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Long-term effects of three types of permeable pavements on nutrient infiltrate concentrations

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Abstract

There is limited information about long-term effects of permeable pavement parking lots on concentrations of nutrients in infiltrates. A 0.40-ha parking lot that contained three types of permeable pavement including permeable interlocking concrete pavement (PICP), porous asphalt (PA) and pervious concrete (PC) was constructed in 2010 at a U.S. EPA facility in Edison, New Jersey. This study was conducted from October 2010 to August 2017. Water quality samples were collected from the rainfall, parking lot runoff, and infiltrate from these three pavement types. Samples were analyzed for parameters including $\text{NH}_3\text{-N}$, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, TN, $\text{PO}_4\text{-PO}_4$, TOC, ORP and pH. Statistical methods were used to study infiltrate concentration changes with time.

Results showed, for all analytes, there were no differences between permeable interlocking concrete pavement and pervious concrete median concentrations. Data showed distribution of species changed and supported nitrification processes. The trend varied with source. Nitrogen species showed slowly increasing trends in rainwater, PC and PICP infiltrate concentrations while phosphate concentration showed a slightly increasing trend in rainwater and porous asphalt infiltrate. It is recommended that communities select PC and PICP when nitrogen species are the pollutants of concern and PA is more suitable for orthophosphate removal.

Graphical abstract

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Keywords

Permeable pavement parking lot; Nutrients; Nitrification; Trend analysis; Stormwater runoff

1. Introduction

Replacing impervious surfaces with permeable surfaces is one solution for stormwater management that more closely mimics pre-urban hydrological conditions. Permeable pavements have been implemented to reduce urban runoff peak and volume and improve stormwater runoff quality (Baladès et al., 1995; Fassman and Blackbourn, 2010; Razzaghmanesh and Borst, 2018). Different pavement surfaces have different effects on stormwater runoff quality. However, there is limited information regarding the long-term (more than two years) effects of permeable pavements on stormwater runoff quality (Scholz and Grabowiecki, 2007; Imran et al., 2013; Kayhanian et al., 2019).

Human activities are an important source of excess nutrients (USEPA, 2009). Discharge of excess nutrients into water bodies can cause seasonal eutrophication and algal blooms. Increased levels of nutrients such as phosphorous cause increase in phytoplankton growth and provide a toxic environment for aquatic creatures. Implementing permeable pavement may be a strategy to control pollutant loads from the source.

Permeable pavements have been implemented in the forms of porous asphalt (PA), pervious concrete (PC) and permeable interlocking concrete pavement (PICP) (Collins et al., 2008; Lucke and Beecham, 2011; Weiss et al., 2017). However, to improve the stormwater quality performance of these systems and to better design and prepare maintenance guidelines, continuous monitoring provides the information that is of interest to engineers and decision makers. It is also essential for successful shifts in policy and program implementations (Kayhanian et al., 2019).

Various aspects of permeable pavements have been considered by earlier researchers. Some studies compare stressor concentrations in the surface runoff from the permeable pavements and, in others, infiltrate concentrations (runoff passing through the pavement section) with other surfaces or infiltrates.

Runoff water quality samples of asphalt pavement, concrete paver and crushed-stone driveways in two replicates were collected in Connecticut by Gilbert and Clausen (2006). Flow-weighted composite runoff samples were collected weekly and analyzed for total

suspended solids (TSS), total Kjeldahl nitrogen (TKN), nitrate (NO_3^-), ammonia (NH_3), and total phosphorous (TP) for 22 months. The results showed larger pollutant concentrations were from the asphalt and crushed stone surfaces than from the concrete pavers.

In a study in Rhode Island, effects of porous pavement on stormwater quality were investigated by Boving et al. (2008). They reported that nutrients including NO_3 and PO_4 were observed in the infiltrate and contaminants concentration in percolated water varied seasonally. The nutrient concentration was larger in spring and fall because of fertilizer application to the surrounding green spaces.

Various physical and chemical pollutant removal mechanisms have been associated with the permeable pavement systems. These include sorption, adsorption, biodegradation, settling and filtration (Imran et al., 2013; Winston et al., 2016). Clogging of permeable pavements can reduce the treatment ability of these pavement systems.

Welker et al. (2013) studied a permeable pavement parking lot that included half PC and half PA. They concluded that permeable pavements performed well regarding water quality because of sorption onto the surface of pavements and underlying stone and adsorption to the bed soils.

Nitrification is a microbial process by which reduced nitrogen compounds (primarily ammonia) are sequentially oxidized to nitrite and nitrate. The nitrification process is primarily accomplished by two groups of autotrophic nitrifying bacteria that can build organic molecules using energy obtained from inorganic sources, in this case ammonia or nitrite (USEPA, 2002). The nitrification process has been investigated as a reason for nitrogen species variation of permeable pavement infiltrates by few of the earlier researchers.

