Nutrient Infiltrate Concentrations from Three Permeable Pavement Types

Robert A. Brown¹ and Michael Borst²

¹ *Corresponding Author*, formerly Oak Ridge Institute for Science and Education Postdoctoral Fellow at the U.S. Environmental Protection Agency, 2890 Woodbridge Ave., MS-104, Edison, New Jersey, USA, 08837; PH (732) 906-6898; email: rob.brown.rab@gmail.com

² Chemical Engineer, U.S. Environmental Protection Agency, 2890 Woodbridge Ave., MS-104, Edison, New Jersey, USA, 08837; PH (732) 321-6631; email: borst.mike@epa.gov

Abstract

While permeable pavement is increasingly being used to control stormwater runoff, field-based, side-by-side investigations on the effects different pavement types have on nutrient concentrations present in stormwater runoff are limited. In 2009, the U.S. EPA constructed a 0.4-ha parking lot in Edison, New Jersey, that incorporated permeable interlocking concrete pavement (PICP), pervious concrete (PC), and porous asphalt (PA). Each permeable pavement type has four, 54.9-m², lined sections that direct all infiltrate into 5.7-m³ tanks enabling complete volume collection and sampling. This paper highlights the results from a 12-month period when samples were collected from 13 rainfall/runoff events and analyzed for nitrogen species, orthophosphate, and organic carbon. Differences in infiltrate concentrations among the three permeable pavement types were assessed and compared with concentrations in rainwater samples and impervious asphalt runoff samples, which were collected as controls. Contrary to expectations based on the literature, the PA infiltrate had significantly larger total nitrogen (TN) concentrations than runoff and infiltrate from the other two permeable pavement types, indicating that nitrogen leached from materials in the PA strata. There was no significant

1
2
3
4 difference in TN concentration between runoff and infiltrate from either PICP or PC, but TN in
5
6 runoff was significantly larger than in the rainwater, suggesting meaningful inter-event dry
7
8 deposition. Similar to other permeable pavement studies, nitrate was the dominant nitrogen
9
10 species in the infiltrate. The PA infiltrate had significantly larger nitrite and ammonia
11
12 concentrations than PICP and PC, and this was presumably linked to unexpectedly high pH in
13
14 the PA infiltrate that greatly exceeded the optimal pH range for nitrifying bacteria. Contrary to
15
16 the nitrogen results, the PA infiltrate had significantly smaller orthophosphate concentrations
17
18 than in rainwater, runoff, and infiltrate from PICP and PC, and this was attributed to the high pH
19
20 in PA infiltrate possibly causing rapid precipitation of orthophosphate with metal cations.
21
22 Orthophosphate was exported from the PICP and PC, as evidenced by the significantly larger
23
24 infiltrate concentrations compared with influent sources of rainwater and runoff.
25
26
27
28
29
30
31
32

33 **Keywords:** permeable pavement; permeable interlocking concrete pavement; pervious concrete;
34
35 porous asphalt; nitrogen; orthophosphate.
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1. Introduction

Green infrastructure stormwater control measures (SCMs), such as permeable pavement, have been installed to manage hydrologic and water quality impacts of stormwater runoff. Research has shown widespread effectiveness for permeable pavement systems in reducing and delaying peak flow rate, reducing runoff volume, and capturing heavy metals and other particulate-bound pollutants from stormwater runoff (Bean et al., 2007; Brattebo and Booth, 2003; Collins et al., 2008; Drake et al., 2012; Legret and Colandini, 1999; Roseen et al., 2009). Few studies have evaluated the effects of permeable pavement on nutrients in stormwater runoff. The available results describe permeable pavement as ineffective at reducing nitrate (NO_3), total nitrogen (TN), and orthophosphate (PO_4) concentrations (Bean et al., 2007; Collins et al., 2010; Drake et al., 2014; Eck et al., 2012; Roseen et al., 2009). Nutrients, although necessary for life, are stressors of concern because elevated concentrations can lead to eutrophication in surface water systems. In the U.S., states, territories, and other jurisdictions report nutrients as a leading cause of impairment in estuaries, lakes, and rivers (USEPA, 2009). Drake et al. (2013) suggested further investigation is needed on evaluating the source, fate, and transport of nutrients in permeable pavement systems. Collins et al. (2010b) also specified a need to quantify nitrogen cycling and removal processes within SCMs, including permeable pavement.

Most permeable pavement field research has been conducted at sites with a single pavement type, making it difficult to differentiate the effect of pavement types on performance. As described in Table 1, a few recent studies have conducted side-by-side comparisons of different pavement types (Collins et al., 2010; Drake et al., 2014; Welker et al., 2012). However, at least one commonly-installed permeable pavement type was absent in each, so a study is

needed which compares permeable interlocking concrete pavement (PICP), pervious concrete (PC), and porous asphalt (PA).

Table 1. Summary of research studies with side-by-side comparisons of multiple permeable pavement types.

Location [References]	Number of Permeable Pavement Sections Tested by Type:			Inflow Source	Sample Type
	Permeable Interlocking Concrete Pavement (PICP)	Pervious Concrete (PC)	Porous Asphalt (PA)		
Kinston, North Carolina [Collins et al. (2010)]	3 ^a	1	Absent	Direct rainfall only	Flow-weighted composite
Vaughan, Ontario [Drake et al. (2012, 2014) and Drake (2013)]	2	1	Absent	Direct rainfall only	Flow-weighted composite
Villanova, Pennsylvania [Welker et al. (2012)]	Absent	1	1	Run-on plus direct rainfall	Porewater samples from the underlying in situ soil

^a One of the three PICP sections was concrete grid pavement (CGP). CGP is considered a subset of PICP, but the void space between concrete blocks is filled with sand instead of the small aggregate that is typically used in PICP.

Previous studies have described that the primary nitrogen transformation and retention processes in permeable pavement systems include: nitrification and filtration of particulate-bound nitrogen. Another process that been suggested (Collins et al., 2010b), but has not been confirmed, is denitrification through an internal anaerobic zone.

Permeable pavement systems are designed with an open-graded subbase to temporarily detain runoff before slow release through an underdrain or into permeable underlying soils. The subbase typically drains at a rate where it remains in an aerobic state suitable for nitrification. Collins et al. (2010) described that the pH in PICP and PC effluent, which was consistent with pH measured in Drake et al. (2014), was within or near the optimal range [pH of 7.6–8.8 (Coyne, 1999)] for growth of *nitrosomonas* and *nitrobacter*, the bacteria responsible for nitrifying ammonium to nitrite and then to nitrate. As a result, ammonia (NH₃) and organic nitrogen present in rainwater and run-on are transformed to nitrate. In Collins et al. (2010) and Drake et

1
2
3
4 al. (2014), the effluent ammonia (NH_3) and total Kjeldahl nitrogen (TKN) concentrations from
5
6 all of the PICP and PC sections were significantly smaller than impervious asphalt runoff
7
8 concentrations. The combined nitrite and nitrate ($\text{NO}_{2,3}$) concentration in the effluent was
9
10 significantly larger than the concentration in impervious asphalt runoff, except from the PC
11
12 section at the Ontario site (Drake, 2013) and the concrete grid pavement (CGP) section at the
13
14 North Carolina site (Collins et al., 2010). In these two cases, there was no significant difference
15
16 between the effluent and runoff $\text{NO}_{2,3}$ concentrations.
17
18
19
20

21 Without an anaerobic zone, little, if any, TN concentration reduction occurs from
22
23 permeable pavement systems (Collins et al., 2010b). The Ontario site had a low-permeability
24
25 soil and a ball valve installed at the underdrain outlet to increase hydraulic retention time within
26
27 the aggregate layer. These conditions were believed to create an anoxic zone favorable for
28
29 denitrification (Drake et al., 2014); however, mean and median NO_3 concentrations were larger
30
31 in the effluent than in impervious asphalt runoff. At the North Carolina site, there was no
32
33 significant TN concentration reduction in the effluent from any permeable pavement section
34
35 (Collins et al., 2010). One PICP section that had an inadvertent sump (or internal water storage
36
37 zone) created when the underdrain was installed at a higher elevation than designed provided the
38
39 largest TN load reduction (Collins et al., 2010). However, this section had significantly larger
40
41 $\text{NO}_{2,3}$ concentrations than all other permeable pavement sections tested and was the only section
42
43 that had significantly larger TN concentrations than the impervious asphalt runoff; therefore, the
44
45 increased concentration shows that the load reduction did not result from denitrification but
46
47 through volume reduction. This design feature in permeable pavement systems needs more
48
49 research to confirm that anaerobic conditions develop and that there is an adequate and
50
51 appropriate carbon source to support denitrification.
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Filtration can reduce TN released in the effluent from permeable pavement systems; however, its effectiveness will be dependent on the influent composition and whether particulate-bound organic nitrogen is present. Permanent TN removal from the system will depend on maintenance practices because the particulate-bound organic nitrogen will be trapped near the surface and could remobilize if the organic matter decomposes. The Ontario site provided an example of this process and its success in reducing TN. Mean effluent TN concentrations for the three permeable pavement surfaces tested were about 35 to 45% smaller than the mean TN concentration in impervious asphalt runoff, and the TN reduction was attributed to particulate filtration of leaf litter and organics attached to suspended solids (Drake et al., 2014). The largest nitrogen component in the impervious asphalt runoff at this site was total organic nitrogen (TON), and TON was the nitrogen component with the largest load reduction when comparing runoff and effluent loads (Drake et al., 2014).

