Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts

Eban Zachary Bean[1]; William Frederick Hunt, Ph.D., P.E.[2]; and David Alan Bidelspach, P.E.[3]

Abstract: Four permeable pavement applications in North Carolina's Coastal Plain were constructed and monitored to determine their effectiveness of reducing runoff quantity and improving water quality. Sites were either constructed of permeable interlocking concrete pavers (2), porous concrete (1), or concrete grid pavers (1). One site of each pavement type was monitored for runoff reduction for periods ranging from 10 to 26 months. Measured runoff depths from rainfall events over 50 mm were used to determine permeable pavement equivalent curve numbers for the sites, which ranged from 45 to 85. Only the two permeable interlocking concrete pavement (PICP) sites were monitored for water quality. Runoff and exfiltrate samples were intended to be collected, in addition to runoff monitoring, from the Swansboro PICP site. However, no runoff was produced during this study from the Swansboro PICP site for rainfall events up to 88 mm. From exfiltrate concentrations, nutrient retention was estimated to be 3.4 and 0.4 kg/ha/year for total nitrogen and total phosphorus, respectively. For the Goldsboro PICP site, water quality of asphalt runoff and PICP exfiltrate were compared. Analysis of water quality samples from the second site determined that concentrations of total Kjeldahl nitrogen, ammonia, total phosphorus, and zinc were significantly ($p \leq 0.05$) lower in permeable pavement exfiltrate than asphalt runoff.

DOI: 10.1061/(ASCE)0733-9437(2007)133:6(583)

CE Database subject headings: Porous materials; Flexible pavements; Concrete pavements; Stormwater management; Water pollution; Best Management Practice.

Introduction

Urbanization leads to increased runoff volumes, peak flow, and pollutant loadings as well as reduced time to peak and groundwater recharge (USDA NRCS 1986). Additionally, urban runoff carries sediment, nutrients, and heavy metals into surface waters (He et al. 2001; Davis et al. 2001; Lee and Bang 2000; Barrett et al. 1998). These factors result in surface water degradation by way of erosion, sedimentation, flooding, and even fish kills. In the United States, 46% of identified estuarine water quality impairment cases were attributable to stormwater runoff (USEPA 1996). In 2000, stormwater runoff was among the top three sources of pollution in lakes, ponds, reservoirs, and estuaries (USEPA 2000).

The Clean Water Act (CWA), passed by Congress in 1972, initially focused on point source pollution, such as industrial wastewater and municipal sewage discharges (USEPA 1972). In the mid-1970s, the National Pollutant Discharge Elimination System (NPDES) program was implemented to create standards for point source (NPS) pollution (USEPA 2001). In 1987, Congress amended the CWA by establishing Phase I and Phase II of the NPDES Permitting Program to address point-source pollution, including those which resulted from stormwater runoff (USEPA 1999).

As a result of NPDES rules, the state of North Carolina implemented a stormwater credit system for best management practices (BMPs) (NCDENR 1995). Regulated pollutants in North Carolina included nitrogen, phosphorus, pathogenic bacteria, and total suspended solids. BMPs were given credit based on their ability to reduce these pollutants in addition to mitigating peak flow (NCDENR 1995). Additional rules developed for the Neuse and Tar-Pamlico River Basins use impervious area to design and size BMPs (NCDENR 2001, 1998).

Accredited BMPs include wet detention ponds, stormwater wetlands, sand filters, bioretention areas, grassed swales, extended dry detention basins, filter strips, and infiltration devices (NCDENR 1999). Permeable pavement, which is defined as any paved surface designed to reduce runoff by allowing infiltration, is typically used in parking lots, fire lanes, walkways, and driveways. Due to concerns of poor siting, construction, and maintenance, which can lead to clogging, permeable pavement was no longer a state-accepted BMP. However, several studies have shown that maintenance can potentially restore permeable pavement infiltration capability after clogging has occurred (Gerritts and James 2002; Hunt et al. 2001; Bean et al. 2007). Pratt et al. (1995) showed that permeable noninterlocking concrete pavements infiltrated between 34 and 47% of rainfall.

[1]Graduate Research Assistant, Agricultural and Biological Engineering, Univ. of Florida, P.O. Box 110570, Gainesville, FL 32611-0570. E-mail: ezbean@ufl.edu

[2]Assistant Professor and Extension Specialist, Biological and Agricultural Engineering Dept., North Carolina State Univ., Box 7625, Raleigh, NC 27695-7625. E-mail: bill_hunt@ncsu.edu

[3]Extension Associate, Biological and Agricultural Engineering Dept., North Carolina State Univ., Box 7625, Raleigh, NC 27695-7625. E-mail: dabidels@ncsu.edu

Note. Discussion open until May 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on March 28, 2006; approved on April 9, 2007. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 133, No. 6, December 1, 2007. ©ASCE, ISSN 0733-9437/2007/6-583–592/$25.00.

