POOROUS PAVEMENT AND WATER QUALITY:
INVESTIGATION OF A PARKING LOT AND ITS POTENTIAL
IMPACT ON SUBSURFACE WATER

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ABSTRACT

A non-polymer modified porous pavement parking lot on the University of Rhode Island campus was recently constructed in an environmentally sensitive area, i.e., in close proximity to a drinking water well field. The objective of this study was to investigate possible impacts of organic and inorganic pollutants (including bacteria) originating from a permeable asphalt parking lot on the water quality immediately beneath it. Another aspect of this study was to evaluate the functioning of the permeable pavement, including clogging and restricted vertical percolation. Four nested sample ports (shallow and deep) were installed below low and high traffic areas, including one port outside the parking lot. At least initially there was a good hydraulic connection between the parking surface and the shallow sample ports. The percolation to the deeper ports, however, was hampered for two reasons: over-compaction of material covering the deep sample ports and the presence of a geotextile layer at the base of the parking lot structure that may have acted as a hydraulic barrier. Clogging of the permeable surface was most pronounced in heavy traffic areas and below snow pile storage areas. Sand brought in by cars during winter was identified as the principal cause for clogging, but at the same time may have provided sorption sites for metal contaminants. Cars also brought up to 65.23 g/m² yr road salt (as chloride) into the parking lot. No bacteria, BOD, and lead were found in percolating water. Polycyclic aromatic hydrocarbons (PAH) were present at concentrations near detection limit. Nutrients (nitrate and phosphate) were being leached into the ground via the permeable parking lot surface at annual flux rates of 0.45 g/m² yr to 0.84 g/m² yr. A multi-species tracer test demonstrated a retention capacity of the permeable parking lot structure >90% for metals. About 27% and 52% of the released nutrients and salicylate were not recovered. Bio-consumption of these compounds of was identified as a possible explanation for the low tracer recoveries.
INTRODUCTION

Development and urbanization has resulted in increased impervious land cover, such as pavement and parking lots. Because the volume of urban stormwater is a direct function of the extent of impervious surfaces (U.S. EPA 1983), increases in development result in greater incidents of storm water runoff. Stormwater runoff is a widespread source of non-point-source pollution to ground and surface waters. Thus, many federal and state agencies are now calling for better-contained pavement drainage to control pollution from stormwater runoff.

Stormwater runoff may contain elevated concentrations of heavy metals originating from corrosion or ordinary wear of brakes, tires, and other vehicle parts (Pitt and others, 1994; Sansalone and Buchberger, 1997; Davis and others, 2001, Sorme and Lagerkvist, 2002; Dempsey and Swisher, 2003). Runoff may also contain elevated levels of organic compounds, including petroleum hydrocarbons (Boving, 2002, Dempsey and Swisher, 2003). Additional sources of stormwater contamination include accidental releases of toxic substances, application of road salts (Howard and Beck, 1993), excess application of fertilizer (Vaze and Chiew, 2002) and pesticides (Schiff and Sutula, 2004), microorganisms such as E. Coli. (Borst and Selvakumar, 2003), deposition of airborne soot (Maruya and others, 1996) and exhaust emissions (Dannecker and others, 1990).

In the Nationwide Urban Runoff Program (NURP) study conducted by EPA in the early 80’s, copper, lead, and zinc were detected in more than 90% of stormwater samples and 14 toxic organic compounds (predominantly PAHs) were detected in more than 10% of
the samples (U.S. EPA 1983). With precipitation, these contaminants wash off impermeable surfaces or erode with soil particles to which they are attached, collect in drainage structures, and eventually discharge into surface- or groundwater bodies, potentially allowing the contaminants to enter drinking water resources. In stormwater, these pollutants exist as either suspended or dissolved matter.

Parking lots are common impervious surfaces associated with development and urbanization that result in stormwater pollution. Hoffman and others (1982) found that approximately 0.47 g/m²yr hydrocarbons were flushed from the parking lot of a 12.5 ha section of a shopping complex. As much as 17% of the hydrocarbons were in solution. Latimer and others (1986) examined polycyclic aromatic hydrocarbons (PAHs) in stormwater runoff from a shopping center parking lot with a total drainage area 0.05 km². They found that the runoff entering and leaving a detention pond contained dissolved PAH concentrations similar to Hoffman and others (1982). These studies suggest that there is a significant hydrocarbon mass flux associated with parking structures.

