A Monitoring Field Study of Permeable Pavement Sites in North Carolina

E. Z. Bean, EI
Graduate Research Assistant
Department of Biological and Agricultural Engineering
North Carolina State University, Box 7625
Raleigh, NC 27695-7625;

W. F. Hunt, Ph.D., PE
Assistant Professor and Extension Specialist
Department of Biological and Agricultural Engineering
North Carolina State University, Box 7625
Raleigh, NC 27695-7625

D. A. Bidelspach, EI
Extension Associate
Department of Biological and Agricultural Engineering
North Carolina State University, Box 7625
Raleigh, NC 27695-7625

Abstract

Asphalt surfaces have greatly increased the amount of pollutant-carrying runoff entering surface waters. To counteract this, permeable pavement can be installed to allow water to infiltrate, thus reducing runoff and maybe acting as a filter. Three permeable interlocking concrete pavements (PICP) sites were monitored across North Carolina in Cary, Goldsboro, and Swansboro. The Cary site was located in clay soil and flowrates and samples of exfiltrate and rainfall over 10 months were collected and analyzed for pollutant concentrations. The Goldsboro site was constructed to compare the water quality of asphalt runoff to exfiltrate of permeable pavement. The site was located on a sandy soil and samples were analyzed for pollutants over a span of 18 months. The Swansboro site was constructed and instrumented to monitor runoff flow and rainfall rates and collect exfiltrate and runoff samples from the permeable pavement lot over 10 months. The site was located on a very loose sandy soil and experienced no runoff. PICP exfiltrate from the Goldsboro site had significantly lower concentrations of Total Phosphorus and Zinc compared to asphalt runoff. Total Nitrogen (TN) concentrations were close to significantly lower in exfiltrate, but did show an increasing trend of TN removal.

Introduction

Permeable pavement is an alternative to traditional asphalt and concrete surfaces. It allows stormwater to infiltrate into either a storage basin below the pavement or exfiltrate to the soil and ultimately recharge the water table, while also potentially removing pollutants (EPA, 1999). Urbanization has had a detrimental effect on our surface waters systems. Increased runoff rates from paved surfaces have increased peak flow, time to peak, runoff volumes, and pollutant loads through stream channels causing erosion and stream bank instability along with overland erosion (NRCS, 1986). Parking lot runoff also carries pollutants, such as sediments, nutrients, and heavy metals, into surface waters. In an effort to reduce these effects of urbanization, several municipalities in North Carolina established regulations that limit the amount of impervious surfaces (Bennett, 2003). Permeable pavement may be a solution; reducing both runoff and pollutants. As a result, the use of permeable pavement is poised to grow.

North Carolina has implemented a stormwater credit system for developed sites to manage onsite runoff. Several best management practices (BMPs) were given credits for pollutant reduction, sediment reduction, and peak flow detention, but permeable pavement was not included. Permeable pavement use is only allowed as a BMP under the "innovative BMP" classification. Innovative BMPs however must be monitored on an individual basis to assess their performance (Bennett, 2003), but few landowners have been willing to assume the cost of the required monitoring.

Recent studies have found positive results using permeable pavement with respect to both runoff reduction and water quality improvement. The use of permeable pavement, instead of traditional asphalt, has been shown to decrease surface runoff and lower peak discharge significantly (Pratt 1995; Booth, 1996; Hunt et al., 2001). Permeable pavements have also been shown to act as a filter of such pollutants as lead and automotive oil (Pratt, 1995; Brattebo and Booth, 2003).

The goals of this study were as follows: (1) develop an SCS curve number and rational coefficient for two field sites, (2) monitor pollutant levels of PICP exfiltrate and PICP runoff, and (4) offer basic siting guidelines based upon these results.

Study Sites

Three PICP sites were instrumented for water quality testing, two of which were also instrumented to measure water quantity (Fig. 1). The western-most site, in Cary, was

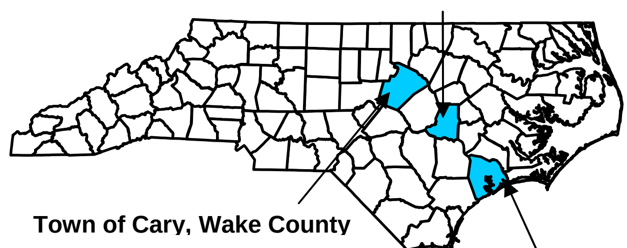

Figure 1. North Carolina map illustrating research site locations.