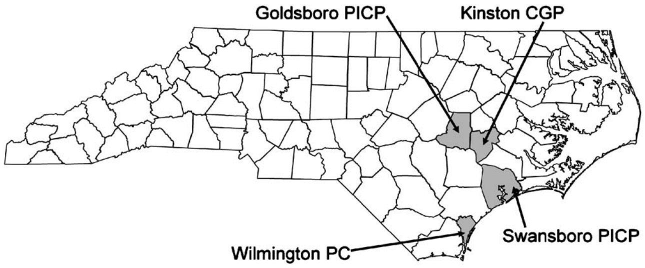

Fig. 1. Monitoring site locations across North Carolina

Permeable pavements, when designed, sited, and maintained properly, can greatly reduce runoff. Brattebo and Booth (2003) compared four types of permeable pavements to asphalt: Permeable interlocking concrete pavements (PICP), concrete grid pavers (CGP), and plastic reinforcing grid pavers (PRGP) with gravel, and PRGP with grass. The pavements received 570 mm of rainfall during the study; the largest event was 120 mm, and the highest recorded intensity was 7.8 mm/h. For 15 rainfall events, runoff was produced by PRGP with grass five times and PRGP with gravel once. No runoff was reported from PICP and CGP (Brattebo and Booth 2003).

Studies have also found that permeable pavement can reduce pollutant loadings. Brattebo and Booth (2003) and Rushton (2001) reported that permeable pavement exfiltrate contained lower Zinc (Zn) and copper (Cu) concentrations than asphalt runoff. In France, a bridge paved with impervious asphalt was monitored for runoff pollutants and then repaved with porous asphalt and monitored again. Loadings of total suspended solids (TSS), total Kjeldahl nitrogen (TKN), nitrite and nitrate (NO_{2+3}-N), ammonium (NH_4-N), Cu, and Zn from porous asphalt were lower than impervious asphalt loadings; significantly lower for TSS, Cu, and Zn. Pagotto et al. (2000) reported that these pollutants were removed by filtering.

This study sought to determine whether water quality and quantity benefits of permeable pavement sites in the Southeast United States were similar to previous research findings. Four permeable pavement lots [two PICP, one CGP, and one porous concrete (PC)], located in the Coastal Plain of North Carolina (Fig. 1), were monitored for runoff reduction, water quality impacts, or both. Sites are identified by the surrounding municipalities and pavement types: Kinston (CGP), Wilmington (PC), Swansboro (PICP), and Goldsboro (PICP) (Fig. 2).

Fig. 2. Photographs of monitoring sites: (A) Kinston CGP site; (B) Wilmington PC site; (C) Swansboro PICP site; and (D) Goldsboro PICP site

J. Irrig. Drain Eng., 2007, 133(6): 583-592

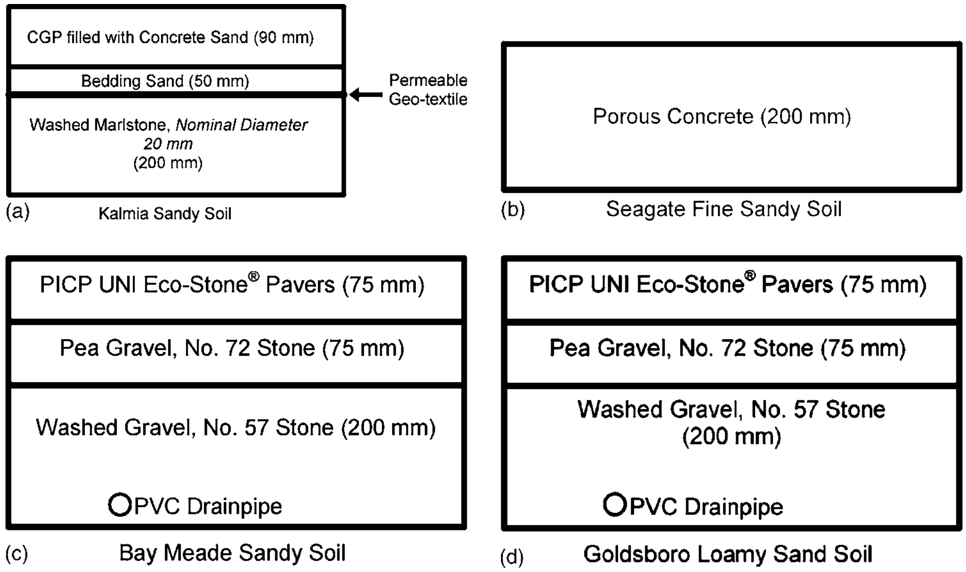

Fig. 3. Diagram of permeable pavement cross sections: (a) Kinston CGP site; (b) Wilmington PC site; (c) Swansboro PICP site; and (d) Goldsboro PICP site

Methods

Monitoring Site Background

Each permeable pavement cell was unlined to allow for groundwater recharge. The Kinston CGP site was constructed in 1999 to provide overflow parking for a City of Kinston municipal building. The 630 m^2 site had an approximate slope of 0.5% on a Kalmia sandy soil (saturated hydraulic conductivity, K_{sat}, of approximately 200 mm/h) (USDA, NRCS 2005). The 90 mm thick CGP was filled with coarse grade sand, which has a K_{sat} of >250 mm/h. Under the CGP, 50 mm of bedding sand was laid onto a permeable geotextile that separates the bedding sand from 200 mm of washed marlstone (nominal diameter: 70 mm) [Fig. 3(a)]. The washed marlstone layer, having a porosity of 35%, provided nearly 70 mm of water storage depth. The surface infiltration rate at this site was 580 mm/h (Bean et al. 2007).