Nitrogen removal by four, side-by-side types of permeable pavement and an asphalt surface were conducted in North Carolina (Collins et al., 2010). In this seven-month study the pavements were able to reduce the nitrogen concentration and the pavement surfaces buffered acidic rainfalls. It was concluded that the larger concentration of NO_2^- and NO_3^- on the pavements when compared with asphalt runoff was an indication of possible nitrification process.

Bean et al. (2007) monitored two PICP sites with a control asphalt surface in North Carolina. The pavement system was designed to be aerobic. They found larger NO_2^- and NO_3^- concentrations in the infiltrate (runoff passed through the pavement section) from the permeable pavement areas than the asphalt runoff. Nitrification was mentioned as a reason for larger NO_3^- and NO_2^- concentrations and using a riparian buffer for denitrification process was recommended in this study.

In one of the rare, long-term studies, a five-year study was carried out on a porous asphalt pavement site in the cold weather of New Hampshire by Roseen et al. (2009). The main goal of this study was to examine the effects of frost extension into the porous media on performance. Whereas the pavement showed promising performance for cationic and undissolved contaminants, limited TP removal (42%) and no removal for NO_3 was reported.

In another study by Drake et al. (2014a), winter performance of one pervious concrete section, two permeable interlocking concrete pavement systems, and an asphalt surface were monitored. The pavement sections' effluent concentration for TP and TN were reduced by 50% when compared with asphalt runoff. It was believed that the large concentration of nutrients in the asphalt runoff came from winter salt application. They also concluded that there is a possibility of denitrification.

Water quality performance of the PC and two PICP sections were also studied in non-winter seasons or warm months at the same study site. The results showed removal of $\text{NH}_4^+ + \text{NH}_3$, NO_2 and total oxidized nitrogen (TON). However, the NO_3 concentration and loading increased in warmer seasons. PICP also showed mixed performances for the treatment of PO_4 . They concluded that the larger concentration of NO_3^- comes from the nitrification process during warmer seasons.

As indicated above, the literature shows there are limited studies regarding long-term effects of various types of permeable pavements on macronutrient infiltrate concentrations, with most studies conducted for less than two years. Kayhanian et al. (2019), after several years of study on various aspects of permeable pavements in California, suggested permeable pavement water quality studies should be continued to correspond to the expected 20-year life span of the systems. With such data, it would be possible to predict the future behavior of permeable pavement or other stormwater control measures using statistical techniques.

Long-term water quality data or time series create an opportunity to better understand data trends. Helsel and Hirsch (2002) suggested an adaptation of the Kendall non-parametric test to detect trends in water quality time series. However, there is a possibility of facing a large percentage of below detection results when dealing with water quality time series. Researchers have used various methods to handle these types of datasets. Roseen et al. (2009) substituted half of the detection limit for non-detects, regardless of the percentage of below detection data in the dataset. In another study, substitution of half detection limit was used when censored data were <10% of the entire dataset. Otherwise, the EPA ProUCL method was used for the cases where the censored data were between 10% and 50% of the dataset (Drake et al., 2014b, Drake et al., 2014a).

A review of literature showed that currently there is limited information about the long-term effects of parking lots paved with different types of pavements on stormwater infiltrate quality. There is inconclusive information regarding the chemical process on infiltrate concentrations. This study aimed to compare the long-term results of three common permeable pavements with earlier studies, to suggest implementing the suitable type of permeable pavements for nutrient management and protecting water bodies.

2. Experimental set up

U.S. EPA constructed a 0.4-ha, 110-space parking lot at the Edison Environmental Center (EEC) in 2009 in Edison, New Jersey (O'Connor, 2017; Liu and Borst, 2018). This study site is located at 40°30'47.4"N latitude and 74°21'29.5"W longitude.

The parking lot design contained three commonly-used permeable pavements including PICP, PC, and PA. Each monitored pavement section is 42.7-m long by 11.6-m wide. Permeable sections are installed side by side in three rows (Fig. 1, Fig. 2).

The northern and southernmost rows are single parking stalls paved with PC and hot mix asphalt (HMA). All the non-permeable pavement surfaces of the parking lot are paved with HMA. The parking lot was built on a 1.6% longitudinal slope from north to south with no cross slope (O'Connor, 2017; Selvakumar and O'Connor, 2018).