The abatement of stormwater runoff pollutants is typically dealt with structural best management practices (BMP) (Whipple and others, 1983). Porous pavement has become a popular BMP alternative for stormwater management because these pavements permit precipitation to infiltrate into the subsurface even during storm events instead of pooling and running off the pavement surface (Thelen and others, 1972). There are several types of permeable pavement with monolithic pervious concrete and porous asphalt the least expensive and most similar to conventional pavements (Millar
First developed in the 1970s, porous asphalt consists of an open-graded coarse aggregate, bonded together by asphalt cement, with sufficient interconnected voids to make it highly permeable to water (USEPA, 1999). Recent advances in asphalt technology, i.e. introduction of polymer-modified asphalts, have increased the durability of porous asphalt structures (NAPA, 2003; Ferguson, 2005). Unlike conventional asphalt, water infiltrates through porous asphalt into the soil below. Thus, groundwater recharge is considered a major potential benefit of permeable pavement. The percolating water, however, can potentially carry with it automobile derived pollutants. The pollutants may move through the permeable pavement and structures into deeper parts of the subsurface.

Meyer and Singhal (2004) and McNally and others (2005) offer reviews of permeable pavement systems including studies of porous asphalt. Permeating runoff water from a porous asphalt surface had considerably lower loads of pollutants in comparison to a catchment drained by the sewer system (Legret and others 1996). Also, metallic pollutants accumulated on the porous asphalt surface and did not migrate within the reservoir structure (Legret and Colandini 1999). Copper, lead, and zinc, and to a lesser extent cadmium, were retained in the porous asphalt by clogging particles (Legret and others, 1999). Porous pavement reduced the suspended solids, lead, and COD load by 50%, 93%, and 89%, respectively in comparison to conventional pavement (Baladés 1992, Ranchet and others 1993, Stotz and others 1994). Similar high removal rates for TSS, metals, and oil and grease were reported by Cahill and others, 2005. Wilde (1994) found that porous pavement retained all the sand, most silt, and the largest clay particles,
but smaller clay particles and colloids were apparently not filtered out. Lindesy and others (1992) observed that two of three porous pavement facilities they studied had failed due to sediment accumulation and the lack of proper maintenance.

Considering the potential benefits of permeable pavement, a non polymer-modified porous asphalt parking lot was constructed on the University of Rhode Island (URI) campus, Kingston RI. The parking lot lies in an environmentally sensitive area, i.e., about 0.5 km upgradient from a drinking water well field and on top of a regional aquifer. This study summarizes the results from tests and observations carried out on the URI porous asphalt parking lot. The two major objectives were to (1) determine the fate and transport of metals (Zn, Pb, Cu, Fe), nutrients (nitrate and total phosphate), PAH and bacteria moving through the porous parking lot and (2) evaluate the functioning of the parking lot structure in terms of clogging and restricted flow. Other objectives that were addressed during the study included:

- Measure precipitation and calculate the percentage of the precipitation falling on the permeable parking lot that actually makes it to the groundwater
- Develop analytical capabilities for the analysis of organic and inorganic pollutants
- Quantify and evaluate spatial and temporal variability of the contaminant flux using an existing network of four nested water sampling ports.
- Determine the mass flux rates for critical compounds (such as PAH or metals)
• Create an on-campus demonstration site that provides hands-on, experiential learning environment for students

• Facilitate long term water quality monitoring program.
MATERIALS AND METHODS

In the summer and fall of 2002, an 800 parking space (24,200 m²) porous asphalt parking lot was constructed on the University of Rhode Island, Kingston, campus (Figure 1). The porous asphalt used at this parking lot was not polymer-modified. Full use of the parking lot commenced in September 2004. As shown in Figure 2, the geology at the site consists of about 60 m stratified material deposited in a glacio-fluvial environment (predominantly sand and gravel), sitting on top of fractured granitic bedrock (Urish and Spizuoco, 1991). A thin (0.3 to 0.9 m) veneer of loess covers the stratified material deposits (Stolt, 1998). The site was used for agriculture prior to construction. The Chipuxet River runs less than 1 km west from the parking lot. The unconfined Chipuxet aquifer serves URI and the Town of North Kingstown as their major drinking water resource. Depth to groundwater at the site is approximately 7 m. Hydraulic conductivity values in the test area range from 0.02 to 0.085 cm/s (Dickerman, 1984). Climatological data were obtained from the nearby URI weather station, including a 25-year record of pan evaporation (Tables 1 and 2).

The parking lot structure was constructed by removing the uppermost 0.9 m of surficial deposits. The base of the excavation was covered by approximately 5 cm sand and a fabric liner (geotextile), followed by 0.6 m backfill of crushed granite (cobble-sized gravel), followed by 0.3 m of pebble-sized gravel backfill. A 15 cm layer of porous asphalt was installed on top of the compacted backfill. During the construction of the parking lot, three water sampling stations were installed inside the parking lot. The locations of these three sample stations were selected to represent high-traffic and low
traffic zones (Figure 1). One sampling station was installed outside the parking lot to measure contaminant fluxes in the natural soil material. In addition, rain water samples and runoff from a nearby conventional asphalt parking lot was collected during one particular storm event in September 2004.