The Wilmington PC site was constructed on Seagate fine graded sand (K_{sat} of approximately 300 mm/h) (USDA, NRCS 2005) in August, 2001. The site was a parking lot for an environmental education park in the City of Wilmington. The lot was slightly graded (0.33%) and runoff was measured from April 2002 to August 2003. The 370 m^2 lot consisted of a 200 mm thick porous concrete layer poured directly on the native soil; no gravel storage layer or geotextile separated the porous concrete from the sub grade [Fig. 3(b)]. The porous concrete had a porosity of approximately 20%, resulting in a storage depth of about 40 mm. The surface infiltration rate of the site was determined to be approximately 230 mm/h (Bean et al. 2007), which should not have substantially limited total infiltration.

The Swansboro PICP site was constructed in the fall of 2003 on Bay Meade sandy soil (K_{sat} of approximately 300 mm/h) (USDA, NRCS 2005) for runoff and water quality monitoring. The 740 m^2 site served as an overflow parking lot for various businesses. The surface had a slight slope (0.4%) and the system was unlined to allow for groundwater recharge. UNI Eco-Stone, 76 mm thick, was placed on top of 75 mm of No. 72 stone, pea gravel, which overlaid 200 mm of No. 57 washed gravel (ASTM 2003) [Fig. 3(c)]. The washed No. 57 stone layer acted as a storage layer for stormwater. A surface infiltration rate of 20×10^3 mm/h was recorded at the Swansboro PICP site (Bean et al. 2007).

The Goldsboro PICP site was constructed in the summer of 2001 as parking for a retail store. The 120 m^2 lot was located on Goldsboro loamy sand soil (K_{sat} of approximately 150 mm/h) (USDA, NRCS 2005) and was constructed to facilitate water quality monitoring. The 76 mm UNI Eco-Stone overlaid 75 mm of No. 72 stone pea gravel, which in turn overlaid 200 mm of washed No. 57 gravel (ASTM 2003) [Fig. 3(d)]. The surface infiltration rate for the Goldsboro PICP site was recorded 40×10^3 mm/h (Bean et al. 2007).

Runoff Monitoring

The Kinston CGP site was continuously monitored for 26 months between June 1999 and July 2001. Runoff was directed into a drop box (0.7 m $\times$ 1.2 m) equipped with a 90° V-notch weir. Behind the weir, a flume stick level recorder (Global Water model WLU) measured the water level every 2 min during each event. A 100 mm pipe drained the drop box and discharged the runoff 20 m away. Rainfall data were collected with a tipping bucket rain gauge (Global Water Model RG200) 30 m from the lot and recorded by a Global Water data logger at 15 min intervals. Runoff rates were determined using water level measurements in the weir box, which were correlated to flow rates using weir flow equations. Infiltration was calculated as the volumetric difference between rainfall and runoff.

The Wilmington PC site was monitored for 17 months between April 2002 and August 2003. Runoff was collected into a drop box (0.5 m $\times$ 1 m) where flow was quantified using a pressure transducer and a 90° V-notch weir. Rainfall was collected using a tipping bucket rain gauge with a Global Water data logger at 5 min intervals. Runoff rates and infiltration were determined using the same methods used at the Kinston PICP site.

The Swansboro PICP site was monitored for 10 months from March to December 2004. The pavement surface slope directed runoff to a 90° V-notch weir structure. An ISCO 6712 automatic

J. Irrig. Drain Eng., 2007, 133(6): 583-592

sampler and ISCO 730 bubbler module were programmed to record the water level behind the weir every 5 min to calculate runoff rates. Runoff flow rates were calculated using water level data and calibrated weir flow equations. Rainfall was measured at 5 min intervals by an ISCO 674 tipping bucket rain gauge and recorded by the ISCO 6712 automatic sampler. Like the first two sites, infiltrate volumes were calculated by way of a water balance, by subtracting runoff volume from rainfall volume for each event.

Individual events were separated by a 6 h lapse in rainfall. Events from each site that produced more than 50 mm of rainfall were analyzed to determine equivalent Soil Conservation Service (SCS) Curve Numbers (CNs). During the 26 months of monitoring the Kinston CGP site, six events met this criterion (Table 1) including Hurricanes Dennis (123 mm, Sept. 5, 1999), Floyd (369 mm, Sept. 16, 1999), and Irene (110 mm, Oct. 17, 1999). For comparison, the 1 year, 24 h event for Kinston is 76 mm (NOAA 2004). During Hurricane Floyd, runoff submerged the outlet pipe, introducing error into runoff rate calculations.