Four alternating sections of each pavement type were lined to capture and convey stormwater into the sampling tanks through underground pipes (Fig. 2). The five layers of the profile from top to bottom for PICP sections included 7.90 cm porous paver, 5.10 cm of American Association of State of Highway Transportation Officials (AASHTO) No.8 aggregate, 10.20 cm of AASHTO No.57 aggregate, a varied depth of AASHTO No.2 stone made of recycled concrete aggregates (RCA), and a permeable geotextile layer placed on an uncompacted subgrade layer as the bottom layer (Fig. 3).

For PC and PA, 15.25 cm porous concrete and 7.65 cm porous asphalt were directly placed on the RCA layer (Fig. 3). The various depths of the RCA layers were for maintaining the parking lot longitudinal slope. The ratio of impervious area to permeable pavement area is 0.66:1. This parking lot is used regularly by visitors and facility staff during working days. In this study, samples were collected from permeable pavement infiltrates, rainwater, and parking lot runoff according to the sampling plan (Fig. 2).

It was initially planned to collect water samples from the first two sampleable rainfall events each month that provided the minimum volume requirements. This plan was followed from the start of the study (10/28/2010) until 05/10/2013, and resumed from 06/06/2014 until the end of the study (08/23/2017). In the more recent sampling period the samples were collected quarterly. The same method was used for all sample collection and only the sampling interval varied. Samples were analyzed from 47 rain events during an 82-month period.

The study was conducted under an approved quality assurance plan that required duplicates of all samples and a filtered and unfiltered field blank sample for each sampling event. For detailed water collection protocol see Brown and Borst (2015). The collected samples were immediately carried to the on-site laboratory where they were logged into the sample management system and filtered, and then refrigerated or frozen until shipment. Following Method 415.3 by Potter and Wimsatt (2009), filtration used 0.45 μm polypropylene (GHP membrane, Pall Corp., Port Washington, NY) for removing particulates. Samples were shipped by overnight delivery in coolers with cold packs to the EPA laboratory in Cincinnati, Ohio, for analysis as described in Brown and Borst (2015). Only pH, TOC, and ORP were analyzed at the on-site laboratory. Standard EPA analytical methods were used for analysis. The TON concentration was calculated as the difference between the TN concentration and the sum of the measured nitrogen species for unfiltered samples.

The total number of samples analyzed including quality control for each stressor was 504 for PICP, 489 for PA, 408 for PC, 144 for runoff, and 110 for rainwater. There are differences in the number of samples because the study did not always get a sample from each location.

3. Statistical methods

Analytical tests reported many observations (Fig. 4) below laboratory detection limits. When censored data were <15% of the entire dataset, a simple data substitution with half of the detection limit was selected, following USEPA (2000). Multiple imputation technique as recommended by Rubin (1996) using EPA ProUCL Version 5.1 (ProUCL, 2015) with regression on order statistics (ROS) method used for censored data of above 15%.

Normality tests were conducted and, in case of non-normality of both the original and the log-transferred data, non-parametric methods were used for data analysis. Non-parametric Kruskal-Wallis ANOVA with following multiple (2-tailed) comparison was employed for water quality comparisons among rainwater, parking lot runoff, PA, PC and PICP infiltrates.

Most statistical tests were computed with Statistica, Version 9.1 (Statsoft, 2009) unless noted otherwise. A significance level of $\alpha = 0.05$ was used for all comparisons. For trend analysis, the Mann-Kendall trend test was used to identify series trends with time for infiltrates. For trend analysis, the imputed data were used for analysis. All of the trend analyses were conducted using ProUCL Version 5.1 (ProUCL, 2015). Ordinary least square (OLS) regression was used for calculating slope of the trend lines and a significance level of $\alpha = 0.05$ was selected.

4. Results

4.1. pH and oxidation-reduction potential (ORP)

The pH of samples for all sampled events is shown in Fig. 5. Non-parametric Kruskal-Wallis ANOVA was employed ($H(4, N = 606) = 462.06$ $p < 0.01$) and there was a statistically significant difference among pH median values. Three statistical groups were recognized from the data. There was no statistical difference between rainfall and parking lot runoff median concentration or median of PICP and PC infiltrate concentration. PA infiltrate showed the largest pH with a statistically significant difference with other groups.

4.2. Oxidation-reduction potential

A non-parametric Kruskal-Wallis showed there is a statistically significant difference among ORP from the five sources ($H(4, N = 470) = 135.0934$ $p < 0.001$). The median ORP of PA infiltrate was smaller than other sources. There were no statistically significant differences among PC, PICP, RW and RO. RW and parking lot runoff showed the largest median ORP.