Figure 1: Locations of the nested sampling ports (circles: S: shallow/D: deep) within and immediately adjacent (2 S/D) to the permeable asphalt parking lot. Triangles and roman numerals: infiltration rate measurement points. Scale as indicated.

Each sampling station consisted of two sample ports (nested) installed at 1 m and 1.5 m levels below the parking lot surface (i.e., 8 individual sample ports). The sample ports
were custom made 1 m² stainless steel pans with a 5 cm rim, sloping gently to a central hole fitted with a brass connector (Picture 1). The 5 cm rim provided each pan with about 15 l water storage capacity (equivalent to an approximately 0.6 in rain event if the entire rainwater volume had infiltrated). The infiltrating water intercepted by these sample ports was pumped to the surface by a battery powered peristaltic pump via 6 mm Teflon tubing that let from the underside of the pan to an adjacent well (i.D. 20 cm) and then, as shown in Fig. 3, to the surface. The Teflon tubing was protected by flexible 12 mm PVC tubing.

Figure 2: Generalized geologic cross section of the Chipuxet River valley through the permeable parking lot site. Arrow marks approximate location of the study site (modified after Johnston and Dickerman, 1985).
Each sample port consisted of a 1 m² stainless steel pan. The pan was graded towards a central outlet and connected to Teflon tubing (clear) protected by a larger-diameter PVC tube (black). Note that a 5 cm rim surrounded the edge of the pan. This provided each pan with about 15 l water storage capacity (equivalent to an approximately 0.6 in rain event). Percolating water intercepted by the pan was pumped to the surface using a peristaltic pump (Figure 3). The shallow sample port was installed immediately above the geotextile liner (Figure 3). The deeper sample ports were installed adjacent to the shallow ports, but 0.6 m below the geotextile liner and within the stratified material deposits (Picture 2). The sample ports and the remaining area of the parking lot were covered by granitic backfill (Picture 3). For the construction of the sample station outside the parking lot, the excavated soil was separated into top soil, loess, and stratified material. After installation of the shallow and deep sample ports outside the parking lot, these ports were covered with the excavated material in the opposite sequence they were removed.
Figure 3: Schematic cross section of a shallow sample port (not to scale). The shallow sample ports were installed above a geotextile liner (1 m bgs), while the deeper ports were installed below it and within the local sediment (1.5 m bgs; not shown).
**Picture 2:** Installation of a deep sample port within the stratified drift deposits. The construction worker connects the Teflon tube leading from the stainless steel pan (left) towards the PVC well (center).

**Picture 3:** The parking lot sub base consisted of (from top to bottom) coarse granitic gravel (dark material in lower right corner), medium granitic gravel (light material in center), fabric liner (geotextile), and a layer of sand over the natural soil.
A fluorescein tracer (a conservative tracer) test was conducted to ensure that the sample ports were working properly and to determine the approximate breakthrough times of percolating rain water. A solution containing 1,000 mg/L fluorescein was released above each of the eight sampling ports (Picture 4). Percolating rain water from subsequent storms (varying in intensity from less than 2.5 cm to more than 7 cm of rain) carried the tracer downwards and towards the sample ports. The aqueous concentration of fluorescein was measured using a Shimadzu 1601 UV-Vis spectrometer (wavelength: 491 nm).

After over 2.5 years of operation, infiltration rates were determined at nine sites throughout the porous asphalt parking lot (Fig. 1). Locations were selected based on the location of existing sample ports, high traffic areas, and areas interpreted as quasi-undisturbed pavement. A 1 liter graduated plastic cylinder was set on the parking lot
surface and a tight seal was applied using a chalking paste. The cylinder was then
instantaneously filled to the 1 liter mark and the infiltration rate was determined as
amount of time per unit drop in water level. Each test was carried out twice and the
averages were calculated.

The hydraulic head necessary to initiate percolation through the geotextile liner was
measured. A layer of new geotextile (dry and pre-wetted) was tightly attached to the
bottom of an open 1 liter (5 cm inner diameter) graduated cylinder. The cylinder with
the geotextile was then slowly immersed into water and the depth of immersion at which
water was braking through the layer was noted. The average of three repeats was
reported.