During the 17 month monitoring period at the Wilmington PC site, 21 events were recorded with rainfall totals ranging from 2.5 to 97 mm (Table 2); two of which were greater than 50 mm. The largest event was slightly greater than the 1 year, 24 h event depth of 94 mm (NOAA 2004). Rainfall data not collected on site (August through October 2002) were obtained from the Wilmington International Airport, approximately 3 km from the site.

During 10 months of monitoring, no runoff was measured from the Swansboro PICP site. A total of 1,070 mm of rainfall occurred on site, including five events that were greater than 50 mm. The largest event, 88 mm, was approximately equal to the 1 year, 24 h event depth for Swansboro (NOAA 2004).

Two methods using the SCS Curve Number method were used to analyze rainfall and runoff data (USDA, NRCS 1986). In the first method, runoff depths were plotted against corresponding rainfall depths. A linear regression was then performed on data points with at least 2 mm of rainfall. The x intercept for the linear regression was then calculated and assumed to be an adequate approximation of the storage depth. The storage depth was then used to calculate a CN for the data. The predicted rainfall-runoff relationship for the calculated CN was also plotted for comparison.

In the second method, Eq. (1) (Ponce and Hawkins 1996) was used to calculate storage depths (S) for events with rainfall depths of at least 50 mm. The curve number (CN) was then calculated from Eq. (2) (USDA, NRCS 1986) [Eqs. (2) and (3)]. The mean, median, and standard deviation were then calculated for the storage depth and CN. In addition, CNs were calculated for the mean and median storage depths. Due to Eq. (2) being nonlinear, the mean and median CNs may not be equal to the CNs calculated from the mean and median storage depths

$$S = 5[P + 2Q - \sqrt{4Q^2 + 5PQ}] \tag{1}$$

$$\mathrm{CN} = 25400/(S + 254) \tag{2}$$

$$Q = (P - 0.2S)^2/(P + 0.8S) \tag{3}$$

Table 1. Rainfall and Runoff Depths at the Kinston CGP Site

Date	Rainfall (mm)	Runoff (mm)
July 8, 1999	15	0
July 15, 1999	68	13
July 24, 1999	31	0
August 14, 1999	21	0
August 27, 1999	19	0
August 30, 1999	23	0
September 5, 1999	123	39
September 16, 1999	369	361
September 21, 1999	21	0
September 28, 1999	65	40
October 17, 1999	110	104
November 26, 1999	13	0
January 10, 2000	16	0
January 24, 2000	36	0
January 30, 2000	19	0
February 12, 2000	29	0
February 14, 2000	13	0
March 3, 2000	72	0
March 21, 2000	15	0
April 18, 2000	14	0
April 28, 2000	18	0
May 23, 2000	46	10
May 28, 2000	25	8
June 4, 2000	13	0
June 19, 2000	21	0
June 22, 2000	17	0
July 12, 2000	21	0
July 15, 2000	42	13
July 21, 2000	16	0
July 25, 2000	46	23
July 31, 2000	15	0
August 16, 2000	37	9
August 27, 2000	15	2
August 28, 2000	16	0
August 30, 2000	30	0
August 31, 2000	28	0
September 3, 2000	13	0
September 5, 2000	35	0
September 18, 2000	32	0
September 23, 2000	38	0
November 19, 2000	21	0
November 25, 2000	18	0
February 4, 2001	14	0
February 17, 2001	15	0
February 22, 2001	15	0
March 4, 2001	21	0
March 22, 2001	32	0
March 29, 2001	17	0

Water Quality

All water quality samples were collected and acidified with sulfuric acid (H_2SO_4) to a pH of 2 within 24 h of each event's cessation. Samples were then refrigerated until pollutant analysis was conducted. One 76 mm PVC drainpipe, capped with a hand valve, was installed at the bottom of the gravel storage layer during the construction of both the Swansboro and Goldsboro PICP lots. To isolate individual events for sampling, the drainpipes were opened to drain any residual exfiltrate within the storage basins and drainpipes.

Runoff from asphalt and PICP exfiltrate were collected at the Goldsboro PICP site. Water quality samples were collected from

J. Irrig. Drain Eng., 2007, 133(6): 583-592

Table 2. Rainfall and Runoff Depths, Maximum 15 min Intensities and Duration, for Events at the Wilmington PC Site