None of the paired field studies collected effluent samples from PA. However, there have been several individual pavement studies that used PA materials, and they describe similar results indicating that nitrification was a dominant process affecting nitrogen composition in the effluent. A PA research site in Durham, New Hampshire, had a median effluent pH of 7.1 (Roseen et al., 2012), so it was expected that PA effluent would, in general, be near a neutral pH and on the lower end of the optimal pH range for nitrifying bacteria. The average dissolved inorganic nitrogen (DIN, sum of $\text{NO}_{2,3}$ and NH_3) concentration in the effluent from the PA site in New Hampshire was 35% larger than the average concentration in impervious asphalt runoff (Roseen et al., 2009). Paired samples from permeable friction course (PFC) and impervious asphalt from two sites near Austin, Texas, described that median $\text{NO}_{2,3}$ concentrations were larger and median TKN concentrations were smaller from PFC compared with impervious

1
2
3
4 asphalt runoff, but only TKN from one site was significantly different (Eck et al., 2012). PFC is
5
6 a similar material to PA, except it is installed over impervious pavement instead of an open-
7
8 graded aggregate layer.
9

10
11 Taken as a whole, the field study results are inconclusive about whether PA has an effect
12
13 on TN. The research site in Pennsylvania that collocated PA with PC (Welker et al., 2012) used
14
15 first flush samplers to collect impervious asphalt runoff samples before infiltrating into the
16
17 permeable pavement and porewater samplers to collect samples at two depths (15 and 30 cm)
18
19 into the underlying soil for each system (Welker et al., 2012). With nine or fewer porewater
20
21 samples at each location, the porewater sampled beneath the PA had a larger average TN
22
23 concentration than porewater sampled beneath the PC for each depth, but the difference was not
24
25 significant at either depth (Welker et al., 2012). The TN concentrations measured in first flush
26
27 samplers at the PA and PC sites were not significantly different, and only the PA site had a larger
28
29 average TN concentration in the porewater samples than from the corresponding first flush
30
31 sampler (Welker et al., 2012). For the PA site in New Hampshire, DIN was the only nitrogen
32
33 parameter measured, so it is not possible to evaluate the net effect on TN for this PA system.
34
35 While there was no comparison to runoff from an adjacent impervious asphalt site, Winston et al.
36
37 (2012) reported that average TN concentrations from four PFC sites (ranging from 1.48 to 2.60
38
39 mg/L) were on the upper end of published concentrations from highway and parking lot runoff.
40
41 The authors speculated that the large nitrogen concentrations resulted from atmospheric
42
43 deposition from hog farming in the area (Winston et al., 2012).
44
45
46
47
48
49
50
51
52

53 Only a few permeable pavement studies have reported PO_4 concentrations. Drake et al.
54
55 (2012) described that effluent PO_4 concentrations from the two PICP sites were significantly less
56
57 than the concentrations in the runoff samples, while the effluent PO_4 concentration from the PC
58
59
60
61
62
63
64
65

1
2
3
4 site was significantly larger than the runoff concentration. The PFC study in Texas showed no
5
6 significant difference for dissolved phosphorus concentrations from PFC and impervious HMA
7
8 (Eck et al., 2012).
9

10
11 The objective of this research is to evaluate the effect of three commonly-installed
12
13 permeable pavement types (PICP, PC, and PA) on infiltrate concentrations of nutrient
14
15 constituents, including: TN, NO₃, NO₂, NH₃, TON, PO₄, and total organic carbon (TOC), at an
16
17 actively-used parking area designed for field research on permeable pavement systems. The
18
19 infiltrate will also be compared with rainwater and impervious asphalt runoff to investigate
20
21 stressor sources and evaluate whether there is a net reduction or export.
22
23
24
25

26 27 **2. Material and Methods**

28 29 **2.1. Site Description**

30
31 In 2009, the U.S. EPA constructed a 0.4-ha, 110-space, parking lot at the Edison
32
33 Environmental Center (EEC) in Edison, New Jersey. The design incorporated three different
34
35 types of permeable pavement (PICP, PC, and PA) in the 42.7-m long by 11.6-m wide head-to-
36
37 head parking rows (Fig. 1). The southernmost single row of parking stalls and the 7.6-m wide
38
39 driving lanes were paved with impervious hot mix asphalt (HMA). The parking lot was built on
40
41 a 1.6% longitudinal slope from north to south with no cross slope. The design impervious area
42
43 to permeable pavement area ratio is 0.66:1. Facility staff and visitors use the parking lot
44
45 regularly, and the typical parking load is one or two cars per parking stall per workday, with
46
47 observed preferential parking nearer the doors of the adjacent building. Detailed site
48
49 descriptions and monitoring methods are described in Borst and Brown (2014) and Brown and
50
51 Borst (2014).
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure 1.tif

Fig. 1. Aerial photograph of the site in use (left), and site layout with numbered locations of the lined sections sampled for water quality and associated drainage areas (right).

The length of each permeable pavement row was divided into nine equally-sized 4.74-m long by 11.6-m wide sections. In four of these sections (Fig. 1), an impermeable liner (0.45 mil ethylene propylene diene monomer) was installed 0.4 m below the surface with vertical sidewalls to create an open-topped box. The lined sections are numbered 1 to 4 from west to east. The liner captures all infiltrating water and routes it through polyvinyl chloride (PVC) piping to 5.7-m³ high-density polyethylene (HDPE) collection tanks (Model TCB1500, Pentair Aquatic Eco-Systems, Apopka, Florida) on the east side of the parking lot. Each section receives direct rainfall and runoff from the travel lane immediately uphill of the lined section. All sheet flow from this driving lane fully infiltrates into the permeable pavement section, so each section receives similar inflow volumes, as measured and reported in Brown and Borst (2015). The HDPE collection tanks are roughly cylindrical with conical bottoms, and have a working storage capacity ranging from 3.4 to 4.1 m³. The tanks will capture all infiltrate for a rain event up to 38 mm.

The storage gallery under the parking lot is constructed of compacted recycled concrete aggregate (RCA), crushed and screened on site to American Association of State Highway and Transportation Officials (AASHTO) No. 2 gradation. The 0.15-m thick layer of PC and 0.076-m thick layer of PA were installed directly on the compacted RCA. The PICP was installed with multiple aggregate layers. A 0.10-m thick layer of AASHTO No. 57 aggregate was placed on the RCA to act as a choker course for a 0.05-m thick bedding layer of AASHTO No. 8 aggregate that was also placed in the 13-mm gaps between the 0.079-m thick pavers (model: ECO Paver,

EP Henry, Woodbury, NJ). The site receives road salt as a part of the winter operating protocol, and it is applied from a truck-mounted spreader. Sand is not mixed with or applied with the salt.

2.2. Sampling Methods

This paper focuses on 13 rainfall events sampled during a 12-month period starting in October 2010, which was 12 months after the parking lot opened. The sampling strategy targeted the first sampleable rain event of each month. For each event, duplicate samples were collected of rainwater, HMA runoff, and the infiltrate from each collection tank. The rainfall depth distribution for the sampled events included several large events; four of the 13 sampled events (31%) exceeded 25 mm. Detailed characteristics for each sampled rain event are in the supplementary section.

When the event produced adequate water in the infiltrate collection tank, the analytical sample was collected directly from the tank after circulating the collected water for 15 minutes using a gasoline-powered centrifugal trash pump. The samples were collected from near the center of the tank using a PVC bailer and transferred to pre-cleaned sample bottles [meeting EPA protocol C requirements (Scientific Specialties Service, Inc., Hanover, Maryland)]: 100-mL HDPE for nitrogen and phosphorus species or acidified 40-mL amber glass for TN and TOC. Duplicate sample sets were collected for analysis of both filtered and unfiltered nutrients. The filtration step took place at the on-site laboratory after collection, using 0.45 μm polypropylene filters (GHP membrane, Pall Corp., Port Washington, NY). An additional sample was collected at each location in a 100-mL HDPE sample bottle for determination of pH and oxidation reduction potential (Eh) using an ion-specific electrode (Orion DUAL STAR pH/ISE Meter, Thermo Fisher Scientific Inc., Beverly, MA).

