<MDL	0	45	<MDL	<MDL	<MDL	<MDL
Arsenic	mg/L	0.001	0.1		6.3	48	<MDL	0.005	<MDL	<MDL	63.3	49	<MDL	0.005	0.002	0.002	14.0	50	<MDL	0.002	<MDL	<MDL
Selenium	mg/L	0.001	0.1	0.01	2.1	48	<MDL	0.005	<MDL	<MDL	0	49	<MDL	<MDL	<MDL	<MDL	0	50	<MDL	<MDL	<MDL	<MDL

Table B1 cont'd: Summary of water quality results

					Asphalt Runoff						Bioswale Infiltrate						Permeable Pavement Infiltrate					
	Units	MDL	SWGL[1]	DWGL[2]	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median	%> MDL	n	Min	Max	Mean	Median
Polycyclic Aromatic Hydrocarbons																						
Phenanthrene	ng/L	10	30		76.5	34	<MDL	240	33	23	31.4	35	<MDL	150	18	<MDL	20.6	34	<MDL	48	11	<MDL
Anthracene	ng/L	10	0.8		0	34	<MDL	<MDL	<MDL	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Fluoranthene	ng/L	10	0.8		58.8	34	<MDL	330.0	32.1	13.0	11.4	35	<MDL	48.0	7.3	<MDL	2.9	34	<MDL	12.0	5.2	<MDL
Pyrene	ng/L	10			50.0	34	<MDL	240.0	25.2	<MDL	8.6	35	<MDL	37.0	6.5	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Benzo(a) anthracene	ng/L	20	0.4		5.9	34	<MDL	45.0	11.5	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Chrysene	ng/L	10	0.1		8.8	34	<MDL	270.0	14.5	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
7,12-dimethylybenz (a)anthracene	ng/L	10			0	34	<MDL	<MDL	<MDL	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Benzo(b) fluoranthene	ng/L	10			11.8	34	<MDL	170.0	15.9	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Benzo(k) fluoranthene	ng/L	10	0.2		0	34	<MDL	<MDL	<MDL	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Benzo(e) pyrene	ng/L	10			17.6	34	<MDL	76.0	9.6	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Benzo(a) pyrene	ng/L	1		0.01	11.8	34	<MDL	33.0	*1.7*	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Perylene	ng/L	10	0.07		0	34	<MDL	<MDL	<MDL	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Ideno(1,2,3-c,d)pyrene	ng/L	20			0	34	<MDL	<MDL	<MDL	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Dibenzo (a,h) anthracene	ng/L	20	2		0	34	<MDL	<MDL	<MDL	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL
Benzo(g,h,i) perylene	ng/L	20	0.02		5.9	34	<MDL	100.00	14.71	<MDL	0	35	<MDL	<MDL	<MDL	<MDL	0	34	<MDL	<MDL	<MDL	<MDL

1. Surface water guidelines (SWGL) are provincial Water Quality Objectives (PWQO) where applicable, otherwise they are Canadian Water Quality Guidelines. The chloride threshold is from Environment Canada and Health Canada, 2001. Mean and median values that have been underlined and/or italisized indicate exceedence of surface and/or drinking water guidelines, respectively. 2. Drinking water quality guidelines (DWGL) are from OMOE, 2006. 3. Operational or aesthetic objective. 4. MDL = method detection limit. 5. ND = not detectable.