instrumented to collect rainfall and measure rainfall rates. PICP exfiltrate was collected for water quality analysis and exfiltrate flow rates from under drains were recorded. About 70 miles east of the Cary site, the Goldsboro site was constructed to collect asphalt runoff and exfiltrate for analysis and comparison. The site is a divided parking lot, where the parking stalls are PICP and the drive paths are asphalt. The eastern-most site, Swansboro, is a public parking lot. The site was constructed with PICP to collect runoff and exfiltrate samples for water quality and monitor rainfall intensities and runoff rates. Each monitoring site is located in a different geographic region: the piedmont, coastal plain and coast, respectively.

Cary

The PICP driveway in Cary (Fig. 2a) was constructed in Fall of 2003 with a surface area of 480 m^2. The pavers are 8 cm (3 in.) thick, and were laid over a compacted layer of at least 25 cm (10 in.) of washed No. 57 stone (ASTM D448). The storage basin under the pavers is divided into two separately drained basins. Two 10 cm (4 in.) drain pipes provide outlets for exfiltrate. Precipitation was measured by an ISCO rain gauge. The storage basin was lined with an impermeable geo-textile to prevent seepage into the soil, so any water not draining from the underdrains was assumed to be runoff.

Goldsboro

The parking lot in Goldsboro, (Fig. 2b) was constructed in the summer of 2001. An 8 cm (3 in.) drainage pipe was installed under a section of the PICP during construction to collect exfiltrate samples. The pipe drains about 120 m^2 of permeable pavers. The 8 cm thick pavers overlay 8 cm of No. 78 stone, which are, in turn, over 20 cm of washed No. 57 stone (ASTM D448). To capture asphalt runoff, the drive path was graded so that runoff would flow towards a metal channel, where it could be collected by a Sigma 900™ automated sampler.

Swansboro

The Swansboro parking lot (Fig. 2c) was constructed in the fall of 2003 with an area of 975 m^2. Pavers, 8 cm (3 in.) thick, were overlaid 8 cm (3 in.) of No. 78 stone, which overlaid 20 cm (8 in.) of washed No. 57 stone (ASTM D884). An 8 cm (3 in.) drain pipe was installed during construction to collect exfiltrate for water quality analysis. The site

Figures 2a, 2b & 2c. Photographs of Cary, Goldsboro, and Swansboro PICP sites.

was slightly sloped so that runoff would flow to a concrete swale, which emptied into a weir box to measure runoff rates.

Materials & Methods

Both the Cary and Swansboro sites were equipped with ISCO 6712 automatic samplers for flow monitoring and sample collection. At Cary, the two exfiltrate drainage pipes each flowed into a weir box with a baffle and a 90^o V-notch weir. One box was equipped with a pressure transducer to record the water level every five minutes for flow measurement. The other weir box was equipped with an ISCO 6712 with a 730 Flow Bubbler Module for flow measurement and sample collection. At the Swansboro site, the runoff weir box was also intended to collect samples and monitor flow. However, since no runoff occurred, no runoff samples or measurements were collected or recorded. ISCO Rain gauges were also installed at the Cary and Swansboro sites. By quantifying the volume of water entering the Cary site (rainfall), and measuring exfiltrate rate, the volume of runoff could be determined. In Swansboro, the runoff volume was known, and the exfiltrate volume was calculated. Each rain gauge had the same accuracy of 0.025 mm (0.01 in.) of rainfall per tip.

For water quality evaluation, the Cary and Swansboro ISCO samplers collected 200 ml of exfiltrate or runoff every 5 minutes while the water level was higher than the height of the weir invert. At the Cary site, rainfall was captured using a plastic motor oil catch basin. At the Goldsboro site, runoff was collected where the curb opens into a grassy swale. A Sigma 900™ suctioned 75 ml (0.03 oz.) of runoff every 20 minutes from a metal channel installed between the asphalt and swale. Exfiltrate for both sites was collected by opening a hand valve at the end of a drain pipe running under a the PICP cell. For sampling, the hand valve would initially be opened to flush any residual exfiltrate from the previous storm event. After the initial flush, the valve was closed and then reopened to collect a sample into either a 250 or 500 ml (8.5 or 17 oz.) bottle. After the sample was collected the valve remained open to allow additional exfiltrate to drain out. Once the pipe was empty the valve was closed again for the next storm.