1
2
3
4 When the event did not produce adequate volume in the collection tank, the sample was
5
6 collected from a pre-cleaned 18.9-L HDPE bucket, positioned before the event to intercept the
7
8 inflowing water. The bucket was sealed and taken to the on-site laboratory for mixing and
9
10 sampling. Most samples (63%) were collected from the tanks after circulating the collected
11
12 water. All infiltrate samples were considered event mean concentrations (EMCs). The infiltrate
13
14 volume from two largest events sampled exceeded the working capacity of each collection tank.
15
16 Based on the measured relationship of infiltrate volume and rainfall depth (Brown and Borst,
17
18 2015), the average fraction of total infiltrate captured for these events was about 0.63 and 0.76.
19
20 In these cases, the captured volume is assumed to be representative of the entire infiltrate volume
21
22 since the entering water causes a well-mixed solution.
23
24
25
26
27

28 Rainwater was sampled using an elevated, 2-m diameter, conical-bottom, HDPE tank
29
30 located about 500 m south of the parking lot. The runoff samples were collected from two of the
31
32 curb cuts at the south end of the parking lot using automatic samplers (Model 900 and 900MAX;
33
34 American Sigma, Loveland, Colorado) programmed to collect time-weighted samples.
35
36
37

38 The collected samples were immediately carried to the on-site laboratory where they
39
40 were logged into the sample management system and filtered (if specified), and then refrigerated
41
42 or frozen until shipment. Samples were shipped by overnight delivery in coolers with cold packs
43
44 to the EPA laboratory in Cincinnati, Ohio, for analysis. Only pH and Eh were analyzed at the
45
46 on-site laboratory. All analytical methods and detection limits are described in Table 2. The
47
48 TON concentration was calculated as the difference between the TN concentration and the sum
49
50 of the measured nitrogen species for unfiltered samples only. Filtered TOC samples were
51
52 excluded from the statistical analyses because the filtered field blank sample collected from each
53
54
55
56
57
58
59
60
61
62
63
64
65

event had measureable TOC concentrations. More details on quality assurance and the field blank results are described in the supplementary section.

Table 2. Description of preservation and analytical methods with associated detection limits for water quality parameters analyzed.

Stressor (Abbreviation)	Preservation Method	Analytical Method	Detection Limit (mg/L)
Ammonia as N (NH ₃ -N) ^a	-20°C ^b	EPA 350.1	0.03
Nitrite as N (NO ₂ -N) ^a	-20°C ^b	EPA 353.2	0.01
Nitrate as N (NO ₃ -N) ^a	-20°C ^b	EPA 353.2	0.02
Total Nitrogen (TN) ^a	H ₃ PO ₄ ; 4°C	EPA 415.3	0.01
Total Organic Carbon (TOC) ^a	H ₃ PO ₄ ; 4°C	EPA 415.3	0.10
Orthophosphate as PO ₄ (PO ₄ -PO ₄) ^a	-20°C ^b	EPA 365.1	0.025
pH	4°C	ISE	N/A
Oxidation Reduction Potential (Eh)	4°C	ISE	N/A

^a Unfiltered and filtered (0.45 µm) samples were analyzed.

^b Samples before February 2011 were preserved at 4°C.

All four tanks were always sampled for the PICP and PA infiltrate, and all four tanks were sampled for the PC infiltrate in every event except four, when only three tanks were sampled. The rainwater collection system was sampled in all events except one (11/16/2010). At the runoff sampling stations, only one event did not have a sample for either station (05/04/2011) and seven events included one station only. The total number of samples (filtered, unfiltered, and duplicate) analyzed for each stressor was 208 for PICP and PA, 192 for PC, 66 for runoff, and 48 for rainwater. Overall, 93% of the expected samples were collected.

Rainfall depth was measured with four tipping bucket rain gauges (RGD-01 and RG2-M, Onset Computer Corp., Bourne, MA) mounted on the roof of the building adjacent to the parking lot. The reported rainfall depths and intensities were calculated as the average measured by the four rain gauges.

2.3. Statistical Methods

Most statistical tests were computed with Statistica, Version 9.1 (StatSoft, 2009). Data sets with a large proportion of results below the laboratory-reported detection limit were analyzed using ProUCL 5.0 (USEPA, 2013). A significance level of $\alpha=0.05$ was used for all comparisons.

The analytical data contain a number of results below the laboratory reported analytical detection limits for NH_3 , NO_2 , and PO_4 . The frequency below the detection limit by sample source and stressor are described in Fig. 2. When the censored data is less than 15% of the entire dataset, USEPA (2000) recommends simple substitution of half the detection limit. The recommended 15% threshold was greatly exceeded for NH_3 from all three permeable pavement types and for PO_4 in runoff, rainwater, and the PA infiltrate, so regression on expected order statistics (ROS) for a log-normal distribution was applied (Helsel, 2005). The analyses for NH_3 used the unfiltered samples only. Substitution of half the detection limit was applied for all stressors when calculating the summary statistics of average concentration by event.

Figure 2.tif

Fig. 2. Frequency of samples below analytical detection limits for stressors with nondetects.

Using a general linear model, a repeated-measures analysis of variance (ANOVA) was conducted on stressor concentration results. Location by section number (1–4), duplicate samples by sample number (1 or 2; all samples were collected in duplicate), and whether the sample was filtered [yes (“filtered”) or no (“total”)] were set as the repeated measures factors (within effects) because they represent repeated measures on the same subject (pavement type for a given event). For the nitrogen and phosphorus species that exist primarily in the dissolved form (NO_2 , NO_3 , NH_3 , and PO_4), the *a priori* expectation was that there would be no significant

1
2
3
4 concentration difference between the unfiltered and filtered samples from the same sampling
5
6 location for a given event. It was assumed that filtration by the permeable pavement would also
7
8 result in no significant difference between unfiltered and filtered TN concentrations for the
9
10 infiltrate samples. If the within effect for filtration method (yes/no) proved to be significant, the
11
12 unfiltered and filtered samples were separated in the repeated measures analysis. The effect for
13
14 filtration method only had a significant difference for PO₄ [$F(1, 8) = 9.13$, $p\text{-value} = 0.017$], so
15
16 unfiltered (T-PO₄) and filtered (D-PO₄) samples were analyzed separately. Event number and
17
18 pavement type were set as the independent statistical treatments (between effects), and the
19
20 analysis of the between effects was restricted to first-order effects.
21
22
23
24

25
26 The statistical treatment “event number” is a somewhat ambiguous factor as many
27
28 elements could influence the physical differences. By selecting the first event of each month that
29
30 met established criteria for sample collection, there was an attempt to randomize these effects.
31
32 The obvious effects would include, for example, the known seasonal rainfall patterns, antecedent
33
34 dry period, rainfall depth, and rainfall intensity.
35
36
37

38 Assumptions required for repeated-measures ANOVA include: (1) normal distribution,
39
40 (2) homogeneity of variance, and (3) sphericity. All combinations of the within effects for each
41
42 sampling location were tested with the Kolmogorov-Smirnov (K-S) test to determine whether the
43
44 stressor concentrations were normally distributed. The homogeneity of variance for the within
45
46 and between effects were tested with Bartlett’s test. Compound symmetry, or sphericity, of the
47
48 first and second order interactions for within effects was tested with the Mauchly test of
49
50 sphericity. None of the stressors tested satisfied all three assumptions using the raw
51
52 concentrations. A log-transformation was applied to satisfy the required assumptions for TOC,
53
54 T-PO₄, and NO₃. To address a violation of the sphericity assumption for log-transformed TN,
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 NO₂, and D-PO₄, the statistical conclusions for the within effects and all interactions were
5
6 verified with a multivariate analysis of variance (MANOVA), following the procedures outlined
7
8 by Quinn and Keough (2006), because the MANOVA approach does not require a sphericity
9
10 assumption. The Fisher's Least Significant Difference (LSD) method was used, as
11
12 recommended in Milliken and Johnson (1997), for post-hoc contrasts.
13
14

15
16 For stressors that had at least one pavement type treated with ROS (NH₃, T- PO₄, and D-
17
18 PO₄), the log-transformed concentrations by pavement type were normally distributed but had
19
20 unequal variances. Despite unequal variances, a one-way ANOVA was used to test the effect of
21
22 pavement type because the sample sizes were nearly equal, which increases the robustness of the
23
24 one-way ANOVA for unequal variance (Milliken and Johnson, 1997).
25
26

27
28 Permeable pavement infiltrate concentrations were compared with rainwater and runoff
29
30 samples using a factorial ANOVA. The factorial ANOVA was used to test for effects from the
31
32 following factors: sample source, event number, and when applicable, whether the sample was
33
34 filtered. The raw concentrations from each set of duplicate samples were averaged after the
35
36 results from the repeated measures ANOVA on the infiltrate samples confirmed that the infiltrate
37
38 collection tanks had been adequately homogenized. Only five events had runoff samples
39
40 collected from both curb cut inlets, so a Wilcoxon signed-rank test was used to test if the
41
42 concentrations by event were similar for the two sampling locations. With a limited number of
43
44 samples, there was no significant difference for any stressor measured, so the runoff samples
45
46 collected from both curb cut inlets were averaged by event. The normal distribution and
47
48 homogeneity of variance assumptions were tested and satisfied for the log-transformed data.
49
50 Two events were excluded because either the rainwater or the runoff was not sampled. For
51
52 stressors that had multiple sample sources treated with ROS, a Welch's Test (Welch's ANOVA)
53
54
55
56
57
58
59
60
61
62
63
64
65

was used to test the effect of sample source because the sample sizes and variances were unequal (Milliken and Johnson, 1997).