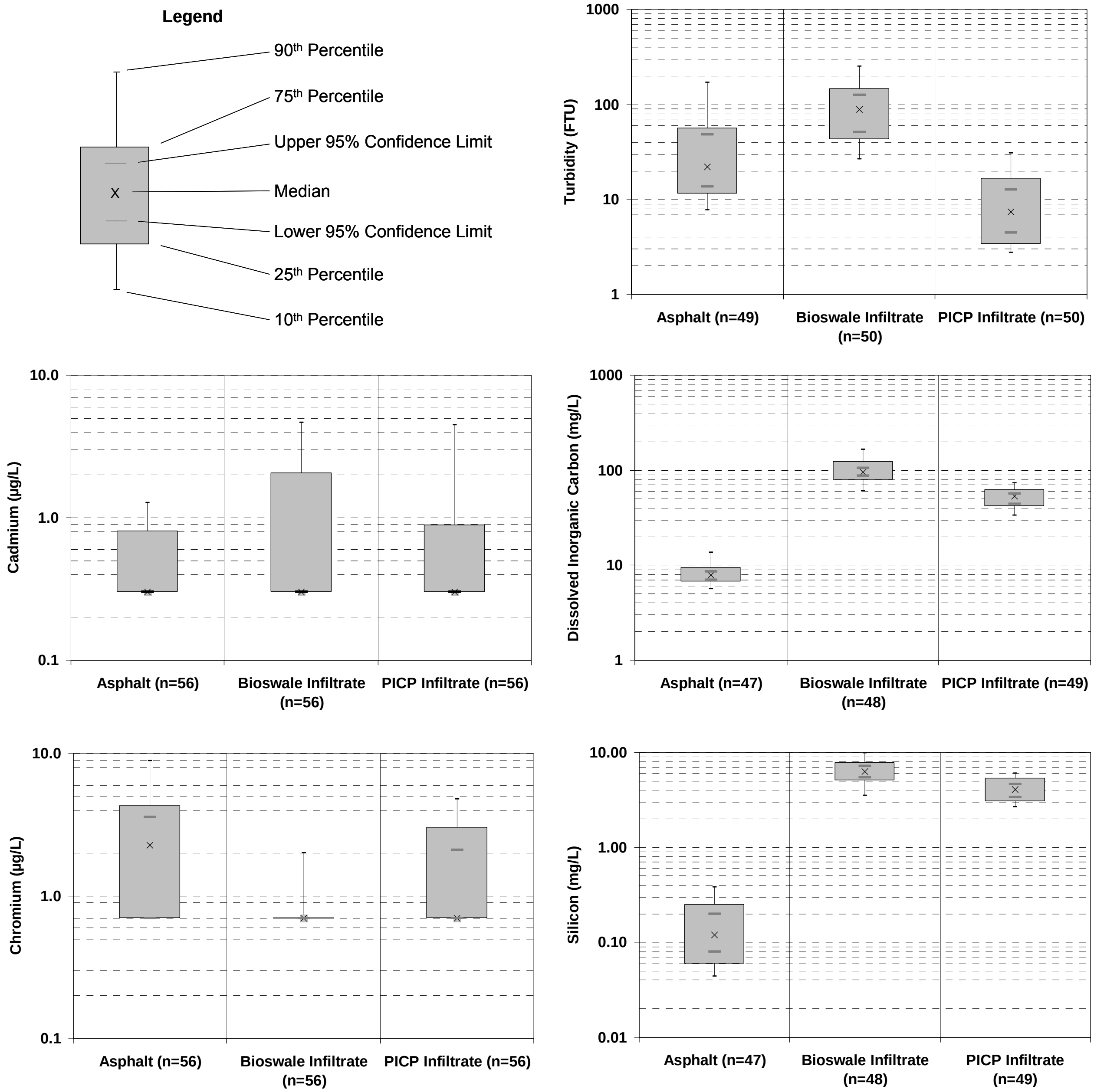
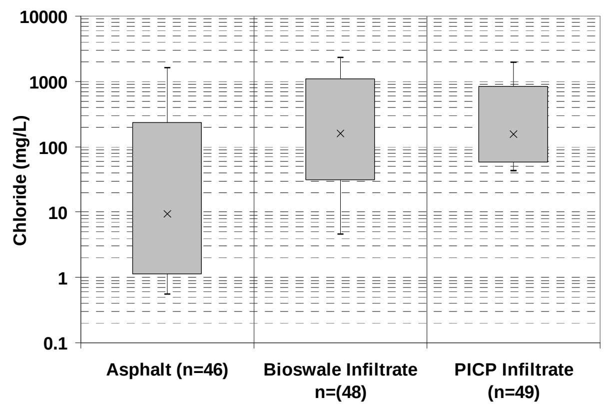
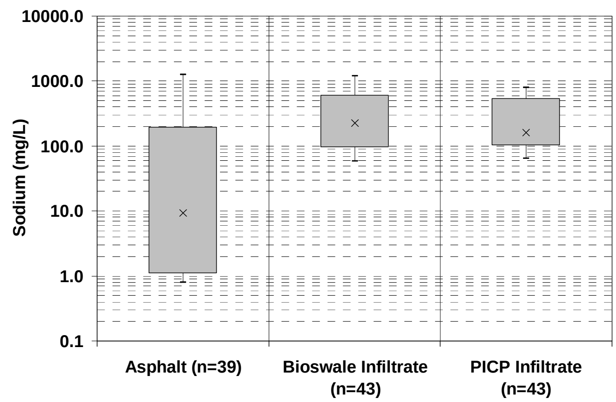
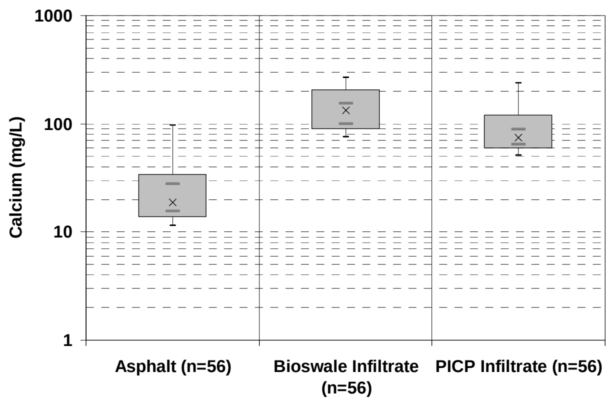
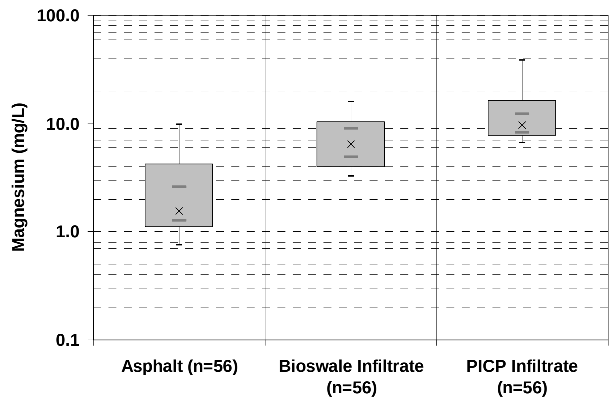