4.3. Nitrogen species

4.3.1. Ammonia—There was a statistically significant difference among the median concentration in the sample sources ($H(4, N = 1506) = 442.4407$ $p < 0.001$). Rainwater and runoff had the largest median concentration. PA showed an intermediate level of ammonia,

less than RW and RO and larger than PICP and PC. There was no statistical difference between PC and PICP median concentrations.

4.3.2. Nitrite

A non-parametric Kruskal-Wallis ANOVA was conducted ($H(4, N = 1506) = 692.1647$, $p < 0.001$) and the results showed a significant statistical difference among median of nitrite concentrations. PA infiltrates showed the largest median concentration. There was no statistically significant difference between PC and PICP infiltrate median concentrations and the median concentrations of this group were smaller than PA and larger than RW and RO.

4.3.3. Nitrate—A non-parametric Kruskal-Wallis ANOVA was conducted ($H(4, N = 1506) = 99.0438$, $p < 0.001$) and the results showed a significant statistical difference among median NO_3 concentrations. The results were divided into two statistical groups that had statistically different median concentrations. The first group contained PA, PICP and PC and the second group RW and RO. The infiltrate concentrations did not differ and were larger than the RO and RW concentrations.

4.3.4. Total nitrogen—A non-parametric Kruskal-Wallis test: $H(4, N = 1463) = 62.44$, $p < 0.001$, showed that there is a significant statistical difference among TN of all sources. The infiltrate from PA showed the largest median concentration. There was no statistical difference among median concentrations from PICP, PC, RW and RO.

4.4. Orthophosphate

There is a significant statistical difference among PO_4 of all sources ($H(4, N = 1506) = 546.9840$, $p < 0.001$). Infiltrate from PC and PICP had the largest median concentration. The RW and RO had an intermediate concentration while PA had the smallest median PO_4 concentration.

4.5. Total organic carbon (TOC)

Non-parametric Kruskal-Wallis ANOVA showed that there was significant statistical difference among TOC median concentrations with ($H(4, N = 1476) = 346.66$, $p < 0.01$). PA had the largest median concentration and RW had the smallest. Infiltrates from PC, PICP and RO showed intermediate values.

4.6. Infiltrate concentration trend with time

Nutrient data were used to create time series of infiltrates concentrations for trend analysis with time. In case of non-detected data, the imputed data were used for the trend study. A non-parametric Mann Kendall test was used for trend investigation. The statistical results are reported in Table 1. The trend pattern varies with source. For PA, NH_3 and PO_4 , results showed increasing trends, NO_2 showed a decreasing trend, and NO_3 , TN and TOC did not show any trends. For PC, PICP and RW, all the nitrogen forms (NH_3 , NO_2 , NO_3 and TN) showed increasing trends with time; PO_4 showed a decreasing trend in infiltrates of PC, no trend in PICP infiltrates, and an increasing trend for RW. TOC showed a decreasing trend in infiltrate of both pavements with time, and an increasing trend for RW. For RO, all nitrogen

forms and PO_4 infiltrates did not show any trend with time; however, TOC showed a decreasing trend.

5. Discussion

5.1. pH, ORP and macronutrients

The median pH was larger for parking lot runoff than rainfall. The results showed that the rainfall was acidic, and that parking lot runoff and the infiltrates from the three types of pavement were alkaline. PA's infiltrate showed the largest pH median value, supporting the conclusions of Collins et al. (2010) who claimed permeable pavements behaved like a buffer for acidic rainfall in a study in North Carolina.

Summary statistics for samples collected from permeable pavement infiltrate, parking lot runoff, and rainwater are reported in Table 2. PA showed the smallest PO_4 and largest median concentration values for NO_2 , TON, TN and TOC. Median concentrations of PC and PICP infiltrates were statistically equivalent for all analyzed infiltrates. The largest PO_4 and NO_3 concentrations were observed in the PICP infiltrate. The smallest values of NH_3 were reported from the PC and PICP. All permeable pavements were able to reduce the NH_3 concentration when compared with parking lot runoff at curb cut locations. PA was able to remove most of the PO_4 . Mean and median of event concentrations reported in Table 2, Table 3 were used for comparing the results of this study with earlier studies.

NH_3 median concentrations were larger in RW, RO and PA infiltrate in this study than NH_3 median concentrations in the earlier study by Brown and Borst (2015), while the median NH_3 concentration in PC and PICP infiltrates were smaller in this study. As reported by Brown and Borst (2015), PA showed different behavior than other types of permeable pavement. This long-term study confirmed that after eight years, the PA showed continuous inconsistency with other types of pavement and that NH_3 median concentrations have also increased. The results validate that leaching of the construction and binding materials is more likely the source of contaminations in PA infiltrate.