A Spearman test was conducted to determine whether concentrations from any of the sample sources were correlated with rainfall depth or antecedent dry period (ADP). Spearman rank correlation coefficients were also calculated to determine if there was a correlation between rainwater and runoff concentrations and if either influent source was correlated with infiltrate concentrations by event. The nonparametric correlation test used the non-transformed, unfiltered samples only.

3. Results

The repeated measures ANOVA results from all three pavement types with pooled unfiltered and filtered samples (NO_2 , NO_3 , and TN) and from unfiltered TOC samples are described in Table 3, and the repeated measures ANOVA results for T- PO_4 and D- PO_4 from PICP and PC only are described in Table 4. For the repeated measures ANOVA that included all three permeable pavement types, pavement type (Pavement) had a significant effect on concentration for all stressors tested (NO_3 , NO_2 , TN, and TOC). The remaining stressors that used ROS and a one-way ANOVA also described a significant effect on pavement type: T- PO_4 [$F(2, 301) = 300.2$, $p\text{-value} < 0.0001$], D- PO_4 [$F(2, 301) = 313.5$, $p\text{-value} < 0.0001$], and NH_3 [$F(2, 300) = 37.5$, $p\text{-value} < 0.0001$]. The Fisher's LSD post-hoc results by stressor are presented in Table 5. In general, the PA infiltrate concentrations were significantly larger than concentrations in the PICP and PC infiltrate for TN, NO_2 , NH_3 , and TOC, and they were significantly smaller for T- PO_4 and D- PO_4 . There were no significant differences between the PICP and PC infiltrate for TN, NH_3 , TOC, T- PO_4 , and D- PO_4 . The NO_3 results varied from this pattern, as the PICP infiltrate concentration was significantly larger than the concentrations in the

1
2
3
4 PC and PA infiltrate, and there was no significant difference between the PC and PA infiltrate.
5
6
7 While some stressors had a significant difference by permeable pavement type, the ecological
8
9 relevance towards receiving surface water systems varied. This is an important perspective to
10
11 consider when evaluating whether a significant difference is also meaningful. For example, the
12
13 larger TN concentration in PA (average EMC: 1.15 mg/L) compared with PICP (0.77 mg/L) and
14
15 PC (0.81 mg/L) will have more of an ecological impact than the larger NO₃ in PICP (0.68 mg/L)
16
17 compared with PC (0.62 mg/L) and PA (0.62 mg/L).
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 3. Repeated measures ANOVA comparing the three permeable pavement types by the within effects for location (LOCATION), duplicate samples (DUP), and filtration method (FILT).

Effect	DF	TN ^{ab}		TOC ^a		DF	NO ₃ ^{ac}		NO ₂ ^{abc}	
		F-Stat	p-value	F-Stat	p-value		F-Stat	p-value	F-Stat	p-value
Pavement	2	47.26	<0.0001	26.07	<0.0001	2	8.51	0.0025	146.61	<0.0001
Event	12	132.57	<0.0001	26.58	<0.0001	11	121.11	<0.0001	3.21	0.0137
LOCATION	3	1.76	0.166	1.90	0.142	3	2.04	0.119	18.55	<0.0001
LOCATION*Pavement	6	2.95	0.0146	2.99	0.0146	6	5.28	0.0002	2.33	0.0454
LOCATION*Event	36	0.88	0.651	1.16	0.315	33	0.78	0.781	1.22	0.251
DUP	1	2.46	0.135	3.63	0.075	1	0.34	0.568	0.11	0.741
DUP*Pavement	2	0.79	0.469	2.75	0.094	2	1.38	0.276	0.39	0.681
DUP*Event	12	0.94	0.531	0.33	0.971	11	0.29	0.980	2.01	0.091
FILT	1	0.27	0.610	N/A ^d	N/A ^d	1	1.92	0.182	0.58	0.458
FILT*Pavement	2	2.68	0.096	N/A ^d	N/A ^d	2	0.07	0.936	0.73	0.497
FILT*Event	12	0.47	0.906	N/A ^d	N/A ^d	11	0.61	0.799	1.45	0.233
LOCATION*DUP	3	1.80	0.159	1.51	0.224	3	1.14	0.340	1.34	0.271
LOCATION*FILT	3	6.44	0.0008	N/A ^d	N/A ^d	3	2.22	0.096	0.37	0.773
DUP*FILT	1	0.16	0.696	N/A ^d	N/A ^d	1	0.17	0.689	0.12	0.730

Note: bold denotes a statistically significant effect ($p < 0.05$), and DF = degrees of freedom.

^a Data were log-transformed to satisfy normality and homogeneity assumptions.

^b Despite log-transformation, the sphericity assumption was still violated, so MANOVA was used and confirmed that the statistical conclusions held true.

^c When all 13 events were included, FILT*Event had a significant interaction. The result was that the filtered sample had a significantly larger concentration than the unfiltered sample on 01/18/2011, so this event was excluded.

^d Test was not applicable because the effect FILT was not included for TOC; only unfiltered samples were tested.

Table 4. Repeated measures ANOVA comparing two permeable pavement types (PICP and PC) by the within effects for location (LOCATION) and duplicate samples (DUP).

Effect	DF	T-PO ₄ ^{ab}		D-PO ₄ ^{abc}	
		F-Stat	p-value	F-Stat	p-value
Pavement	1	0.05	0.825	1.38	0.274
Event	12	3.72	0.0356	2.27	0.126
LOCATION	3	1.28	0.302	1.31	0.294
LOCATION*Pavement	3	1.94	0.150	2.28	0.105
LOCATION*Event	36	1.80	0.067	0.93	0.586
DUP	1	0.41	0.541	1.40	0.271
DUP*Pavement	1	0.003	0.959	2.73	0.137
DUP*Event	12	0.38	0.938	5.25	0.0127
LOCATION*DUP	3	1.12	0.361	0.22	0.881

Note: bold denotes a statistically significant effect ($p < 0.05$).

^a Data were log-transformed to satisfy normality and homogeneity assumptions.

^b Repeated measures ANOVA was conducted on PICP and PC only because of the large frequency of samples below the detection limit from PA.

^c MANOVA was tested to confirm the same statistical conclusions held true because the sphericity assumption was violated.

Table 5. Post-hoc pairwise comparison by pavement type using Fisher's LSD test.

Stressor	PICP vs. PC		PICP vs. PA		PC vs. PA		Analysis Method
	Result	p-value	Result	p-value	Result	p-value	
NH ₃ , total only	PICP ~ PC	0.14	PICP < PA	<0.0001	PC < PA	<0.0001	One-way ANOVA
NO ₂	PICP < PC	0.021	PICP < PA	<0.0001	PC < PA	<0.0001	RM ANOVA
NO ₃	PICP > PC	0.0034	PICP > PA	0.0009	PC ~ PA	0.86	RM ANOVA
TN	PICP ~ PC	0.77	PICP < PA	<0.0001	PC < PA	<0.0001	RM ANOVA
T-PO ₄	PICP ~ PC	N/A ^a	PICP > PA	<0.0001	PC > PA	<0.0001	One-way ANOVA
D-PO ₄	PICP ~ PC	N/A ^a	PICP > PA	<0.0001	PC > PA	<0.0001	One-way ANOVA
TOC	PICP ~ PC	0.19	PICP < PA	<0.0001	PC < PA	<0.0001	RM ANOVA

Note: bold denotes a statistically significant effect ($p < 0.05$).

^a This pair was not tested using Fisher's LSD because the repeated measures ANOVA used on these two pavement types only described no significant difference, and the repeated measures ANOVA is a more powerful statistical test.

Event number (Event) was a significant effect for all stressors tested with the repeated measures ANOVA that included all three pavement types (NO₃, NO₂, TN, and TOC). The post-hoc test identified homogenous groups of events and showed that the events on 06/09/2011 and 07/25/2011 had the largest TN concentration, followed by the events on 08/03/2011 and 01/18/2011. The events on 06/09/2011 and 07/25/2011 were also the largest homogenous group

1
2
3
4 for NO₃, but only the event on 08/03/2011 was included in the next largest group. Based on the
5
6 average concentrations by event, the event on 01/18/2011 had the largest NO₂ and NH₃
7
8 concentrations. The homogenous group with largest TOC concentration included events on
9
10 06/09/2011, 07/25/2011, and 08/03/2011.
11
12
13

14 The repeated measure for the duplicate samples (DUP) was not a significant effect for
15
16 any stressor tested, and the repeated measure for location of the lined-section (LOCATION)
17
18 pooled across the pavement types was only significant for NO₂. The post-hoc test showed that
19
20 the concentration from Section #4 (eastern-end lined section) was significantly larger than the
21
22 other sections and Section #2 was significantly smaller than the others. There were three
23
24 significant interactions. First, the interaction of location and filtration method
25
26 (LOCATION*FILT) was significant for TN. Second, the interaction of duplicate samples and
27
28 event number (DUP*Event) was significant for D-PO₄ in PICP and PC. Three events
29
30 (05/04/2011, 07/25/2011, and 08/03/2011) had a significant difference between Sample #1 and
31
32 Sample #2. Finally, in the repeated measures ANOVA that included all three pavement types,
33
34 the interaction of location and pavement type (LOCATION*Pavement) was significant for all
35
36 stressors tested, and these interactions are described in Table 6. This interaction resulted from
37
38 the variability for at least one pavement type not being consistent across the parking row. In
39
40 general, PC had the fewest pairwise differences among sections, with Section #3 having the
41
42 largest TN and NO₃ concentrations. In the PICP, Section #4 (easternmost) had the largest TN,
43
44 NO₂, and NO₃ concentrations but the smallest TOC concentration. In the PA, Section #2 had the
45
46 smallest TOC, TN, NO₂, and NO₃ concentrations. Section #3 and Section #4 had the largest TN
47
48 concentration, with Section #3 having the largest NO₃ and Section #4 having the largest NO₂
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

concentrations. When only PICP and PC were included in the repeated measures ANOVA for PO₄ (Table 4), there was no significant interaction of location and pavement type.