Date	Rainfall (mm)	Max. intensity (mm/h)	Duration (h)	Runoff (mm)
May 3, 2002	2.5	2.5	10	0
May 4, 2002	5.1	10	3	0
May 4, 2002	2.5	2.5	4	0
May 29, 2002	10	20	9	0.23
June 15, 2002	15	25	6	0.3
June 18, 2002	20	25	6	0.91
June 18, 2002	5.1	20	2	0.15
August 28, 2002	97[a]	20[a]	10	72
October 13, 2002	5.1[a]	2.5[a]	3	0
October 15, 2002	13[a]	2.5[a]	15	0.15
March 30, 2003	7.6	7.6	4	0.15
April 8, 2003	38	25	10	12
April 10, 2003	28	53	8	3.5
April 11, 2003	7.6	15	4	0.076
May 8, 2003	18	30	4	1.1
June 7, 2003	10	15	3	0.15
June 18, 2003	53	28	19	2.1
June 20, 2003	43	89	1	15
July 29, 2003	58	74	8	32

[a]Data from Wilmington International Airport (NOAA, NCDC 2005).

the Goldsboro PICP site from June 2003 to December 2004. The asphalt drive path at the Goldsboro PICP site was sloped to direct runoff toward a curb cut with a down slope collector channel. A Sigma 900 Max automatic sampler was programmed to collect a 75 mL sample from the collector channel every 20 min, regardless of whether runoff was occurring. The Swansboro PICP site was constructed to collect PICP runoff and exfiltrate. At the Swansboro PICP site, an ISCO 6712 automatic sampler was programmed to take a 100 mL sample of runoff every 5 min during runoff events.

Table 3 lists pollutant analysis methods and minimum detectable levels. All samples from both sites were analyzed for NO_{2+3}-N, TKN, NH_4-N, total phosphorus (TP), and orthophosphate (PO_4). In addition, samples from the Goldsboro PICP site were analyzed for TSS, zinc (Zn), and copper (Cu). Organic nitrogen (ON) concentrations were calculated as the difference in concentrations of TKN and NH_4-N; particle bound phosphorus (PBP) concentrations were calculated as the difference in concentrations of TP and PO_4. Total nitrogen (TN) concentrations were calculated as the sum of TKN and NO_{2+3}-N. For analysis purposes, concentrations less than the minimum detectable level (MDL) were assumed to be half of the MDL.

Three different laboratories were used for nutrient and pollutant analyses. Tritest Laboratories of Raleigh analyzed collected samples for all pollutants from the Goldsboro PICP site between June 11, 2003, and February 12, 2004. The remaining TSS samples were analyzed at the North Carolina State University (NCSU) Water Quality Group Laboratory. The Soil Science Analytical Services Laboratory (ASL) analyzed for all remaining pollutants for the Swansboro PICP samples and the Goldsboro PICP samples collected from August 3 through December 12, 2004.

Asphalt runoff and PICP exfiltrate pollutant concentrations from the Goldsboro PICP site were analyzed to determine whether pollutant populations were statistically different. Skewness was calculated for each population to determine whether a normal or lognormal distribution existed. Depending upon a population's normality, either a Student t-test was performed on nontransformed data, a Student t-test was performed on the log-values of the concentrations, or a Sign test was conducted (SAS 2003).

Results and Discussion

Runoff Depth Analysis

Data from these three sites indicate that permeable pavements may not only reduce runoff, but also eliminate runoff entirely under certain rainfall depths, intensities, maintenance conditions, antecedent conditions, and designs.

Resulting CNs for five events with rainfall depths over 50 mm from the Swansboro PICP site are listed in Table 4. As no runoff was produced from the Swansboro PICP site, the CN calculations were solely limited by rainfall totals, rather than both rainfall and runoff for typical calculations. The minimum CN calculated for any event was 37. This CN was associated with a total rainfall depth of 88 mm, equal to the 1 year, 24 h event (NOAA 2004).

Table 3. Pollutant Analysis, Abbreviation, and Minimum Detectable Level for Two Laboratories, Tritest and ASL

Test performed	Abbreviation	Analysis method (USEPA 1983; 1993)	MDL (mg/L) Tritest	MDL (mg/L) ASL
Total nitrogen calculation	TN	$TN=TKN+NO_{2+3}$-N	N/A[a]	N/A[a]
Nitrate–nitrate	NO_{2+3}-N	EPA 353.2	0.02	0.1
Total Kjeldahl nitrogen	TKN	EPA 351.2	0.25	0.1
Ammonium	NH_4^+-N	EPA 350.1	N/A[a]	0.1
Organic nitrogen calculation	ON	$ON=TKN-NH_4$-N	N/A[a]	N/A[a]
Total phosphorus	TP	EPA 365.4	0.05	0.01
Orthophosphate	PO_4	EPA 365.1	N/A[a]	0.01
Particle bound phosphorus calculation	PBP	$PBP=TP-PO_4$	N/A[a]	N/A[a]
Total suspended solids	TSS	EPA 160.2	1	N/A[a]
Zinc	Zn	EPA 200.8	0.01	N/A[a]
Copper	Cu	EPA 200.8	0.01	N/A[a]

Note: MDL=minimum detectable level.

[a]Analysis was not conducted by laboratory.