All samples were either frozen or acidified with H_2SO_4 within 24 hrs. One drop of sulfuric acid was added for every 50 ml (1.7 oz.) of sample. All samples from the three monitoring sites were analyzed for concentrations of: Total Kjeldahl Nitrogen in Water (TKN) [EPA 351.2], Nitrate-Nitrite in Water (NO_{3+2}-N) [EPA 353.2], Total Nitrogen (TN), and Total Phosphorus (TP) [EPA 365.4]. The initial eight sets of samples from Goldsboro were also analyzed for Copper (Cu) [EPA 200.8] and Zinc (Zn) [EPA 200.8] concentrations, while the final six storms were analyzed for Ammonia in Water (NH_4-N) [EPA 350.1] and Phosphate (PO_4) [EPA 365.1]. Either the Soil Science Analytical Lab at North Carolina State University or Tritest of Raleigh performed analysis. All runoff and exfiltrate from Goldsboro and exfiltrate from Cary were also analyzed for total suspended solids (TSS) except for storm 13 and storm 15 for Goldsboro and Cary, respectively. TSS samples were analyzed at the NCSU Water Quality Group lab [EPA 160.2]. For statistical analysis, pollutant concentrations found less than the minimum detectable level, were set to be half of the minimum detectable level.

Results: Hydrologic Performance

Runoff and rainfall data from the Swansboro site were collected for ten consecutive months, from March until October of 2004. Exfiltrate and rainfall data were analyzed at the Cary site for only two months, July and August of 2004, due to many technical issues.

During the entire monitoring period at the Swansboro site, from March 1 until December 31, 107 cm (42 in.) of rainfall fell and no runoff occurred. The largest storm recorded was 8.8 cm (3.5 in.). Four storms occurred with over 5 cm (2 in.) rainfall totals. An SCS curve number of 35 (the minimum) was determined by back calculating through the SCS runoff curve number method (NRCS, 1986) using rainfall depth totals ranging from 4.3 cm – 7.7 cm (1.7- 3 in.). A minimum rational coefficient of 0 was determined by back calculating the Rational Method (APWA, 1981). During the summer of 2004, a single ring infiltration test was conducted for a study by the authors and found extremely high surface infiltration rates, 2000 cm/h (800 in./h) mean surface infiltration rate (Bean et. al., 2004). The combination of being located on very permeable soil, having a large storage volume and having a surface free of fines was the explanation for no runoff from the site.

Table 1 shows results from three storms that occurred during July and August at the Cary site. In 2003, the site had a surface infiltration rate of 230 cm/h (90 in./h) (Bean et al., 2004). The Cary PICP attenuated the runoff in three ways (1) Runoff Volume (66% of water entering the site left through exfiltration, leaving 34% to runoff), (2) Peak Runoff Rate (reduced by 67%) and, (3) Peak Outflow Delay (78 minutes). It should be noted that only three storms had sufficient data to be fully analyzed. However, the data is fairly consistent for three storms, each separated by approximately seven days each. More data needs to be collected from this site.

Date	Rainfall Totals (cm)	Volume Attenuation %	Peak Attenuation %	Delay to Peak (hrs)
7/22/2004	1.5	88	81	1.3
7/29/2004	1.6	53	44	1.5
8/5/2004	1.7	57	75	1.1
Mean	**1.6**	**66**	**67**	**1.3**

Table 1. Hydrologic summary of results from Cary PICP site.

Results: Water Quality

Water quality data was collected for 14 storms from the Goldsboro site from June, 2003, until December, 2004. Table 2 summarizes the mean pollutant concentrations and factors of significance. Data was analyzed using paired t-tests to determine p-values (SAS, 2003). It was hypothesized that concentrations of these pollutants from exfiltrate samples would be significantly (p-value $\leq$ 0.05) lower than asphalt runoff concentrations. Table 2 shows that exfiltrate concentrations of Zn, NH_4-N, TP, and TKN were significantly lower than concentrations of the same pollutants in the runoff. Cu had substantially lower exfiltrate concentrations than runoff concentrations, but not significantly. TN, TSS and

Pollutant Analysis	Mean Runoff	Mean Exfiltrate	p-value	Storms
Zn by ICP/MS-Water mg Zn/l	*0.067*	0.008	**0.0001**	1-8
NH_4-N/Water mg N/l	*0.35*	0.05	**0.0194**	9-14
TP/Waters mg P/l	*0.20*	0.07	**0.0240**	1-14
TKN/Water mg N/l	*1.22*	0.55	**0.0426**	1-14
Cu/MS-Water mg Cu/l	*0.016*	0.006	*0.0845*	1-8
TN Calculation mg N/l	*1.52*	0.98	0.1106	1-14
TSS mg/l	*43.8*	12.4	0.1371	1-12,14
PO_4 mg P/l	*0.06*	0.03	0.2031	9-14
NO_{3+2}-N/Water mg N/l	0.30	*0.44*	0.2255	1-14

Table 2. Pollutant summary for Goldsboro site.