Table 6. Fisher's LSD pairwise comparison of location by pavement type for stressors with a significant interaction and average event mean concentration [EMC] (mg/L) for infiltrate by section.

Pavement Type	Section Number ^a	TN		NO ₂		NO ₃		TOC	
		Avg EMC	Homogenous Groups by Pavement Type ^b	Avg EMC	Homogenous Groups by Pavement Type ^b	Avg EMC	Homogenous Groups by Pavement Type ^b	Avg EMC	Homogenous Groups by Pavement Type ^b
PICP	1	0.83	A	0.020	B	0.70	AB	7.1	A
	2	0.71	B	0.014	C	0.62	B	6.0	AB
	3	0.74	B	0.018	BC	0.63	B	6.5	AB
	4	0.87	A	0.023	A	0.78	A	6.2	B
PC	1	0.75	AB	0.040	A	0.59	AB	6.4	A
	2	0.78	AB	0.020	B	0.61	AB	8.8	A
	3	0.89	A	0.030	AB	0.67	A	10.1	A
	4	0.80	B	0.032	AB	0.62	B	9.0	A
PA	1	1.15	AB	0.18	B	0.60	B	13.2	A
	2	1.05	B	0.14	C	0.62	B	9.6	B
	3	1.18	A	0.14	BC	0.72	A	12.1	A
	4	1.19	A	0.29	A	0.53	B	11.8	A

^a Section #1 is the westernmost section (closest to the adjacent building, and Section #3 is the easternmost section (farthest from the building).

^b The grouping category "A" represents the homogenous group with the largest concentration.

Including rainwater and runoff samples with the infiltrate samples in a factorial ANOVA, sample source, event number, and the interaction were significant ($p < 0.0001$) for all stressors tested (TN, NO₂, NO₃, TON, and TOC). The factor for filtration method and all interactions with it were not significant ($p > 0.05$) for any stressor tested (TN, NO₂, and NO₃). The post-hoc comparison of pairwise results by sample source and Welch's Test results for NH₃, T-PO₄, and D-PO₄ are described in Table 7. In comparison with all sample sources, rainwater had the smallest concentrations for TOC, TN, and all nitrogen species except NH₃, which was the sample source with the largest concentration. Runoff, the other influent source, had the largest NH₃,

TON, and TOC concentrations, with the latter two stressors having no significant difference when compared with PA infiltrate. The TN concentration in runoff was not significantly different from PICP and PC infiltrate, but it was significantly smaller than in PA infiltrate. The T-PO₄ concentrations in both influent sources (runoff and rainwater) were significantly smaller than the PICP and PC infiltrate, but they were both significantly larger than the PA infiltrate. A summary of descriptive statistics for the non-transformed concentrations from each sample source and stressor when averaged by event are described in Table 7 and graphically in Fig. 3 for average EMCs with homogenous groups presented.

Figure 3.tif

Fig. 3. Average event mean concentration (EMC) by sample source and stressor with summary results of Fisher's LSD post-hoc pairwise comparison (A is group with the largest concentration and C or D is the smallest); TOC is the only stressor on the right (R) axis.

Table 7. Event-average summary statistics of non-transformed stressor concentrations by sample source.

	Event-Average	PICP (N = 13 events)	PC (N = 13)	PA (N = 13)	Runoff (RO) (N = 12)	Rainwater (RAIN) (N = 12)	Fisher's LSD post-hoc pairwise comparison ^a
NH ₃ -N (total only)	Mean Median IQR Range	0.035 0.023 0.016–0.031 0.015–0.17	0.030 0.018 0.017–0.024 0.015–0.14	0.066 0.044 0.022–0.068 0.015–0.20	0.22 0.11 0.085–0.21 0.036–0.90	0.30 0.16 0.10–0.33 0.026–1.46	RO ~ RAIN > PA > PICP ~ PC Welch's F(4, 90) = 51.2, p < 0.0001 ^b
NO ₂ -N	Mean Median IQR Range	0.019 0.013 0.008–0.015 0.006–0.099	0.029 0.015 0.011–0.023 0.006–0.14	0.19 0.16 0.095–0.31 0.062–0.35	0.025 0.024 0.021–0.030 0.012–0.042	0.010 0.010 0.005–0.013 0.005–0.019	PA > RO > PC > PICP ~ RAIN F(4, 172) = 291.5, p < 0.0001
NO ₃ -N	Mean Median IQR Range	0.68 0.62 0.31–0.77 0.24–1.55	0.62 0.45 0.26–0.75 0.17–1.65	0.62 0.50 0.23–0.83 0.23–1.49	0.39 0.28 0.15–0.42 0.11–1.10	0.29 0.22 0.13–0.32 0.07–0.83	PICP > PC ~ PA > RO > RAIN F(4, 172) = 99.1, p < 0.0001
TON (by calculation)	Mean Median IQR Range	0.05 0.01 -0.03–0.04 -0.04–0.37	0.14 0.09 0.03–0.11 0.00–0.67	0.29 0.20 0.14–0.36 0.04–0.73	0.26 0.16 0.08–0.28 0.05–1.09	0.08 0.02 -0.04–0.14 -0.11–0.55	PA ~ RO > PC > PICP ~ RAIN F(4, 95) = 36.7, p < 0.0001
TN (total only)	Mean Median IQR Range	0.77 0.64 0.34–1.17 0.23–1.73	0.81 0.58 0.39–1.25 0.19–1.84	1.15 1.06 0.50–1.58 0.37–2.52	0.86 0.57 0.37–0.84 0.24–2.97	0.66 0.50 0.26–0.70 0.10–2.79	PA > PICP ~ PC ~ RO > RAIN F(4, 229) = 97.1, p < 0.0001
T-PO ₄ -PO ₄ (total only)	Mean Median IQR Range	0.15 0.13 0.098–0.23 0.013–0.28	0.16 0.15 0.11–0.20 0.059–0.39	0.018 0.015 0.013–0.021 0.013–0.043	0.075 0.052 0.027–0.10 0.013–0.19	0.055 0.016 0.013–0.052 0.013–0.31	PICP ~ PC > RO > RAIN > PA Welch's F(4, 85) = 112.4, p < 0.0001 ^b
D-PO ₄ -PO ₄ (filtered only)	Mean Median IQR Range	0.11 0.12 0.096–0.15 0.013–0.18	0.16 0.13 0.11–0.16 0.049–0.40	0.018 0.013 0.013–0.016 0.013–0.046	0.085 0.075 0.013–0.13 0.013–0.24	0.066 0.023 0.013–0.070 0.013–0.36	PICP ~ (PC & RO) > RAIN > PA PC > RO Welch's F(4, 82) = 109.5, p < 0.0001 ^b
TOC (total only)	Mean Median IQR Range	6.43 4.92 2.02–7.48 1.38–20.5	9.04 7.70 3.55–10.1 1.66–30.2	11.7 11.2 4.57–12.4 4.36–30.3	12.0 7.03 4.51–14.1 3.82–34.9	1.98 1.27 0.70–2.06 0.46–9.61	PA ~ RO > PC > PICP > RAIN F(4, 95) = 281.9, p < 0.0001

^a All stressors were log-transformed except TON when running the Fisher's LSD post-hoc test after the ANOVA indicated sample source was a significant effect.

^b A Welch's Test was used to test the effect of sample source because the variances and sample sizes were unequal.