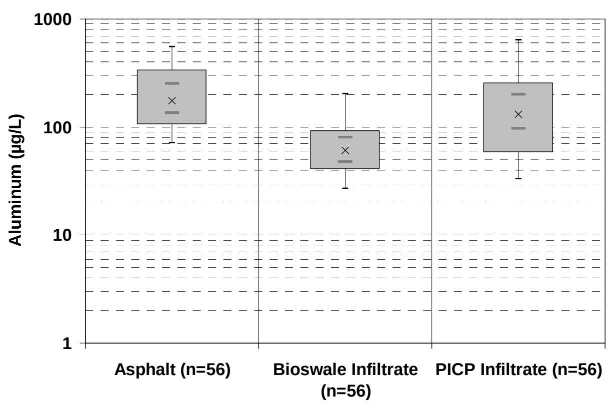
Figure B1: Box plots and 95% confidence limits (non parametric) for selected variables











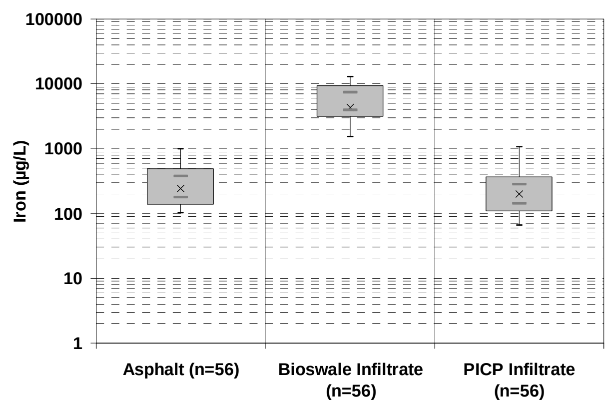


Figure B1 (continued): Box plots and 95% confidence limits (non parametric) for selected variables. Confidence limits are not shown for chloride and sodium because of a seasonal bias in the data set.