The NO_2 median concentration in PC and PICP infiltrates was smaller than RO median concentration in this study, which is supported by the results of Drake et al. (2014b), Drake et al. (2014c) and Brown and Borst (2015). The NO_3 median concentration in PA, PC and PICP infiltrates was larger than RW and RO median concentrations in this study. Results of Drake et al. (2014b) supported this finding and Drake et al. (2014c) reported the opposite fact that NO_3 concentration was reduced. These results are mainly due to the nitrification process and showed that NO_2 is converted to NO_3 . Nitrification is a two-stage microbial process that reduces NH_3 sequentially to NO_2^- and NO_3^- (USEPA, 2002). In the first stage, NH_4 is converted to NO_2 under presence of nitrification bacteria; and in the second stage, NO_2 is converted to NO_3 .

In this study, PA showed the largest combination median of $\text{NO}_3 + \text{NO}_2$ concentrations. For all three pavement types, the infiltrate concentrations were larger than the RO or RW concentrations. These results were supported by Collins et al. (2010), who found larger concentrations for $\text{NO}_3 + \text{NO}_2$ in pavements infiltrates than rainfall in a site in North

Carolina. They also found values of $\text{NO}_3 + \text{NO}_2$ were larger in PICP and PC infiltrate than asphalt runoff. The results suggest that the largest combination median of $\text{NO}_3 + \text{NO}_2$ concentration is associated with PA infiltrate, and that the nitrification process was an unlikely cause since pH values were not within the optimum nitrification process range. The results of current and Collins et al. (2010), suggest that PA media materials are more likely the source of large $\text{NO}_2 + \text{NO}_3$ concentrations in infiltrates.

The mean and median of the recorded infiltrates' TN concentrations in this study were smaller than the values reported by Collins et al. (2010); Drake et al., 2014b, Drake et al., 2014c in North Carolina and Canada. This is mainly because of site-to-site differences and various environmental conditions. However, smaller or nearly equal mean and median infiltrates' TN concentrations than this study were reported by Brown and Borst (2015) and Braswell et al. (2018). In this study, larger median TN concentrations in all infiltrates other than runoff were noted. Therefore the results suggest that after nearly five years, the median TN did not change largely when compared with Brown and Borst (2015) as both studies were conducted at the same site.

The PO_4 median concentration increased in PC and PICP infiltrates and decreased in PA infiltrate when compared with PO_4 median concentration in RO in this study. These results were supported by Brown and Borst (2015). The PO_4 median concentration was increased in PC infiltrates and decreased in PICP infiltrates when compared with RO PO_4 median concentration as reported by Drake et al., 2014b, Drake et al., 2014c.

The analyzed infiltrates showed that the concentration of NO_3 is the largest among all the nitrogen forms in infiltrates of three pavement surfaces of PA, PC and PICP. This may be due to the nitrification process under all surface types. Following reported data (Table 2 and Fig. 6), they showed NH_3 is converted to NO_2 when the RW mean NH_3 (0.37 mg/L) is compared with PA (0.07 mg/L), PC (0.04 mg/L) and PICP (0.04 mg/L) and at the same time the NO_2 concentrations from RW (0.012 mg/L) level increased in PA (0.17 mg/L), PC (0.030 mg/L) and PICP (0.023 mg/L). The first process resulted in larger concentration of NO_2 in PA. After the first stage, data showed that NO_3 of RW (0.39 mg/L) increased in PA (0.57 mg/L), PICP (0.66) and PC (0.63 mg/L) through NO_2 conversion to NO_3 . The results showed the first process generated NO_2 in PA infiltrate and the second process resulted in larger concentrations of NO_3 in PICP and PC infiltrates.

There were other conditions that confirmed the possibility of the nitrification process. pH ranges from 7 to 9 provide a suitable environment for nitrification bacteria. pH values of infiltrate of PC and PICP were within the range of optimum pH for nitrification bacteria of nitrosomonas and nitrobacter (USEPA, 2002) whereas PA infiltrates exceeded the range.

All the ORP values were positive. As reported by Environmental (2008), ORP within the range of 100mv to 350mv is suitable for nitrifying bacteria activities, and in this study median ORP concentrations of the all stressors were in the suggested range of nitrification process. Nitrification process in permeable pavement in summer and denitrification process in winter were reported in a study in Canada (Drake et al., 2014b, Drake et al., 2014c).

Nitrification and denitrification processes in permeable pavement due to the bacteria were also mentioned in other studies (Collins et al., 2010).

Some studies (Bean et al., 2007) recommended a detention time of at least 24 h for denitrification process. In this study, due to the use of lined sections, the infiltrates drained into the collection tanks quickly. This process did not provide enough detention time for denitrification and this may have increased the nitrate concentrations.