PO_4 were lower in concentration in the exfiltrate, but not significantly. However, TN (Fig. 3) shows a possible removal trend that, with more sampling, could become significant. NO_{3+2}-N was the only pollutant to have higher concentrations in the exfiltrate than the runoff.

For each of the six exfiltrate samples (9-14) analyzed for NH4-N, concentrations were less than the minimum detectable level. One explanation for NH_4-N removal and the increase in NO_{3+2}-N could be that NH_4-N was converted into NO_3-N through bacterial nitrification. However, it is unknown whether NH_4-N was converted or filtered.

Figure 3 shows concentrations of TN for each storm. Initially, for storms 1-6, there seems to be no trend developing due to variable concentrations. However for storms 7-14, except 9, exfiltrate concentrations were less than runoff concentrations. This seems to

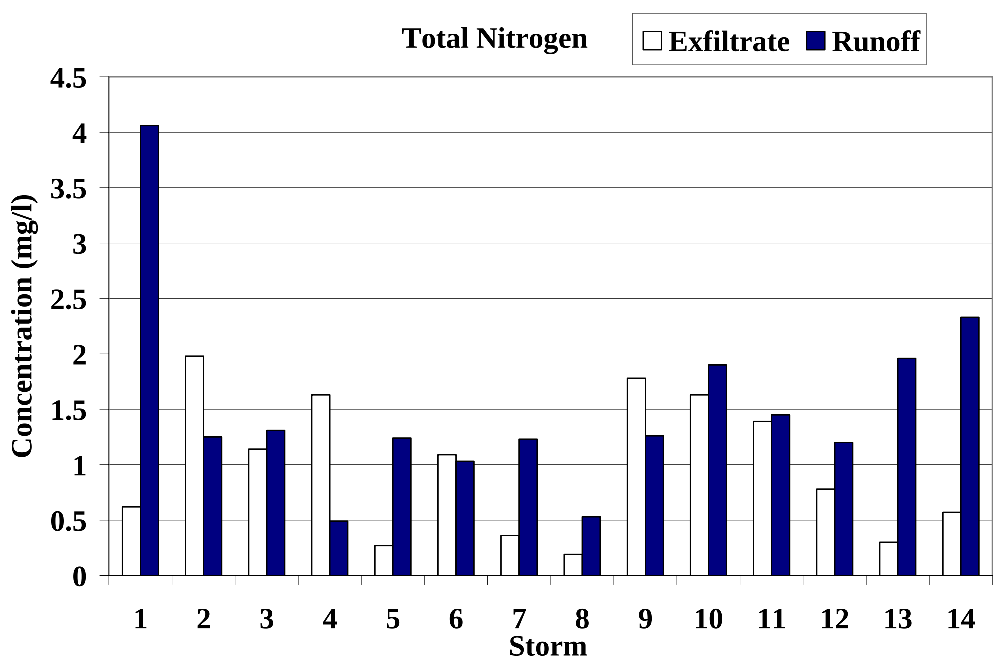

Figure 3. Total Nitrogen Concentrations for Goldsboro site.

indicate a possible developing trend. With a p-value of 0.06, significance may be shown with more samples. Since exfiltrate TN levels were substantially lower than runoff TN levels, TN either stayed in the subbase or was converted and escaped as N_2 gas. It is possible that denitrification of NO_3-N could be occurring at higher rates than nitrification of TKN and NH_4-N. This would result in more nitrogen leaving as N_2 gas, and thus reducing the amount of TN leaving the system in the exfiltrate.