1
2
3
4 The rainfall at this site was acidic, with an average pH of 5.3. Exposure to the HMA
5
6 raised the runoff pH to around neutral (average: 7.3), and each permeable pavement type raised
7
8 the pH to basic conditions. The average pH for each of the four PICP, PC, and PA sections
9
10 ranged from 8.8 to 9.0, 9.1 to 9.4, and 10.7 to 11.5, respectively. The Eh from all sampling
11
12 locations was in a range where NO₃ reduction would not be expected. Detailed summary
13
14 statistics for pH and Eh from each sampling location are described in the supplementary section.
15
16
17
18

19 The Spearman rank correlation coefficients and test results on stressor concentrations
20
21 from each sample source and rainfall event depth or ADP are described in Table 8. In general,
22
23 there was a negative correlation between rainfall depth and the TOC and TN concentrations in all
24
25 five sample sources. A negative correlation with rainfall depth was also present for the dominant
26
27 nitrogen species in the three types of permeable pavement (NO₃) and in runoff and rainwater
28
29 (NO₃ and NH₃). While fewer combinations were significant when testing for correlations with
30
31 ADP, many Spearman rank correlation coefficients were positive and exceeded 0.25.
32
33 Comparing the Spearman rank correlation coefficients for rainfall depth and ADP, the
34
35 correlations, when present, were stronger for rainfall depth. Rainwater and runoff concentrations
36
37 had a positive correlation for TOC, TN, and the two most dominant nitrogen species in rainwater
38
39 (NO₃ and NH₃). Infiltrate from each of the three permeable pavement types had a positive
40
41 correlation with rainwater and runoff concentrations for TOC, TN, and NO₃, and these stressors
42
43 had the largest Spearman rank correlation coefficients. For stressors with fewer than 15% of the
44
45 samples below the detection limit for both pairs of sample sources, infiltrate concentrations had a
46
47 positive correlation with rainwater and runoff concentration, with one exception. The exception
48
49 was T-PO₄ concentration in runoff compared with infiltrate from PICP and PC, which had no
50
51 significant correlation.
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 8. Spearman rank correlation coefficients for tests of stressor concentration by sample source versus rainfall event characteristics of depth and antecedent dry period (ADP).

Rainfall Event Characteristic	Stressor	PICP	PC	PA	Runoff	Rainwater
Depth	TOC	-0.83*	-0.82*	-0.73*	-0.56*	-0.74*
	TN	-0.73*	-0.66*	-0.70*	-0.76*	-0.78*
	NO ₂	0.19	0.03	-0.54*	-0.09	0.34
	NO ₃	-0.76*	-0.69*	-0.76*	-0.76*	-0.71*
	NH ₃	0.02	0.11	-0.33*	-0.49*	-0.78*
	T-PO ₄	-0.09	-0.10	-0.19	-0.43	-0.52
ADP	TOC	0.26	0.23	0.29*	0.51*	0.38
	TN	0.28	0.30	0.30*	0.45	0.41
	NO ₂	-0.31*	0.13	0.08	-0.28	-0.22
	NO ₃	0.29*	0.33*	0.34*	0.35	0.42
	NH ₃	0.32*	-0.01	0.16	0.46	0.48
	T-PO ₄	-0.24	-0.42*	0.06	0.11	0.34
Runoff concentration by event	TOC	0.53*	0.43*	0.56*	N/A	0.85*
	TN	0.85*	0.73*	0.77*	N/A	0.90*
	NO ₂	0.33*	0.30*	0.27*	N/A	0.27
	NO ₃	0.78*	0.74*	0.80*	N/A	0.82*
	NH ₃	0.25*	0.11	0.43*	N/A	0.89*
	T-PO ₄	0.06	-0.04	0.57*	N/A	0.51
Rainwater concentration by event	TOC	0.80*	0.73*	0.80*	0.85*	N/A
	TN	0.81*	0.82*	0.80*	0.90*	N/A
	NO ₂	0.50*	0.10	-0.07	0.27	N/A
	NO ₃	0.87*	0.88*	0.86*	0.82*	N/A
	NH ₃	0.14	-0.04	0.46*	0.89*	N/A
	T-PO ₄	0.26	-0.01	0.46*	0.51	N/A

Notes: Bold and * denotes a statistically significant correlation ($p < 0.05$).

Shading denotes that more than 15% of the samples were below the detection limit.

N/A describes combinations where the correlation test was not conducted on itself.

4. Discussion

4.1. Comparison of Sampling Results to Literature Values

The TN concentration in the infiltrate from each permeable pavement type tested at the EEC was not significantly less than in the runoff. This was consistent with results presented in Collins et al. (2010), but contrary to those in Drake et al. (2014), where TN concentrations in PICP and PC effluent were significantly smaller than the concentration in impervious asphalt runoff. When comparing the concentrations of the nitrogen components present in the runoff at the EEC and at the Ontario permeable pavement site (Drake et al., 2014) to each other and to typical concentrations in urban stormwater runoff, as presented in the National Stormwater

Quality Database (NSQD) (Pitt et al., 2004), the composition of nitrogen in stormwater runoff, more specifically, the lack of particulate-bound organic nitrogen in runoff at the EEC is believed to be one reason why there was no TN reduction at the EEC site but TN reduction was present at the Ontario site.

The runoff concentrations in this study, as presented in Table 7, were frequently less than the median values presented in the NSQD for commercial land uses – 0.5 mg/L for $\text{NH}_3\text{-N}$, 0.6 mg/L for $\text{NO}_{2,3}\text{-N}$, 1.5 mg/L for TKN (Pitt et al., 2004). The largest discrepancy, when compared with the NSQD, is the TKN fraction (calculated as the sum of TON and NH_3). Based on median concentrations, the calculated TKN concentration was about equal to the $\text{NO}_{2,3}$ concentration at the EEC, where TKN was 2.5 times larger than $\text{NO}_{2,3}$ in the NSQD. The small TON concentration at the EEC is attributed to the limited surrounding vegetation and that runoff was solely from impervious HMA, whereas the median impervious percentage of commercial sites in the NSQD was 83% (Pitt et al., 2004).

The median and mean concentrations of nitrogen species and ratio of TKN to $\text{NO}_{2,3}$ from impervious asphalt runoff at the Ontario permeable pavement site (Drake et al., 2014), which measured significant TN concentration reductions, aligned better with those in the NSQD than at the EEC. The dominant nitrogen component in runoff at the Ontario site was TON, and a large portion of the nitrogen reduction was attributed to filtration of leaf litter and other organics attached to suspended solids (Drake et al., 2014). Therefore, the ability of permeable pavement systems to reduce TN concentrations will be an artifact of site conditions. In order to limit the potential for rapid surface clogging, permeable pavement installations are recommended to avoid runoff from vegetated surfaces and locations near large deciduous vegetation, so TN concentration reductions through TON filtration should not be expected for most sites.

Without an impermeable liner, the infiltrate percolates towards groundwater transporting NO_3 . In an assessment of groundwater contamination potential from infiltrating stormwater practices, NO_3 was considered to have low to moderate risk because its abundance in urban stormwater is relatively low (Pitt et al., 1999). The open-graded subbase at the EEC, like most permeable pavement sites, lacked an anaerobic layer to complete the nitrogen cycle. Had an anaerobic zone been present, carbon is a requirement for denitrifying bacteria. In comparing the three permeable pavement types only, the TOC concentrations in the PICP and PC infiltrate were not significantly different, but both were significantly smaller than the concentrations in the PA infiltrate. The TOC concentration in the PA infiltrate was not significantly different from the concentration in the runoff, but both the PICP and PC infiltrate displayed evidence of net carbon retention because the TOC concentration in the infiltrate was significantly smaller than in the runoff. Further studies are needed to explore whether the TOC in the runoff and infiltrate would be both sufficient and in an appropriate form to support the denitrifying bacteria or if an additional carbon source is needed to promote denitrification in permeable pavement systems with an anaerobic zone.

Another explanation for the smaller nitrogen concentrations in the runoff at the EEC site compared with the NSQD is that larger rainfall events were sampled at the EEC causing diluted concentrations because the TOC, TN, NH_3 , and NO_3 concentrations in the runoff at the EEC had a negative correlation with rainfall event depth. The median rainfall depth for events sampled at the EEC (12.4 mm) was larger than that for events sampled from commercial sites (9.9 mm) in the NSQD (Pitt et al., 2004).

4.2. *Comparison to Local and Seasonal Rainfall Concentrations*

As a comparison to local rainwater quality measured in New Jersey, volume-weighted mean NO₃-N concentrations at five locations ranged from 0.39 to 0.50 mg/L (Reinfelder et al., 2004). This was larger than the mean concentration at the EEC (0.29 mg/L), but the difference is partly attributed to the volume-weighted mean reporting units by the NJ Atmospheric Deposition Network. Seasonally, Reinfelder et al. (2004) measured larger NO₃ concentrations during the spring and summer than during the fall and winter. This seasonal effect could be supported from the ANOVA results at the EEC that showed the late spring and early summer events had larger NO₃ and TN concentrations. The three events during this period with the largest concentrations also had small rainfall depths and long ADPs. The negative correlation with rainfall depth and positive correlation coefficients with ADP for TN and the two most dominant nitrogen species (NO₃ and NH₃) in rainwater and runoff confounds the seasonal interpretation. With only one year of monthly sampling analyzed in this paper, the duration is too short to comment definitively on whether the significant effect for event number was influenced by variations in seasonal inputs or rainfall characteristics (e.g., depth, antecedent dry period).