Dissolved oxygen (DO), electrical conductivity (EC), pH, and temperature were
measured regularly in the field. Aqueous samples were routinely analyzed for metals
(Zn, Cu, total Fe), nutrients (nitrate; as NO$_3^-$, and total phosphate; as P). Selected
samples were analyzed for PAHs, lead, chloride, bacteria (fecal coliform and E. Coli)
and biological oxygen demand (BOD). Minimum sample volumes were 1 liter for PAH,
100 ml for bacteria and BOD, and 40 ml for all other compounds. After preservation
with nitric acid, metal and nutrient samples, including two BOD samples, were also
analyzed by an accredited environmental laboratory following standard EPA methods
(metals by EPA Method 200.7; SW-846 6010B (ICP-AAS); nitrate by EPA Method
353.3, total phosphate (as P) by EPA Method 365.2). Alternatively, selected aqueous
samples were analyzed for nitrate and phosphate with a Dionix Ion Chromatograph (DX
120) and properly calibrated Hanna Ion Selective meters (iron, zinc, and copper).
Bacteria (total fecal coliform) analysis was performed by the Rhode Island Watershed Watch laboratory after TEC membrane filtration method (Eaton and others, 1995). PAH were extracted from the filtered (0.7 micron glass fiber filters; Whatman GF/F) aqueous phase after EPA method 3510. Initially, PAH were analyzed by a Shimadzu GC-17A gas chromatograph with flame ionization detector (FID) as described in Boving (2002). After equipment failure, PAH samples were sent to an accredited environmental laboratory and analyzed after EPA Method 8270. Reported is the sum of ten PAHs (Naphthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Chrysene, Benzo(a)pyrene).

Monthly water samples were collected between January 2004 and April 2005. Between late April and June 2005, a multi-species test was conducted to determine attenuation of selected pollutants by the asphalt parking lot. For this test, a suite of seven inorganic (NO$_3^-$, SO$_4^{2-}$, PO$_4^{3-}$, Cl$^-$, Br$^-$, Zn$^{2+}$, Cu$^{2+}$) and one organic tracer (Na-salicylate) were infiltrated above the shallow sample port 3S (Figure 1). This port was chosen for the tracer test because it yielded water most reliably and in sufficient quantity. Na-salicylate was selected because this chemical is a readily biodegradable part of the Naphthalene (a common PAH) degradation cycle. The parking space above the sample port was closed for the duration of the test. Anion and cation concentrations were measured as described above. Salicylate concentrations were determined with a Shimadzu UV-Vis 1601 at 298 nm. The tracer test data was analyzed using the method of moments, where the “zeroth moment (M$^0$) yields the tracer mass recovery (equation 1):

$$M^0 = \int_0^t \overline{C} Q \, dt$$  \hspace{1cm} (Equation 1)
where \( t \) is time, \( \bar{C} \) is the average tracer concentration and \( Q \) is the volume of tracer sample collected at each time. The tracer removal effectiveness was calculated as the difference between amount of tracer released and amount recovered.

In calculating the annual contaminant mass fluxes across the parking lot, the amount of recharge between November 2004 and April 2005 was assumed equivalent to monthly precipitation (total: 712 mm). For the rest of the year it was assumed that the amount of infiltration through the parking lot can be estimated based on the difference between total amount of rain and evaporation losses as determined by pan-evaporation. We acknowledge that the pan-evaporation data may not accurately reflect the evaporation losses over the porous parking lot (i.e. the actual evaporation losses over the parking lot surface are probably lower than the pan-evaporation data suggests). However, in absence of a better measure and supported by our field observations (no or little recharge to the sample ports during summer) the pan-evaporation data provided a useful approximation for the overall recharge history at the site. The 25-year climatological record shows greater pan-evaporation (E) than precipitation between May and August. Thus, we assumed no effective recharge during these months. Recharge during September and October was calculated as the difference between total monthly precipitation (276 mm) and total monthly E (152 mm). The contaminant mass flux was determined by multiplying the volume of precipitation per square meter by the monthly average contaminant concentration. Non-detects (ND) were assigned a value equal to the lower detection limit of that compound (e.g. 0.02 mg/L for Zn\(^{2+}\)).
During winter, the parking lot maintenance guidelines permitted snow ploughing but prohibited the use of de-icing chemicals and sand. Colbeck (1978) noted that snow piles contain fine particulates, which may clog porous pavement once melting occurs. To investigate the amount of sand released indirectly to the parking lot surface, snow samples were collected from snow piles in the parking lot. The melted snow water was passed through a 0.7 micron glass fiber GF/F Whatman filters. After oven drying, the weight of the collected particulates was determined and related to the volume of melt water. Finally, digital traffic counters were installed at both parking lot entrances to determine typical parking lot usage.
RESULTS

During monthly sampling (01/2004 through 04/2005), the parking lot area received between 52 mm (June 2004) and 215 mm (April 2004) rain (monthly average: 113 mm, Table 1). The longest period without rain lasted 10 days (February 2004) followed by 9 days in October 2005 (average time between rain: 3.1 days). The fluorescein tracer test indicated that percolating rainwater reached the shallow sample ports within 6 hours when the total amount of rain was at least 5 cm to 7 cm. Longer breakthrough times (i.e. several days) were observed after less intense storms.

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<td>23</td>
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| Avg. (mm) | 100 | 94 | 136 | 132 | 96 | 106 | 86 | 111 | 106 | 95 | 128 | 113 |
| P - ET (mm) | 100 | 94 | 136 | 132 | -26 | -33 | -65 | -21 | 12 | 27 | 128 | 113 |

Table 1: 25-year precipitation record (mm) from the URI Climatological station, Kingston, RI.
Table 2: 25-year pan-evaporation record (E; in mm) from the URI Climatological station, Kingston, RI.