Figure 4, shows TP concentrations in runoff and exfiltrate. For all but two storms (3 and 10), runoff concentrations were greater than exfiltrate concentrations. Exfiltrate concentrations were greater than 0.1 mg/l only twice. Total phosphorus concentrations were significantly lower in the PICP exfiltrate than the asphalt runoff. This suggests that the PICP system significantly ($p \leq 0.05$) lowered the concentration of TP. This could be a result of phosphorus becoming bound to the storage basin material. Another possible scenario is that phosphorus is infiltrating while bound to sediments, and even though sediment is not significantly reduced, exfiltrate concentrations of TSS are substantially less than runoff. Therefore, the phosphorus could have been removed through sediment filtration, along with possible binding.

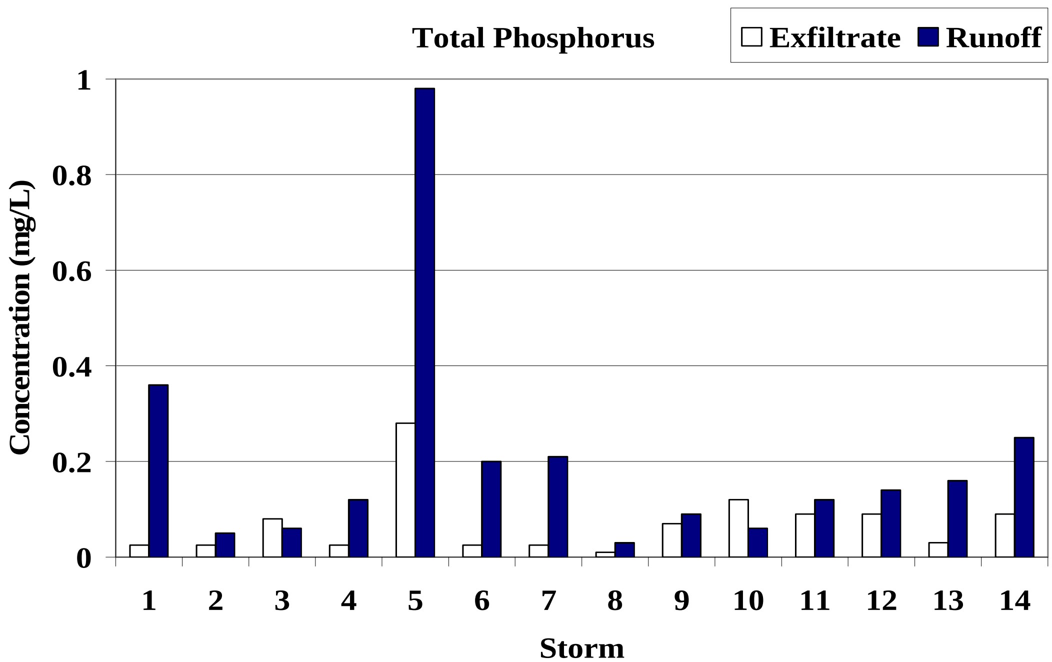

Figure 4. TP concentrations for asphalt runoff and PICP exfiltrate from Goldsboro.

The Cary site was constructed so that inflows would be entirely composed of rainfall and dry deposition; no contributing runoff would enter into the site. Per studies by Wu et al. (1998), this is a reasonable, slightly conservative assumption for TN. However, for TP this assumption is extremely conservative and thus could under predict TP removal rates.

Water quality data from Cary for 15 storms is listed in Table 3. Mean inflow and outflow concentrations are listed along with p-values (paired t-test, (SAS, 2003)) to determine significance. Ammonia was the only pollutant significantly ($p \leq 0.05$) lower in exfiltrate concentration than rainfall concentration. However, NO_3-N is significantly higher in

Pollutant	Rainfall (Inflow)	Exfiltrate (Outflow)	p-value
NO3-N (avg. mg N/l)	0.39	*1.66*	**0.043**
NH4-N (avg. mg N/l)	*0.64*	0.06	**0.034**
TKN (avg. mg N/l)	*2.33*	1.11	0.143
TN (avg. mg N/l)	2.71	*2.77*	0.964
PO4 (avg. mg P/l)	0.08	*0.34*	0.133
TP (avg. mg P/l)	0.26	*0.40*	0.424
TSS (avg. mg/l)	N/A	*12.3*	N/A

Table 3. Mean pollutant concentrations and factors of significance for Cary site.

exfiltrate concentration than in rainfall concentration. Since TN was not significantly removed, this suggests that inflowing NH_4-N and TKN were converted, by ammoniafication and subsequent nitrification, contributing more nitrate to the exfiltrate.