J. Irrig. Drain Eng., 2007, 133(6): 583-592

Table 4. Calculated CNs for Events Greater Than 50 mm from the Swansboro PICP Site

	Rainfall, P (mm)	Runoff, Q (mm)	Storage, S (mm)	Curve no., CN
	88	0	440	37
	77	0	385	40
	63	0	315	45
	56	0	280	48
	51	0	255	50
Mean			335	44
Median			315	45
Standard deviation				5.5
Minimum				37
		CN of mean S	43	
		CN of median S	45	

Because no rainfall events produced runoff from the Swansboro PICP site, the calculated storage depths and CNs were based solely on rainfall depths. Because no runoff was produced from the largest event (88 mm), it is possible that the storage depth could be even greater. Additionally, the actual storage depths of the smaller storms could also be much greater than calculated. Thus, the lowest CN may be most characteristic of the site, as smaller events than the event used to calculate the CN should not produce any runoff either. This analysis is similar to the first method, where the characteristic CN is based off the rainfall depth where the linear regression starts. However, for Swansboro PICP, as no runoff was produced, linear regression cannot be performed, and the largest rainfall depth without runoff must be used instead.

The mean, median, and standard deviation of the five calculated CNs were 44, 45, and 5.5, respectively. For comparison, the CNs of the mean and median storage depths were 43 and 45, respectively. Since even during periods of peak rainfall runoff was not produced, the rational runoff coefficient (C) was equal to 0 [Eq. (4)]. These results may be attributed to three main factors: (1) a surface free of fine sediment accumulation; (2) a large storage base (200 mm depth) of washed No. 57 stone; and (3) a very permeable in situ soil

$$Q_T = CIA \tag{4}$$

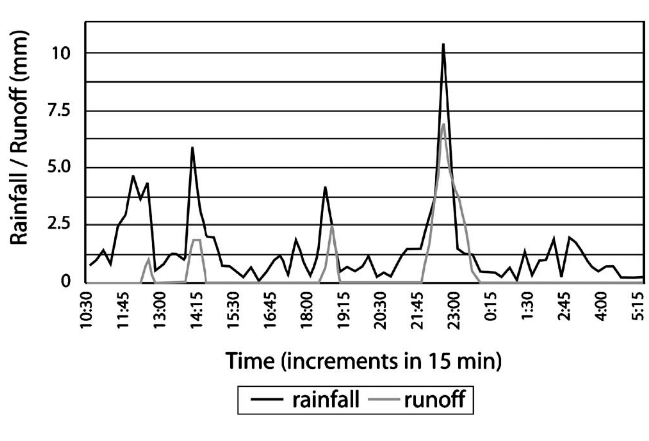

Fig. 4. Rainfall hyetograph and runoff hydrograph from Hurricane Dennis (123 mm, September 5, 1999) at the Kinston PICP site

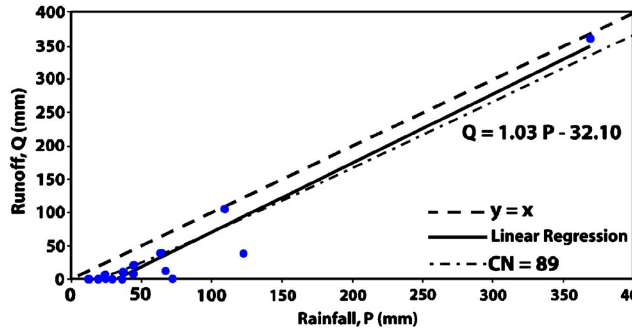

Fig. 5. Rainfall depths versus corresponding runoff depths from the Kinston CGP site

Of the 48 events exceeding 13 mm measured at the Kinston CGP site, runoff was recorded from only 11 events. Fig. 4 shows rainfall and runoff hydrographs from the Kinston CGP site during Hurricane Dennis. As shown by the hydrograph, runoff was produced during intense periods of rainfall lasting less than 15 min.

The Kinston CGP site produced very little runoff (2, 8, and 9 mm for three events) for events up to 38 mm (Table 1). The rainfall-runoff relationship for Kinston CGP is shown as Fig. 5. The estimated storage depth, or x intercept, from linear regression of events producing at least 2 mm of runoff was 31 mm. This was much lower than the designed capacity of 70 mm. However, the largest event to produce no runoff had a rainfall depth of 72 mm. Thus, the storage could be closer to the design capacity, but the surface infiltration rate during the larger storms may have been lower than the rainfall intensity, resulting in runoff production without filling the storage.

In Fig. 6 the same analysis was conducted, except that the Hurricane Floyd event, when monitoring error occurred due to high tailwater, was omitted. The calculated CN was 93, slightly greater than the CN including Hurricane Floyd. However, calculated runoff for a CN of 93 overpredicted actual runoff for all but one rainfall event.