Traffic counter data indicated that on average 813 cars per day used the parking lot during school days (Table 3). Of those, 746 cars entered through the entrance near sample ports 4 S/D, while 67 cars used the other entrance near 3 S/D. Typical weekend traffic was significantly lower (average of 15 cars per day on non-event parking days).
<table>
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<tr>
<th>Date</th>
<th>Count at Main Entrance (near 4S/D) (per axel)</th>
<th>No of 2-axel cars</th>
<th>Count at Entrance near 3S/D (per axel)</th>
<th>No of 2-axel cars</th>
<th>TOTAL Cars</th>
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<tr>
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<td>Sun</td>
<td>11</td>
<td>5.5</td>
<td>7</td>
<td>3.5</td>
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<td>Mon</td>
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<td>665</td>
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<td>Tu</td>
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<td>113</td>
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<td>89</td>
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<tr>
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<td>Th</td>
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<td>Sat</td>
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<td>26</td>
<td>12</td>
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</tr>
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<td>Sun</td>
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<td>1</td>
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<td>Avg. during school days:</td>
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**Table 3:** Traffic counter data collected between 05/01/2005 and 05/12/2005.

**Figure 4:** Results of the fluorescein tracer test conducted during early summer 2004. Black vertical line marks the tracer release date.
Tracer breakthrough at the deep port 3D occurred about 18 hours after the shallow port (3S). Of all deep sample ports within the parking lot, only port 3D yielded water on occasion, i.e. after storms producing >6.25 cm of rain. Yields at port 3D, however, were insufficient for regular sampling. Similarly, the sampling ports 2 S/D outside the parking lot did not yield water either. Both ports were hand excavated and checked for functionality. The 2 S/D ports were found fully operational, but apparently the material covering the sample ports was heavily compacted and became much less permeable than the surrounding material. This caused the flow of infiltrating rainwater to completely circumvent the sample ports. Ports 2 S/D were later destroyed during construction of a parking lot extension.

Picture 5: Debris melting out of a snow pile. Picture was taken near sample station 1 S/D. A pen (center) provides scale.
Picture 6: Sand (light) left on parking lot surface after snow melt.

Concentration of total solids melted out of snow piles within the parking lot ranged from 9.2 mg/L at the top to 3,142 mg/L at the bottom of the piles. After spring melting, these solids formed a visible layer of debris (incl. asphalt particles) on top of the parking lot where the melting occurred (Pictures 5 and 6). Examination of sweep samples under a scanning electron microscope (SEM; Picture 7) revealed that the principal source of fine particulates was sand and organic matter that cars apparently brought in from outside the parking lot during winter.
Scanning electron microscope image (800 times magnification) of debris, mostly sand, some organic fibers, melted out off snow piles within the permeable parking lot.

The infiltration rate test locations (Fig. 1) can be divided in three groups: 1) locations with good infiltration (5 ml/min or higher at II and VII), 2) locations with intermediate infiltration (between 0.5 and 5 ml/min at I and III), and 3) locations with poor infiltration (< 0.5 ml/min at IV, V, VI, VIII, IX). All poorly infiltrating sites were located on the main traffic routes around the parking lot. Those better infiltrating sites were on parking spots.

No bacteria were detected in any samples and BOD and lead concentrations were below detection limits (data not shown). EC readings were the highest January through March when subsurface water temperature was lowest (Table 4 and Figure 5). Concomitantly, chloride concentrations decreased from 930 mg/L in February to below detection limit
Nitrate and phosphate concentrations ranged from below detection limit (ND) to 3.50 mg/l and ND to 2.75 mg/l, respectively (Figures 6 and 7). Sample port 3S nutrient concentrations were generally higher than at port 1S. Copper at sample ports 1S and 3S remained below detection limit until several months after the permeable parking lot was in full operation in Fall 2004 (Table 5 and Figures 8 and 9). Copper concentrations peaked at 1.01 mg/L and 1.28 mg/L in ports 1S and 3S, respectively, during late winter and early spring 2005. Zinc concentrations during the same time period showed a similar trend but were generally lower than copper concentrations, ranging from ND to 0.44 mg/L in both 1S and 3S. During the last available measurement and for no apparent reason, zinc concentration spiked at 2.6 mg/L in 3S in April of 2005. Iron concentration fluctuated between ND and up to 55 mg/L (Table 5), with the highest concentrations measured during winter months.
<table>
<thead>
<tr>
<th>Date</th>
<th>DO (mg/l)</th>
<th>pH</th>
<th>EC (μS/cm)</th>
<th>Temp (°C)</th>
<th>Date</th>
<th>DO (mg/l)</th>
<th>pH</th>
<th>EC (μS/cm)</th>
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**Table 4:** Summary of field parameter measurements on those two sample ports (1S and 3S) that yielded sufficient water for analysis on regular basis.
Figure 5: Electrical conductivity (EC) and water temperature data collected at sample port 3S.
**Figure 6:** Nutrient concentrations at sample port 1S.