The nitrogen species' concentrations in rainwater were significantly smaller than in runoff except for NH₃, which had no significant difference suggesting that the inter-event dry deposition was important. For TOC, TN, and the two most dominant nitrogen species in rainwater (NO₃ and NH₃), there was a strong positive correlation between rainwater and runoff concentrations. The runoff and rainwater quality also had a strong positive correlation with infiltrate concentration from all permeable pavement types for TOC, TN, and NO₃, so the response from influent sources was transferred directly to the infiltrate.

4.3. pH

The pH of stormwater before and after infiltrating through an SCM is important because it affects precipitation, dissolution, and biological transformation of some stressors. The average pH of rainwater reported in this region (New Jersey and eastern Pennsylvania) ranged from 4.85 to 4.96 (Procopio and Aucott, 2013), which is on the lower end of the range for rainwater sampled at the EEC (4.4 to 6.4). This acidic rainwater became basic as it infiltrated through each permeable pavement profile. The optimum pH range for *nitrosomonas* and *nitrobacter* is 7.6–8.8 (Coyne, 1999), so the pH range of the PICP and PC infiltrate was within or slightly above the optimal pH range for these bacteria, and the PA infiltrate greatly exceeded the optimal pH range for these bacteria. It is suspected that the significantly larger NH_3 and NO_2 concentrations in PA infiltrate resulted from incomplete nitrification. The PICP and PC infiltrate were typically within the optimal pH range, and these types of permeable pavement had a larger frequency of samples below the detection limits for $\text{NH}_3\text{-N}$ (0.03 mg/L) and $\text{NO}_2\text{-N}$ (0.01 mg/L).

The pH from PA was not expected to be as high as was measured (event-based average for the four sections ranging from 10.7 to 11.5) based on the median of 7.1 measured from a PA site in New Hampshire (Roseen et al., 2012). Because of the unexpectedly high pH and limited published data, other sources for unpublished data from PA and PFC were explored. “Unpublished measurements collected by Caltrans on runoff from several pervious friction course pavement locations indicated variable pH ranging between 5.7 to 9.1, with an average value of 6.95” (Caltrans, personal communication, April 7, 2015). The source of the high pH from this site has yet to be identified. A deterioration of PA with time is not suspected because since water quality monitoring started at this site in January 2010, three months after the site opened, the pH in PA infiltrate has been high (range: 11.1 to 11.5), and the high pH has

continued through a recently monitored rain event in October 2014, five years after installation (range: 10.6 to 11.5).

4.4. Nitrogen Leaching

The significantly larger TN concentration in the PA infiltrate compared with rainfall, runoff and the other permeable pavement types suggests that nitrogen leached from the PA strata (e.g., asphalt or aggregate in the PA mixture) into the infiltrate. The leaching source is not believed to be from the open-graded subbase material, the RCA, because each of the permeable pavement sections used RCA from the same source. If a portion of the RCA was unknowingly contaminated, the large TN concentrations and high pH would not have been experienced across the entire width of the parking rows for the same pavement type. This is a benefit of the experimental design including replicates of the same permeable pavement type. The RCA is concrete, so this subbase material was expected to provide some buffering capacity, but the pH was not expected to be as high as it was in the PA infiltrate or that it would be higher than in the infiltrate from the PICP and PC.

4.5. Orthophosphate Capture and Export

While the PA infiltrate had a significantly larger TN concentration compared with PICP and PC, it had significantly smaller total and dissolved PO_4 concentrations than PICP and PC. The PO_4 concentrations in the PA infiltrate was less than in runoff, which was contrary to the PFC study in Texas where there was no significant difference for dissolved phosphorus between PFC and impervious HMA (Eck et al., 2012). The significant reduction of PO_4 by the PA and large frequency of samples below the detection limit is suspected to be from rapid precipitation with metal cations. As an example from a study with concentrations typical for wastewater,

precipitation efficiency of phosphate with calcium was shown to increase at a higher pH, and the efficiency exceeded 90% in 10 minutes when the pH was higher than 10.5 (Song et al., 2001). Future research is needed to confirm that the PO₄ reduction was caused by the elevated pH and whether these conditions are typical for PA.

During this 12-month sampling period at the EEC, PO₄ in PICP and PC infiltrate was significantly larger than influent sources of rainwater and runoff, indicating that these systems were a net source of PO₄. Leaching of PO₄ from PICP and PC occurred at a relatively constant rate, regardless of influent concentrations, because event number (Event) was not significant for D-PO₄ when including PICP and PC only (Table 4). For both total and dissolved PO₄, neither PICP nor PC infiltrate concentration correlated to rainfall event depth or concentrations in rainwater or runoff. The significantly larger PO₄ concentrations in PC infiltrate compared with runoff was consistent with Drake et al. (2012), but the results from PICP infiltrate were contrary to Drake et al. (2012). Therefore, additional research is needed to identify the source and conditions that cause PO₄ leaching from these pavement types while giving consideration to representative influent characteristics, such as typical concentrations and pH.

4.6. *Spatial Effects*

The interaction of location and pavement type showed some variability across the individual pavement types for some stressors, but none were consistent with observed parking patterns. The lack of significant differences between the samples collected from the western side to the eastern side of the parking lot when the three pavements were pooled together suggested that parking patterns did not affect NO₃, TN, TOC, T-PO₄, and D-PO₄ concentrations in the infiltrate. If vehicles provided a positive and meaningful contribution to stressor concentrations, the expectation would be that the western-end section (Section #1) would have the largest

1
2
3
4 concentrations because of observed preferential parking nearer the building doors. The only
5
6 stressor that displayed differences across the parking row when the three pavements were pooled
7
8 was NO₂, and its response was not intuitive and could not be described by usage. While the
9
10 effect was statistically significant, the ecological relevance was minor because the collective
11
12 difference between the sections and by pavement type was numerically small when compared
13
14 with the TN concentrations. The NO₂ concentration in the infiltrate from PICP and PC were
15
16 frequently near or below the detection limit (0.01 mg/L), and the mean concentrations in the PA
17
18 infiltrate by section ranged from 0.14 to 0.29 mg/L.
19
20
21
22

23
24 The variability in the nitrogen speciation results across the PA sections corresponded
25
26 with pH in the infiltrate and optimal pH range for nitrifying bacteria. For the PA infiltrate, the
27
28 section (#3) with the lowest average pH (10.7) had the largest NO₃ concentration, and the section
29
30 (#4) with the highest average pH (11.5) also had the largest NO₂ concentration. This pattern
31
32 supports the earlier discussion regarding the high pH in PA infiltrate resulting in incomplete
33
34 nitrification.
35
36
37

38
39 In addition to evaluating whether a spatial response attributed to parking patterns was
40
41 present, the multiple sections for each permeable pavement type increased the statistical power
42
43 of this study. This approach has never been used in a permeable pavement field study to
44
45 evaluate performance associated with nutrients. Based on inspection of the average EMCs
46
47 presented in Table 6, the lack or presence of a significant difference between permeable
48
49 pavement types might have been interpreted differently had only one section been sampled for
50
51 each pavement type. For example, the TN concentrations were not significantly different
52
53 between PICP and PC, but when examining the average EMCs for one section only, the lack of a
54
55 difference is not as clear. As another example, the average NO₃ EMCs are within 0.01 mg/L for
56
57
58
59
60
61
62
63
64
65

Section #2 and PICP has the smallest average EMC for Section #3, but the repeated measures ANOVA described that PICP infiltrate was significantly larger than PC and PA.

5. Conclusions

A comparison of PICP, PC, and PA at the same site that was designed and monitored with replication to increase statistical power yielded some results that had not been observed in previous studies and were not anticipated; most of these inconsistencies were associated with the response from PA. Specifically for PA, the following outcomes of this study require more investigation to determine why PA behaved differently and whether this is a common or abnormal response and how the response changes with age:

- While having similar influent sources and contributions, the PA infiltrate had significantly larger TN concentrations than PICP and PC infiltrate. The TN concentration in PA infiltrate was also significantly larger than influent source concentrations, which provides evidence that nitrogen leached from materials in the PA strata.
- The high pH in the PA infiltrate exceeded the optimal pH range for nitrifying bacteria, possibly contributing to incomplete nitrification. Infiltrate from PA had significantly larger NO_2 and NH_3 concentrations than PICP and PC, which had a pH near the optimal range for nitrifying bacteria. Across the PA parking row, the section with the largest NO_2 concentration had the highest pH, consistent with the hypothesis that elevated pH inhibited nitrification.
- The total and dissolved PO_4 concentrations in the PA infiltrate were significantly smaller than concentrations in both influent sources (runoff and rainwater) and infiltrate from the other two pavement types (PICP and PC) indicating consistent PO_4

removal in the PA. This result was attributed to possible precipitation with metal cations caused by the high pH.