Calculated storage depths and corresponding CNs were determined for the six events greater than 50 mm at the Kinston CGP site. Rainfall and runoff depths for calculated CNs are listed in Table 5. Three events were greater than the 1 year, 24 h event, approximately 76 mm (NOAA 2004). Considering all recorded events over 50 mm, calculated CNs ranged from 42 to 98 with a median of 79 and a mean of 77 (Table 5). The CN of the mean and median storage depth (109 and 72 mm, respectively) was 70 and 78, respectively. By omitting data from Hurricane Floyd, the

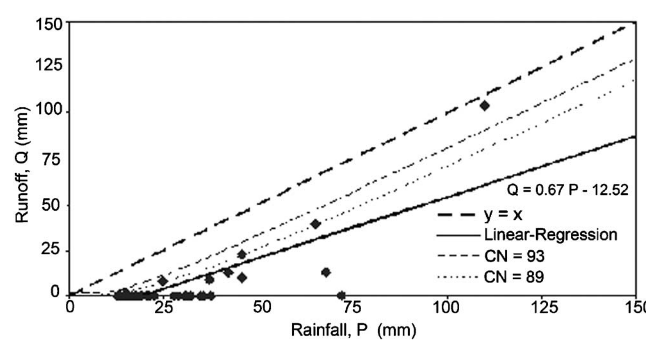

Fig. 6. Rainfall depths versus corresponding runoff depths from the Kinston CGP site without Hurricane Floyd data

J. Irrig. Drain Eng., 2007, 133(6): 583-592

Table 5. Calculated CNs for Events Greater Than 50 mm from the Kinston CGP Site

	Rainfall, P (mm)	Runoff, Q (mm)	Storage, S (mm)	Curve no., CN
(a) Hurricane Floyd data included				
	369	361	7.1	97
	123	39	137	65
	110	104	4.8	98
	72	0	361	41
	68	13	114	69
	65	40	29	90
Mean			109	77
Median			72	79
Standard deviation			135	22
			CN of mean S	70
			CN of median S	78
(b) Hurricane Floyd data omitted				
Mean			129	73
Median			114	69
Standard deviation			141	22
			CN of mean S	66
			CN of median S	69

median and mean CN decreased to 69 and 73, respectively. Additionally, the CN of the mean and median storage depth (129 and 114 mm, respectively) was 66 and 69, respectively.

A vacuum truck swept the lot in mid-August, 2000. Of the 16 events which occurred after maintenance, totaling 345 mm of rainfall, a total of 2 mm of runoff was produced from only one 15 mm event. The largest postmaintenance event was 38 mm. Pre-maintenance events with up to 38 mm depths produced similarly small runoff depths. Most runoff prior to maintenance was produced from events greater than 60 mm. Therefore, while maintenance should have improved the performance of Kinston CGP, without larger events, it is inconclusive whether the hydrologic performance was improved.

The Wilmington PC site produced no substantial runoff (>1 mm) for events up to 30 mm, and only five events produced greater than 2 mm of runoff (Table 2). From linear regression analysis of runoff events greater than 2 mm, the site had an estimated storage depth of 30 mm (Fig. 7), rather than the designed 40 mm, as calculated by the design porosity, thickness, and slope of the PC. If the soil-concrete interface sealed, vertical exfiltration

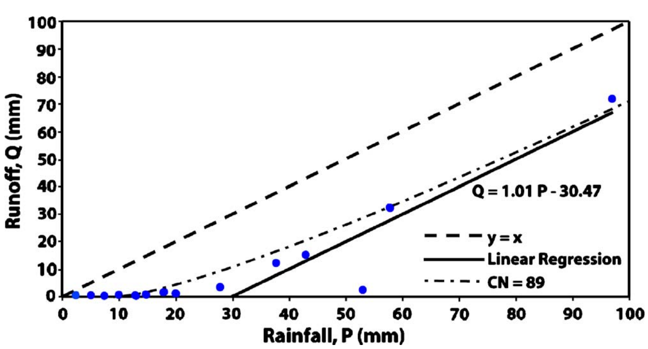

Fig. 7. Rainfall depths versus corresponding runoff depths from the Wilmington PC site

Table 6. Calculated CNs for Events 50 mm or Greater from the Wilmington PC Site

	Rainfall, P (mm)	Runoff, Q (mm)	Storage, S (mm)	Curve no., CN
	97	72	25	91
	58	32	32	89
	53	2.1	166	60
Mean			74	80
Median			32	89
Standard deviation			80	17
			CN of mean S	77
			CN of median S	89

would have been greatly limited. No trend was determined to exist between rainfall intensities and total runoff.

Table 6 lists recorded rainfall and runoff depths along with equivalent CNs for the Wilmington PC site. As rainfall and runoff depths increased, calculated CNs increased. As rainfall depths increased, the storage volume (approximately 30 mm) filled and became a smaller percentage of total runoff. For the three events with rainfall depths over 50 mm, equivalent CNs were 61, 89, and 91.

Modeled runoff values from the calculated CNs for both sites (Figs. 5–7) seem to track closely to the linear regression. However, for a majority of events the CN predicted runoff depths were greater than the observed depths. This was particularly evident when considering more frequent smaller events.