**Figure 7:** Nutrient concentrations at sample port 3S.
**Figure 8:** Metal concentrations at sample port 1S.

**Figure 9:** Metal concentrations at sample port 3S.
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<th>Well 3 Shallow</th>
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<th>0.51</th>
<th>0.45</th>
<th>0.27</th>
<th>11.24</th>
<th>0.04</th>
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</table>

| Mass Flux (g/m² yr) | 65.23 | 0.62 | 0.84 | 0.37 | 7.23  | 0.16 | 0.0010 |

**Table 5:** Summary of anion and cation concentrations, including PAH, collected at samples ports 1S and 3S. ND: non detect, dry: sample port did not yield sufficient water for analysis, n/a: not analyzed. * PAH sampled on 01/06/2004. Also shown are the annual mass fluxes per square meter for each compound.
Total PAH concentrations in port 1S ranged from ND to 2.89 μg/L (avg.: 1.98 μg/L) and from ND to 4.94 μg/L (avg. 2.07 μg/L) in port 3S (Table 5). Only one sample from port 4S was analyzed (parking lot entrance) before clogging made further sampling impossible (2.40 μg/L total PAH; data not shown in Table 5). Rain water PAH concentrations ranged from ND to 3.86 μg/L, while runoff from a nearby conventional asphalt parking lot contained 1.36 μg/L PAH (data not shown in Table 5).

The results of the multi-species tracer test are summarized in Table 6 and Figures 10 and 11. The tracers were released immediately before a storm resulting in 15.7 mm rain. During this tracer test (04/27/05 through 06/01/2005), a total of 157 l/m² rain was recorded. About 54 l (34%) water were retrieved from port 3S. The difference between precipitation and recovered infiltrate reflected the expected evaporation losses.

Conservative tracer recoveries ranged from 92.9% Br⁻ to 108.9% Cl⁻. Sulfate recoveries were also quantitative (107.4%). Nutrient (nitrate and phosphate) recoveries were 73.0% NO₃⁻ and 73.1%, PO₄³⁻, respectively. Both zinc and copper recoveries were low (7.5% Cu²⁺ and 7.8% Zn²⁺). Sodium salicylate recovery was 47.8%.
Figure 10: Relative concentrations (C/Co) of anionic compounds collected from port 3S after application of a multi-species tracer solution. Precipitation data were collected at an adjacent weather station. Note that an early phosphate reading is off-scale (C/Co = 0.30). Salicylate is shown in Fig. 11.
Figure 11: Relative concentrations (C/Co) of zinc and copper collected from port 3S after application of a multi-species tracer. Samples beyond day 10 were at or below detection limit. Although not a metal cation, salicylate was included in this graph for visualization purposes. Precipitation data were collected at an adjacent weather station.
### Table 6: Tracer test data from sample port 3S. Initial concentrations of the tracers released at the parking lot surface are given in parentheses below the relative concentration (C/Co) heading
DISCUSSION

The fairly rapid breakthrough of water following strong storms indicates good vertical connection between the surface and the shallow sample ports. The disproportional longer breakthrough time measured at the deeper port 3D was attributed to the lower hydraulic conductivity of the 0.6 m of stratified material that covered the deeper port in addition to the 1 m gravel pack layer above. However, port 3D yielded water only after strong storms (>6.25 cm precipitation). The failure to produce any water – even after strong storms - at the deep sample ports 1D and 4D (Figure 1), was attributed to overcompaction and the presence of the geotextile layer, which may have served as a hydraulic barrier at the base of the parking lot (Figure 3, Picture 8).

![Pooling water on geotextile liner](image)

**Picture 8:** Demonstration of water pooling on top of the geotextile liner.

Hydraulic tests showed that a head of at least 5 cm water was necessary before flow through clean and dry geotextile occurred. A head of 2.1 cm was necessary when the
geotextile was wet. Hence, a possible scenario explaining the lack of percolating water at
the deep sampler ports is follows: infiltrating water reached the geotextile layer,
accumulated and started flowing laterally on top of the geotextile. Because the geotextile
was not installed perfectly level (nor was it required), water flow must have been directed
by indentations and “channels” on the geotextile surface. Eventually, the water
encountered seams or holes in the geotextile layer or formed pools of sufficient depth to
overcome the geotextile’s infiltration head (min. 2.1 cm). The resulting channelized
infiltration must have occurred at port 3D after strong storms. At ports 1D and 4D,
however, it may be possible that further percolation was inhibited at least partially as the
consequence of unintended heavy compaction of the soil covering the deep ports.