Recorded pH of PA infiltrate was much more alkaline than PC and PICP, which may be one of the reasons for the smaller concentration of PO_4 observed. The PO_4 concentration in infiltrate from PC and PICP was larger than the median concentration of PO_4 in the infiltrate, whereas PA reduced the PO_4 concentration. Drake et al. (2014c) reported larger values for TP and PO_4 in winter than in non-winter seasons, which they attributed to salt application during wintertime. They reported larger phosphorous concentration decreases for PICP than PC.

TON and TOC have been investigated by few of the earlier researchers. TOC generally originates from the dried and dead parts of trees and plants. The results of this study showed larger median concentration of TOC in PA infiltrate than PC or PICP infiltrate. Both PC and PICP showed some TOC removal compared with the RO mean TOC (Table 2). Similar pattern to TOC for TON was evident for all three-pavement systems.

The median of all nitrogen species and orthophosphate from the Table 2 was compared with the available state of New Jersey guideline (NJDEP, 2011) for discharging to surface water and with groundwater effluent limitations for discharges to Class GA waters in New York State (NYCRR, 2018). All the nitrogen forms were below the limitation criteria whereas just orthophosphate concentration in PC and PICP infiltrates were slightly over the suggested limits.

5.2. Trend analysis

The slopes of the trend lines showed that the concentration of several stressors during the eight years since the parking lot's opening is increasing. The increasing trend in nitrogen forms in rainwater can be because of a variety of biological sources, by reported industrial and combustion processes (National Atmospheric Deposition Program, 2016), and by the deposition rate in the study area, which is about 10 (Kg-N/ha). As explained by Welker et al. (2013), adsorption process by pavement surface and below aggregate layers and sorption into the native soil are possible pollutant removal processes in permeable pavement systems. However, over time, materials lost their initial absorbent potential. Our tests showed that pavement materials and aggregates released some elements and increased the infiltrates' concentration levels. In this study, because of the availability of a liner layer, the sorption into the native soils was not possible. In addition to pavements losing their absorption ability, the increasing trend of nutrient in rainfall was another reason for nutrient increases in PC and PICP infiltrates. Moderate removal of NH_3 and NO_3 was reported by Kamali et al. (2017) after a series of laboratory experiments that simulated seven hydrological years of permeable pavement response to stormwater runoff. This behavior was mainly because of permeable pavement clogging and reduction in the system ratio of horizontal over vertical

hydraulic conductivity. For all three types of the permeable pavement in this study surface clogging was not an issue. As reported by Brown and Borst (2014), many infiltration tests on three types of pavement section were conducted from late 2010 until early 2013 and there was minimal reduction in infiltration capacity. The longevity was attributed to the small contributing runoff area.

6. Conclusions and recommendations

In this study, water quality samples from infiltrates of three types of permeable pavements, a parking lot surface runoff, and rainwater were collected during a nearly eight-year period. This length of time provided an opportunity to study the long-term pollutant removal of three common types of permeable pavements.

For all analytes, there were no differences between PICP and PC median concentrations. The PA infiltrate had significantly larger nitrite and ammonia concentrations than other surfaces. In addition, the PA infiltrate had significantly smaller orthophosphate concentrations than other surfaces. PC and PICP did not change the TN concentrations, and PA increased the TN concentrations. Nitrification process was recognized from the changes in nitrogen species. All the nitrogen forms, including NH_3 , NO_2 , NO_3 and TN, showed increasing trends with time in RW and the PC and PICP infiltrates. PO_4 showed an increasing trend in RW, a decreasing trend in infiltrates of PC and no trend in PICP infiltrates. TOC showed a decreasing trend in infiltrate of both PC and PICP with time.

The infiltrate concentration from the PA is nitrogen enriched and phosphate depleted supporting the shorter-term findings from earlier studies and enabling design engineers to match the material selection with local needs for surface water (when the design includes an underdrain) or groundwater (when it does not).

These results further support likely denitrification processes as suggested by earlier researchers, and that could be incorporated into future designs.

These results suggest further investigation of nitrogen forms in several complete seasons from all types of permeable pavement systems is required to have a better understanding of seasonal effects. PA showed unexpected behavior and further detailed studies of PA are warranted. Modification of the parking lot design to effectively use available rain gardens to maintain the denitrification process and protect groundwater is suggested. It is recommended that communities select PC and PICP when nitrogen species are the pollutants of concern and PA is more suitable for orthophosphate removal.