Unlike the Goldsboro site, TP exfiltrate concentrations were, based on means, substantially higher than rainfall concentrations. Wu et al. (1996) showed that 10 – 20% of TP in runoff could be attributed to dry deposition. Since this site also had a lower surface infiltration rate than the Goldsboro site (4000 cm/h) (Bean et al., 2004), due to the presence of fines, increased loadings are most likely due to sediment deposition of clay particles by vehicular traffic. Exfiltrate TSS concentrations for Goldsboro and Cary were essentially equal. This could possibly give a predictable exfiltrate TSS concentration. TN, for the Cary site, was not significantly removed and both rainfall and exfiltrate were higher, based on means, than the Goldsboro site concentrations. This could be attributed to either the Cary site being lined or it being adjacent to a fertilized lawn with.

Since no runoff occurred at the Swansboro site, water quality was not compared between runoff and exfiltrate. However, Table 4 summarizes exfiltrate concentrations. NH_4-N concentrations for each storm were less than the minimum detectable level. The mean TP concentration for Swansboro was comparable to the mean for Goldsboro exfiltrate as well as the range (0.025 – 0.28 mg/l). These two sites were relatively free of fines (Bean et al., 2004), and concentrations of TP in exfiltrate around these concentrations (0.005 – 0.28 mg/l) could be expected for PICP sites free of fines in sandy soil regions.

	NO_3-N mg N/l	NH_4-N mg N/l	TKN mg N/l	TN mg N/l	PO_4 mg P/l	TP mg P/l
Maximum	0.36	0.05	0.65	0.93	0.08	0.14
Mean	**0.17**	**0.05**	**0.18**	**0.36**	**0.03**	**0.06**
Minimum	0.05	0.05	0.05	0.10	0.005	0.005

Table 4. Max., mean and min. pollutant concentrations for Swansboro exfiltrate.

Table 5 presents pollutant loads passing through the Swansboro PICP site. A weighted average of each pollutant was determined by rainfall totals for analyzed storms. The weighted average concentrations were then converted to mass loads. Mass loads were then scaled up from the analyzed storm depths to the total rainfall for the entire monitoring period. TN reduction was seven times higher than TP reduction. Over 10

Pollutant	kg	kg/ha	lbs	lbs/ac
TN	0.40	4.08	0.88	3.64
TP	0.06	0.58	0.12	0.51

Table 5. Total pollutant mass having passed through Swansboro PICP site.

months, for a 0.01 ha (0.24 ac) area, 0.4 kg (0.9 lb) of TN and 0.06 kg (0.12 lb) of TP entered the site. For one complete year, TN could be expected eliminate from runoff approximately 0.5 kg (1.1 lb) or 5 kg/ha/yr of TN and 0.07 kg or 0.7 kg/ha/yr of TP.

Conclusions

Both flow monitoring sites, Cary and Swansboro, had partial and total infiltration, respectively. No runoff occurred at the Swansboro site from March 1st until December 31st. The Cary site shows the potential for being a well performing site, infiltrating 66% of inflow and attenuating peak inflows by 67%. However, more storm data sets need to be collected before general conclusions can be made about the effectiveness of the site.

At the Goldsboro site TP, TKN, NH_4-N and Zn were all present in significantly lower concentrations in exfiltrate samples compared to runoff. At the Cary site, most NH_4-N and some TKN were converted to NO_3-N, but TN concentrations were essentially equal for rainfall and exfiltrate. Sedimentation of clay fines likely contributed to higher TP concentrations in exfiltrate.

As a result of this study, siting guidelines and assessments are listed as follows: (1) sites should be kept clear of fine sediment accumulation to limit TP exfiltrate concentrations; (2) Exfiltrate TSS concentrations could be around 12 mg/l. 3) PICP sites located in sandy soils should perform extremely well as long as a) they are kept free of sediment accumulation, b) they have a several centimeter thick washed No. 57 stone subbase and c) they are unlined over a highly pervious base soil. 4) Low traffic, high infiltrating coastal PICP sites could expect to eliminate 5 kg/ha/yr and 0.7 kg/ha/yr of TP and TN, respectively, from runoff. 5) Permeable pavements in clay have the potential for substantial attenuation of runoff, dependent on maintenance and minimization of fine sediment accumulation. 6) Lined PICP sites in clay soils may have no benefit for Total Nitrogen reduction. 7) PICP significantly removes Zn and substantially removes Cu.

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