If channelized or point infiltration indeed occurred it must be considered detrimental for
two reasons. First, the infiltration below the permeable parking lot is uncontrolled, i.e.
infiltration occurs not by design but depends on the gradient of the geotextile layer
surface as well as the unknown location of holes, seams or depressions in the geotextile.
Second, preferential infiltration of potentially contaminated runoff at discrete points may
exceed the local filtration capacity of the subsurface material resulting in increased
groundwater contamination potential.

Beyond the problem of “point” infiltration, clogging of the permeable surface was
observed in traffic areas (especially at entrance/exit sites, see infiltration rate results) and,
to lesser extent, in areas where snow was piled up during winter. For instance, the
fluorescein tracer released on the surface above sample port 4 S/D (parking lot entrance;
Figure 1) did not infiltrate at all – even after applying moderate hydraulic pressure.
Inspection of the asphalt pore space revealed the presence of sand and other particles. In
fact, the color of the asphalt in the sand-clogged heavy traffic area was significantly lighter than surrounding, less frequently traveled areas. Also, occasional lateral surface runoff and pooling was noticed in the heavy traffic area and in an area where snow was piled up during winter (near 1 S/D), but not anywhere else on the parking lot. Because the maintenance protocol for the permeable parking lot does not permit application of sand (incl. road salt) during winter, the source of the sand must be cars bringing in sand- and salt-loaded snow and ice from regular streets. Upon entering the permeable parking lot, snow and ice break lose when cars turn into the lot or melt off the cars when parked. This explanation is supported by total solid concentrations as high as 3.142 g/L in melt water from snow piles within the parking lot. Although sweeping (not vacuuming!) of the parking lot surface was conducted regularly, the desired removal of the sand from the pore space did not occur. Incursion of sand and ice is also indirectly corroborated by high EC and high chloride readings in water samples from 1S and 3S collected during winter. During June, chloride concentration decreased to below detection limit (5 mg/l) indicating that the road salt was washed out off the parking lot structure by early summer. Because of the failure of the baseline sample port 2 S/D to yield water, it was not possible to directly compare the parking lot removal performance with that of the natural soil. However, nitrate concentrations below the parking lot were comparable to typical urban runoff in Rhode Island (RI DOT, 2000). Overall, nitrate concentrations were well below drinking water limits (e.g. 10 mg/L maximum contaminant level, MCL). Currently, there is no MCL established for phosphate. As demonstrated at sample location 1S (Figure 6), the highest nitrate and phosphate concentrations were measured during spring and fall. Because of the timing and the fact that the parking lot is located next to farm land, it is
likely that the high nutrient concentrations in spring and fall were at least partially caused by fertilizer dust settling on the parking lot – especially at sample location 1S, which was closest to the farm land (Figure 1). Copper and zinc concentrations trended higher after full use of the parking lot commenced. Peak concentrations of copper and zinc occurred during late winter and early spring. Enhanced corrosion of automobile parts during this period may have contributed to the elevated aqueous metal levels. Since then, especially copper concentrations have returned to much lower levels and aqueous concentrations below the parking lot were comparable to stormwater runoff concentrations from typical Rhode Island roads (RI DOT, 2000). Both, zinc and copper, concentrations always remained below recommended limits (5 mg/L MCLZinc and 1.3 mg/L copper; as Treatment Technique level; EPA 2002). PAH concentrations near the lower detection limit (ca. 0.3 μg/L) indicate that very little of these compounds reached the base of the parking lot structure. The highest PAH concentration (4.94 μg/L) was measured below the most frequently occupied parking space (3S). In comparison, PAH concentration in runoff from a nearby conventional parking lot was 1.36 μg/L, whereas rainwater contained between ND and 3.86 μg/L PAH.

Of all ionic compounds analyzed from samples collected from sample ports 1S and 3S, copper and zinc exhibit the lowest annual fluxes (range: 0.04 g/m² yr to 0.37 g/m² yr) with zinc fluxes lower than copper (Table 5). Nitrate and phosphate fluxes were similar to each other, ranging from 0.45 g/m² yr to 0.84 g/m² yr. Iron fluxes ranged from 7.23 g/m² yr to 11.24 g/m² yr, while chloride flux at sample port 3S was 65.23 g/m² yr. The comparable high chloride flux was attributed to road salt carried into the parking lot from the outside. PAH flux at port 1S was 0.0006 g/m² yr compared to 0.0010 g/m² yr at 3S.
The lower PAH flux rate at 1S reflects the lower traffic density observed in this part of the parking lot. Assuming similar input concentrations, the PAH flux through the parking lot was an order of magnitude lower than PAH fluxes from roads in Rhode Island (0.002 to 0.011 g/m² yr; RIDOT, 2000). These results suggest that the parking lot effectively removes PAH. Fluxes of all other contaminants, with the exception of phosphate, were similar to concentrations published by RIDOT (2000) for Rhode Island stormwater runoff. Phosphate fluxes from the parking lot were as much as five times higher than fluxes reported for conventional roadways (0.17 g/m² yr; RIDOT, 2000). We suspect that the higher phosphate fluxes were a consequence of fertilizer being added to the adjacent farm land and reaching the parking lot as dust.