A few outcomes of this study that reinforce existing permeable pavement and stormwater research include:

- Nitrification was suggested by the observation that NH_3 and NO_3 in rainwater and runoff, and TON in runoff were converted to or remained primarily in the form of NO_3 in the PICP and PC infiltrate – the average NO_3 EMC was 88% and 77% of the average TN EMC, respectively. The dominant nitrogen species in PA infiltrate was also NO_3 (54% of average TN EMC).
- Nitrogen removal within these permeable pavement systems was not suggested, based on the observation that TN concentrations in PICP and PC infiltrate were not significantly different than runoff concentrations. Therefore, influent TN will either migrate toward groundwater in systems that allow exfiltration, or in systems where water predominantly exits through an underdrain, the TN load discharged directly to receiving surface water systems may be marginally attenuated with reduced flow from partial infiltration. Overall, the TN and NO_3 concentrations in this situation were small compared with typical concentrations in urban stormwater.
- Larger events were observed to have more diluted concentrations. This factor should be a consideration in reporting of results and selecting events to sample.
- The significantly larger TN concentration in runoff compared with rainwater suggests that the inter-event dry deposition was significant. This result in conjunction with the positive correlation coefficient for ADP implies buildup with time.

- There was no evidence that increased vehicle usage in this parking lot application caused an increase in infiltrate concentrations because sections that experienced more use did not have correspondingly larger concentrations.

Overall, this study confirmed that permeable pavement systems do not reduce TN concentrations from stormwater runoff because of the lack of anaerobic conditions. The effects on the bioavailable form of phosphorus (PO_4) varied by pavement type. The PICP and PC exported PO_4 at a relatively constant rate during this 12-month period, whereas the PA had significant PO_4 concentration reductions. As there are many different PICP types and the materials used in PA and PC mixtures can vary, the responses across applications of similar permeable pavement types have shown some variation to earlier studies. In some applications, construction materials used can cause leaching and elevated concentrations of some stressors. Future studies are needed to explore leaching attributed to permeable pavement construction materials and its potential based on influent conditions (e.g., pH).

The presence of particulate-bound organic nitrogen in runoff from sources such as leaf litter and other organics should affect whether marginal nitrogen reduction through filtration might be expected from permeable pavement systems. Based on design guidance specifying that permeable pavement installations avoid runoff from vegetated surfaces and locations near large deciduous vegetation because of the potential for rapid surface clogging, large particulate-bound organic nitrogen concentrations in runoff are not expected. Therefore, particulate-bound organic nitrogen removal should not be considered a desirable metric for permeable pavement.

Acknowledgements

The authors would like to thank Mr. Keith Kelty of the USEPA's Treatment Technology Evaluation Branch for overseeing the sample analyses and PARS Environmental under contract

EP-C-10-054 for sample collection. The parking lot was constructed as a joint project with EPA's Office of Administration and Resources Management and Region 2. This project was supported in part by an appointment to the Research Participation Program at the National Risk Management Research Laboratory administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy and U.S. Environmental Protection Agency.

Disclaimer:

The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

References

- Bean, E.Z., Hunt, W.F., Bidelsbach, D.A., 2007. Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts. *Journal of Irrigation and Drainage Engineering* 133, 583-592.
- Borst, M., Brown, R.A., 2014. Chloride Released from Three Permeable Pavement Surfaces After Winter Salt Application. *Journal of the American Water Resources Association* 50, 29-41.
- Brattebo, B.O., Booth, D.B., 2003. Long-term Stormwater Quantity and Quality Performance of Permeable Pavement Systems. *Water Research* 37, 4369-4376.
- Brown, R.A., Borst, M., 2014. Evaluation of Surface Infiltration Testing Procedures in Permeable Pavement Systems. *Journal of Environmental Engineering* 140, 1-12.
- Brown, R.A., Borst, M., 2015. Quantifying Evaporation in a Permeable Pavement System. *Hydrological Processes* 29, 2100-2111.
- Collins, K.A., Hunt, W.F., Hathaway, J.M., 2008. Hydrologic Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina. *Journal of Hydrologic Engineering* 13, 1146-1157.
- Collins, K.A., Hunt, W.F., Hathaway, J.M., 2010. Side-by-Side Comparison of Nitrogen Species Removal for Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina. *Journal of Hydrologic Engineering* 15, 512-521.
- Collins, K.A., Lawrence, T.J., Stander, E.K., Jontos, R.J., Kaushal, S.S., Newcomer, T.A., Grimm, N.B., Ekberg, M.L.C., 2010b. Opportunities and Challenges for Managing Nitrogen in Urban Stormwater: A Review and Synthesis. *Ecological Engineering* 36, 1507-1519.
- Coyne, M.S., 1999. *Soil Microbiology: An Exploratory Approach*. Delmar Publishers, Albany, NY.
- Drake, J., Bradford, A., Seters, T.V., 2014. Stormwater Quality of Spring-Summer-Fall Effluent from Three Partial-infiltration Permeable Pavement Systems and Conventional Asphalt Pavement. *Journal of Environmental Management* 139, 69-79.
- Drake, J., Bradford, A., Seters, T.V., MacMillian, G., 2012. *Evaluation of Permeable Pavements in Cold Climates: Kortright Centre, Vaughan*. University of Guelph, Toronto and Region Conservation Authority, Toronto, Canada.

- Drake, J.A.P., 2013. Performance and Operation of Partial Infiltration Permeable Pavement Systems in the Ontario Climate. University of Guelph, Guelph, Ontario.
- Drake, J.A.P., Bradford, A., Marsalek, J., 2013. Review of Environmental Performance of Permeable Pavement Systems: State of the Knowledge. *Water Quality Research Journal of Canada* 48, 203-222.
- Eck, B.J., Winston, R.J., Hunt, W.F., Barrett, M.E., 2012. Water Quality of Drainage from Permeable Friction Course. *Journal of Environmental Engineering* 138, 174-181.
- Helsel, D.R., 2005. *Nondetects and Data Analysis: Statistics for Censored Environmental Data*. John Wiley and Sons, New York, 250 pp.
- Legret, M., Colandini, V., 1999. Effects of a Porous Pavement with Reservoir Structure on Runoff Water: Water Quality and Fate of Heavy Metals. *Water Science and Technology* 39, 111-117.
- Milliken, G.A., Johnson, D.E., 1997. *Analysis of Messy Data - Volume 1: Designed Experiments*. Chapman and Hall, London.
- ONJSC, 2012. Winter Storm Totals. Office of the New Jersey State Climatologist at Rutgers University, Piscataway, NJ.
- Pitt, R., Clark, S., Field, R., 1999. Groundwater Contamination Potential from Stormwater Infiltration Practices. *Urban Water* 1, 217-236.
- Pitt, R., Maestre, A., Morquecho, R., 2004. Report: The National Stormwater Quality Database (NSQD, version 1.1). University of Alabama, Tuscaloosa, AL.
- Procopio, N., Aucott, M., 2013. Atmospheric Deposition: Acidity and Nutrients, Environmental Trends Report. New Jersey Department of Environmental Protection, Office of Science, Trenton, NJ.
- Quinn, G.P., Keough, M.J., 2006. *Experimental Design and Data Analysis for Biologists*. Cambridge University Press, Cambridge, UK.
- Reinfelder, J.R., Totten, L.A., Eisenreich, S.J., 2004. The New Jersey Atmospheric Deposition Network: Final Report. Rutgers University, New Brunswick, NJ.
- Roseen, R.M., Ballesterio, T.P., Houle, J.J., Avellaneda, P., Briggs, J.F., Fowler, G., Wildey, R., 2009. Seasonal Performance Variations for Storm-water Management Systems in Cold Climate Conditions. *Journal of Environmental Engineering* 135, 128-137.
- Roseen, R.M., Ballesterio, T.P., Houle, J.J., Briggs, J.F., Houle, K.M., 2012. Water Quality and Hydrologic Performance of a Porous Asphalt Pavement as a Storm-Water Treatment Strategy in a Cold Climate. *Journal of Environmental Engineering* 138, 81-89.
- Song, Y., Hahn, H.H., Hoffman, E., 2001. The Effects of pH and Ca/P Ratios on the Precipitation of Calcium Phosphate, Second International Conference on Recovery of Phosphate from Sewage and Animal Wastes. Noordwijkerhout, Netherlands, Noordwijkerhout, Netherlands.
- StatSoft, 2009. *Statistica*, Version 9.1. StatSoft, Inc., Tulsa, OK.
- USEPA, 2000. *Guidance for Data Quality Assessment: Practical Methods for Data Analysis* EPA QA/G-9 QA00 Update. U.S. Environmental Protection Agency, Washington, D.C., pp. 1-219.
- USEPA, 2009. *National Water Quality Inventory: Report to Congress - 2004 Reporting Cycle*. EPA 841-R-08-001, U.S. Environmental Protection Agency, Washington DC.
- USEPA, 2013. *ProUCL*, Version 5.0.00. U.S. Environmental Protection Agency, Atlanta, GA.
- Welker, A.L., Barbis, J.D., Jeffers, P.A., 2012. A Side-by-Side Comparison of Pervious Concrete and Porous Asphalt. *Journal of the American Water Resources Association* 48, 809-819.

Winston, R.J., Hunt, W.F., Kennedy, S.G., Wright, J.D., Lauffer, M.S., 2012. Field Evaluation of Storm-Water Control Measures for Highway Runoff Treatment. Journal of Environmental Engineering 138, 101-111.

Figure 1

Figure 2

Figure 3