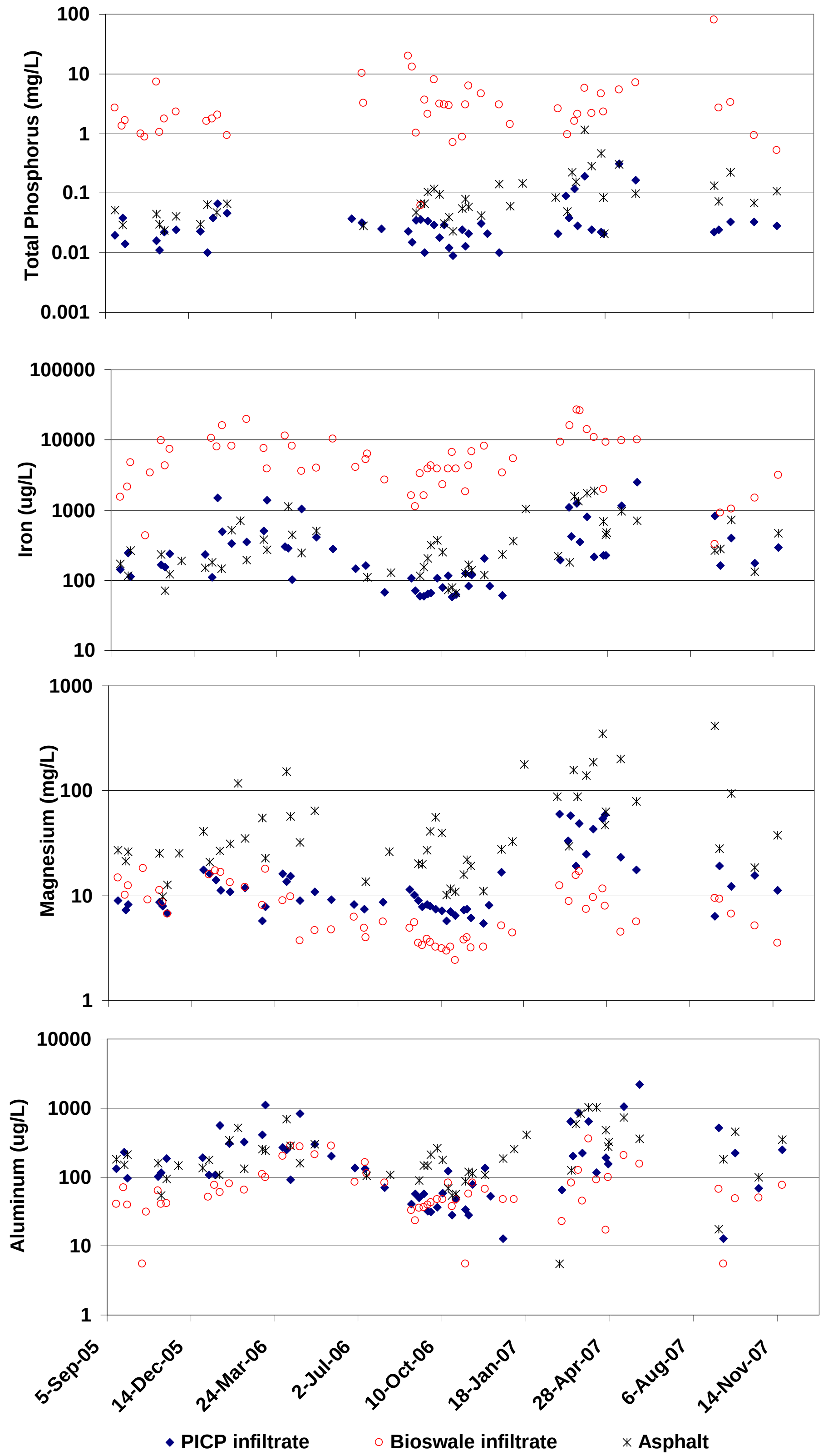


Figure B2: Temporal trends in water quality for selected variables.