Results from multi-species tracer test at sample port 3S indicated that the parking lot is capable of removing metal ions more effectively than nutrients and Na-salicylate. The removal effectiveness for zinc and copper was > 90%, while approximately 27% nutrients and 52.2% Na-salicylate was removed. These removals occurred even though the applied tracer concentrations (Table 6) were several orders of magnitude higher than those found in typical runoff (e.g. RIDOT, 2000). The relative high copper and zinc mass loss was attributed to sorption of these metals to fine particulate matter trapped in the porous asphalt. Similar observations were reported by Legret and others (1999). The loss of more than half of the Na-salicylate was attributed to the presence of biologically active sites (e.g. biofilms) in the parking lot structure. Another possible salicylate removal mechanism sorption. However, more detailed studies of organic contaminants are necessary to fully evaluate the fate and transport of these compounds in the permeable asphalt system.
In this study we examined the fate of contaminants moving through a porous asphalt parking lot. Of the shallow and deep sampling ports placed under the asphalt, only two shallow ports yielded water samples. We concluded that over-compaction and the geotextile fabric placed over the deeper sampling ports impeded infiltration. The presence of the geotextile layer may have resulted in channelized infiltration at point locations, thereby potentially exhausting the contaminant attenuation capacity at these locations faster than anywhere else under the parking lot. A more permeable geotextile fabric may reduce or eliminate this problem. Minimal to no yield of water from one of the three shallow sampling ports suggested that extensive pavement clogging occurred within areas of the parking lot that had the most traffic. These data suggest that porous asphalt in high traffic areas may not function properly in removing stormwater. Similar observations were made by Lindsey and others (1992). Areas of the parking lot that remained porous showed that the asphalt was effective at removing organic and metals contaminants, including bacteria, and was much less effective at removing anions and nutrients. These findings confirm those of Legret and others 1996. Contaminant concentrations varied with the season, i.e. higher nutrient concentrations were found during spring and fall fertilizer application, while higher metal and chloride concentrations were found late winter and early spring when road salting was at its maximum. Because most nutrients appear to have entered the parking via dust deposition, contaminant fluxes could be reduced by more frequent sweeping of the parking lot. But, sweeping is unlikely to lower the flux of chloride and metals that are released from melting ice brought in by cars. More important, sweeping may not remove particles as effective vacuuming. Since this parking lot is relatively new, sampling needs
to continue to determine the long-term contaminant retention capacity of the porous asphalt parking lot.

The results of this study were summarized in a scientific paper (invited) and submitted to the *Journal of Environmental Geology*. The paper is currently in review. Also, several presentations during national and international conferences have been given (Boving et al., 2004 a, b), including presentations to URITC. A *Technical Bulletin* (McNally et al., 2005 a) and a *Case study* paper (McNally et al., 2005b) about porous pavement structures, including results from this study, have been published in cooperation with the University of Rhode Island Cooperative Extension (available at [www.uri.edu/ce/wq](http://www.uri.edu/ce/wq)).

Finally, the parking lot site served as a field trip destination for students to learn more about stormwater treatment technologies.

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Biography of Research Team

Associate Professor Dr. Thomas B. Boving (boving@uri.edu), URI Department of Geosciences received his Ph.D. in Hydrology and Water Resources from the University of Arizona, Tucson. Dr. Boving has published many peer-reviewed articles about the science and application of chemically enhanced flushing technologies and the quality of storm runoff. He has extensive field experience in the application of innovative remediation technologies and groundwater quality monitoring.

Dr. Mark Stolt (mstolt@uri.edu) is an Associate Professor within the Department of Natural Resources Science at URI. He maintains a soil characterization laboratory at the University of Rhode Island for measuring carbon levels and inorganic constituents in soils and soil pore waters. Dr. Stolt has extensive field experience in soils related to ground and surface water contamination from domestic wastewater disposal. He has guided a number of graduate students’ working on environmental science projects related to water quality such as carbon distribution in riparian zone soils in relation to denitrification potential, effectiveness of sand filters in treating domestic wastewater, fate and transport of P and N in shallow–narrow drainfields, and using soil properties to identify sites for domestic wastewater treatment.

Brian Brosnan (BBrosnan@BETA-Inc.com) is a professional Engineer (P.E.) and is a project manager with BETA Group Inc., Lincoln, RI. He was in charge of the planning and construction of URI’s porous parking lot.

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