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Nomenclatures

PICP	Permeable interlocking concrete pavement
PC	Pervious concrete
PA	Porous asphalt
RW	Rainwater
RO	Parking lot runoff
HMA	Hot mix asphalt
CGP	Concrete grid pavers
RCA	Recycled concrete aggregate
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TON	Total oxidized nitrogen
TP	Total phosphorous
NO3	Nitrate as N
NO2	Nitrite as N
PO4	Ortho-phosphate
NH3	Ammonia as N
NH4	Ammonium as N
ORP	Oxidation reduction potential
TOC	Total organic carbon
TSS	Total suspended solids

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Fig. 1.
Aerial image of permeable pavement parking lot in Edison Environmental Center, NJ
(Google earth).

Fig. 2. Site layout with numbered lined sections sampled for water quality and associated drainage areas in Edison Environmental Center (EEC).

Fig. 3.
The profiles of underground layers of three types of permeable pavements.

Fig. 4.
Frequency of samples with stressor concentration below analytical detection limits.

Fig. 5.
Measured pH of all sources, letters indicate the statistical groups.

Fig. 6.
The progress of nitrification process in rainwater and infiltrates.

Table 1.

Results of trend study for pavement sections.

Source/Infiltrate	Stressor					
	NH ₃	NO ₂	NO ₃	PO ₄	TN	TOC
PA	+	–	0	+	0	0
PC	+	+	+	–	+	–
PICP	+	+	+	0	+	–
RW	+	+	+	+	+	+
RO	0	0	0	0	0	–

(+) Infiltrate concentration increased over time or increasing trend, (–) Infiltrate concentration decreased over time or decreasing trend, and (0) Infiltrate concentration did not change over time or no trend.

Table 2.

Summary of statistics in nutrient concentration in three types of permeable pavement infiltrates, parking lot runoff and stormwater (mg/L).

Stressor	Parameter	PA (N = 47events)	PICP (N = 47 events)	PC (N = 38 events)	RW (N = 47events)	RO (N = 40 events)
NH ₃	Mean	0.070	0.040	0.040	0.370	0.205
	Median	0.045	0.015	0.015	0.280	0.121
	IQR	0.015–0.088	0.015–0.042	0.015–0.05	0.113–0.526	0.071–0.206
	Range	0.015–0.452	0.015–0.778	0.015–0.343	0.015–1.485	0.015–1.121
NO ₂	Mean	0.165	0.024	0.030	0.013	0.026
	Median	0.1305	0.0120	0.0140	0.011	0.0230
	IQR	0.061–0.241	0.005–0.322	0.01–0.023	0.005–0.016	0.016–0.031
	Range	0.005–0.772	0.005–0.021	0.005–0.395	0.005–0.059	0.005–0.068
NO ₃	Mean	0.565	0.663	0.631	0.390	0.352
	Median	0.502	0.575	0.478	0.310	0.269
	IQR	0.25–0.78	0.29–0.77	0.264–0.824	0.134–0.528	0.01–1.21
	Range	0.01–2.16	0.01–2.46	0.01–1.931	0.024–1.399	0.137–0.499
TON (by calculation)	Mean	0.20	0.067	0.095	0.021	0.205
	Median	0.16	0.03	0.044	0.005	0.122
	IQR	0.08–0.29	0–0.124	0–0.116	0.079	0.071–0.206
	Range	0–1.441	0–1.284	0–0.946	0.673	0.015–1.121
TN	Mean	1.005	0.775	0.770	0.797	0.752
	Median	0.90	0.64	0.58	0.56	0.50
	IQR	0.06–2.98	0.1–2.38	0.07–2.32	0.1–2.93	0.16–3.15
	Range	0.49–1.325	0.36–1.04	0.34	0.27–1.14	0.31–0.93
PO ₄	Mean	0.025	0.115	0.123	0.065	0.080
	Median	0.013	0.104	0.109	0.026	0.047
	IQR	0.0125–0.116	0.055–0.163	0.064–0.159	0.013–0.078	0.0125–0.547
	Range	0.0125–0.032	0.0125–0.384	0.0125–0.652	0.013–0.474	0.0125–0.095
TOC	Mean	11.15	6.11	7.11	2.39	9.388
	Median	9.7900	2.60	4.6500	1.780	6.140
	IQR	5.6–12.88	0.505–7.77	0.71–70.36	0.32–13.11	1.38–40.8
	Range	2.13–37.48	0.48–40.22	3.05–8.97	1.06–2.74	3.98–9.69

Table 3.

comparison of the results of the current study with other studies.