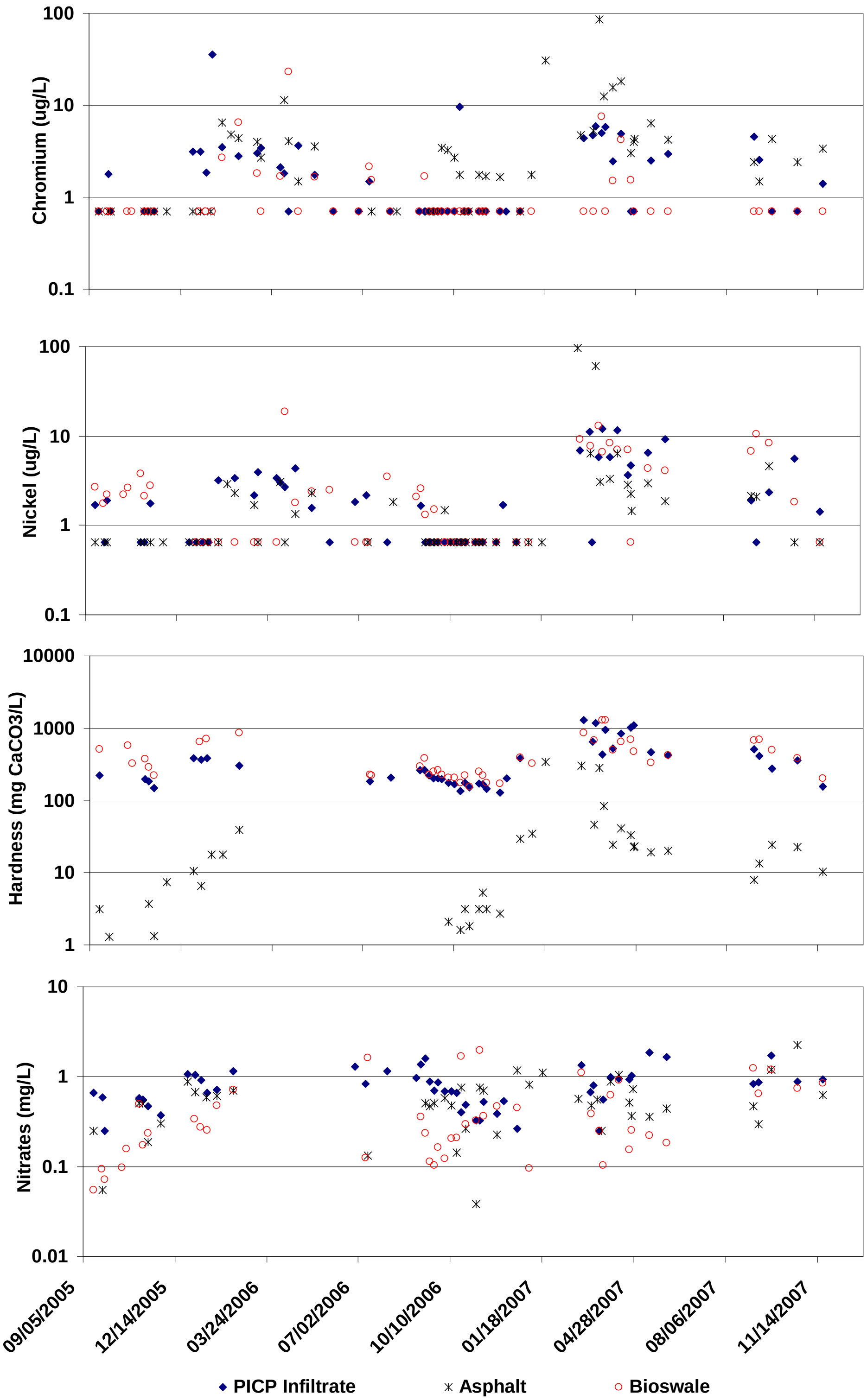


Figure B2 (continued): Temporal trends in water quality for selected variables