Stressor	Parameter	PA		PICP		PC		RW		RO	
		Current study	Other studies	Current study	Other studies	Current study	Other studies	Current study	Other studies	Current study	Other studies
NH ₃	Mean	0.070	0.066 ^b	0.040	0.035 ^b	0.040	0.030 ^b	0.370	0.30 ^b	0.205	0.220 ^b
	Median	0.045	0.044 ^b	0.015	0.023 ^b	0.015	0.018 ^b	0.280	0.16 ^b	0.121	0.110 ^b
NO ₂	Mean	0.165	0.190 ^b	0.024	0.019 ^b , 0.009 ^c , 0.015– 0.022 ^d	0.030	0.029 ^b , 0.032 ^c , 0.024 ^d	0.013	0.010 ^b	0.026	0.025 ^b , 0.067 ^c , 0.07 ^d
	Median	0.130	0.160 ^b	0.012	0.013 ^b , 0.007 ^c , 0.009– 0.018 ^d	0.014	0.015 ^b , 0.014 ^c , 0.018 ^d	0.011	0.010 ^b	0.023	0.024 ^b , 0.034 ^c , 0.06 ^d
NO ₃	Mean	0.565	0.620 ^b	0.663	0.68 ^b , 0.72– 0.81 ^c , 0.82– 0.92 ^d	0.631	0.62 ^b , 0.58 ^c , 0.55 ^d	0.390	0.29 ^b	0.352	0.39 ^b , 0.38 ^c , 0.89 ^d
	Median	0.502	0.500 ^b	0.575	0.62 ^b , 0.60– 0.92 ^c , 0.65– 0.76 ^d	0.478	0.45 ^b , 0.37 ^c , 0.42 ^d	0.310	0.22 ^b	0.269	0.28 ^b , 0.33 ^c , 0.71 ^d
NO ₂ + NO ₃	Mean	0.730	0.810 ^b	0.687	0.90– 1.25 ^a , 0.44 ^e	0.661	0.73 ^a	0.403	0.35 ^a , 0.30 ^b	0.378	0.29– 0.31 ^a , 0.415 ^b , 0.13.13 ^e , f
	Median	0.632	0.660 ^b	0.587	0.78– 0.83 ^a , 0.34 ^e	0.492	0.63 ^a	0.321	0.32 ^a , 0.23 ^b	0.292	0.28– 0.33 ^a , 0.304 ^b , 0.11 ^e
TN	Mean	1.005	1.150 ^b	0.775	1.38– 1.73 ^a , 0.77 ^b , 1.0– 1.10 ^c , 0.92– 1.06 ^d , 0.65 ^e	0.770	1.27 ^a , 0.81 ^b , 0.95 ^c , 0.96 ^d	0.797	1.30 ^a , 0.66 ^b	0.752	1.24 ^a , 0.86 ^b , 1.70 ^c , 2.70 ^d , 2.04 ^e
	Median	0.90	1.060 ^b	0.64	1.22– 1.28 ^a , 0.64 ^b , 1.0– 1.10 ^c , 0.83–	0.58	1.14 ^a , 0.58 ^b , 0.80 ^c , 0.86 ^d	0.56	1.20 ^a , 0.50 ^b	0.50	1.20 ^a , 0.57 ^b , 1.30 ^c , 2.40 ^d , 1.65 ^e

Stressor	Parameter	PA	PICP		PC		RW		RO		
		Current study	Other studies	Current study	Other studies	Current study	Other studies	Current study	Other studies	Current study	Other studies
PO ₄	Mean	0.025	0.018 ^b	0.115	0.98 ^d , 0.52 ^e	0.123	0.16 ^b , 0.10 ^c , 0.058 ^d	0.065	0.055 ^b	0.080	0.075 ^b , 0.11 ^c , 0.037 ^d , 0.013 ^e
					0.15 ^b , 0.019 ^c , 0.020– 0.028 ^d , 0.03 ^e						
	Median	0.013	0.015 ^b	0.104	0.13 ^b , 0.015 ^c , 0.012– 0.023 ^d , 0.03 ^e	0.109	0.15 ^b , 0.088 ^c , 0.043 ^d	0.026	0.016 ^b	0.047	0.052 ^b , 0.029 ^c , 0.032 ^d , 0.010 ^e
TOC	Mean	11.15	11.70 ^b	6.11	6.43 ^b	7.11	9.04 ^b	2.39	1.98 ^b	9.388	12 ^b
	Median	9.790	11.20 ^b	2.60	4.92 ^b	4.650	7.70 ^b	1.78	1.27 ^b	6.14	7.03 ^b

^a(Collins et al., 2010).

^b(Brown and Borst, 2015).

^c(Drake et al., 2014a).

^d(Drake et al., 2014b).

^e(Braswell et al., 2018).

^fRunoff collected from a PICP surface.