Table 7 summarizes calculated CNs for the sites monitored in this study. Analysis of data from this study suggests that constructing permeable pavement with a storage layer improves runoff reduction potential. Other factors that may increase runoff reduction potential include keeping the surface free of fines, performing regular maintenance, and construction on sandy in situ soils (Bean et al. 2007).

Data reported by Bean et al. (2007) show that surface infiltration rates for PICP were higher than PC, which were higher than CGP. Comparatively, based on calculated CNs, the Swansboro PICP site performed better than the Kinston CGP site, which in turn performed better than the Wilmington PC site. While these sites were located within relatively the same region of North Carolina, there were several differences between the sites, such as average daily traffic, soil types, and sediment deposition loading rates. In addition, only one of each pavement type was monitored. Thus, broad conclusions about runoff reduction performance for PICP, PC, and CGP, should not be made from this study.

Water Quality

The Swansboro PICP site was constructed to compare runoff (inflow) versus exfiltrate (outflow) pollutant concentrations from a PICP cell. In this study, runoff was the control while exfiltrate was the treatment. PICP exfiltrate pollutant concentrations represent the stormwater quality after passing through the permeable pavement system. No runoff water quality samples were taken from the Swansboro PICP site, as all rainfall infiltrated. However, 16 exfiltrate samples were collected and analyzed for nutrient concentrations. The Goldsboro PICP site compared PICP exfiltrate (treatment) and asphalt runoff (control). Fourteen asphalt runoff and PICP exfiltrate paired samples were collected and analyzed from the Goldsboro PICP site. The Goldsboro study site

J. Irrig. Drain Eng., 2007, 133(6): 583-592

Table 7. Summary of Curve Numbers

Site	Range	Linear-Regression	Mean CN	Median CN	CN of mean *S*	CN of median *S*
Swansboro PICP	37–45	37	44	45	43	45
Kinston CGP	70–89	89	77	79	70	78
Omit Hurricane Floyd	66–93	93	73	69	66	69
Wilmington PC	77–89	89	80	89	77	89

was a paired watershed rather a comparison of inflow versus outflow. Pollutant loadings in asphalt runoff could not be assumed equal to loadings of water infiltrating the PICP cell; thus, removal rates were not determined for this site. However, the water quality impact that would result from using PICP instead of standard asphalt pavement was determined.

Table 8 summarizes pollutant concentration statistics from the Goldsboro site. Exfiltrate concentrations of TP, Zn, NH_4-N, and TKN from PICP were significantly ($p \leq 0.05$) less than asphalt runoff concentrations. Concentrations of PBP, PO_4, TN, NO_{2+3}-N, ON, Cu, and TSS were not significantly different between asphalt runoff and PICP exfiltrate. NO_{2+3}-N was the only pollutant, on average, which was higher in PICP exfiltrate than asphalt runoff. All six PICP exfiltrate NH_4-N concentrations were less than the MDL, whereas all asphalt runoff concentrations were above the MDL (0.1 mg/L).

Several studies have found permeable pavements to significantly reduce concentrations and loadings of Cu and Zn (Brattebo and Booth 2003; Rushton 2001; Pagotto et al. 2000). This study indicates that use of PICP at the Goldsboro site yielded significantly ($p < 0.05$) lower concentrations of Zn, but not Cu in exfiltrate than runoff.

Even though Cu concentrations were not significantly ($p > 0.05$) different, exfiltrate concentrations were arithmetically less than runoff concentrations. Additionally, seven of the eight exfiltrate samples had concentrations less than the MDL (0.01 mg/L), whereas five of eight runoff samples were greater than the MDL. Neither population of concentrations was determined to be normally distributed, which is required by a student T-test. However the runoff population was log-normally distributed, whereas the exfiltrate population was not, which resulted from all but one concentration being 0.05 mg/L. Thus, a Sign test analysis of the Cu data was performed which returned a p value of 0.2188. Had a chemical analysis with a lower MDL been performed, analysis of the data may have returned that runoff Cu concentrations were significantly higher than exfiltrate concentrations. Thus, PICP would have been shown to yield significantly lower concentrations of Cu, supporting previous research findings (Pagotto et al. 2000; Pratt et al. 1995; Sansalone and Buchberger 1997).

Sansalone and Buchberger (1997) determined that Zn and Cu in runoff were mostly in a dissolved, rather than particulate, form. Sansalone and Buchberger (1997) also examined the pH of runoff and found that the low pH of rainfall and holding time of infiltrate contributed to metals in solution. The researchers suggested that the use of concrete could effectively increase the pH of runoff, causing precipitation of metals (Sansalone and Buchberger 1997). Pratt et al. (1995) recorded pH values for concrete pavers laid on gravel between 6.9 and 9.3; both Zn and Cu precipitate when pH exceeds 7. Therefore, it is possible that the lower concentrations of Zn were due to infiltrate coming into contact with the concrete pavers, causing the pH to rise and the metals to precipitate. Precipitated metals would have collected on the base soil surface and not entered the drain.

Exfiltrate NO_{2+3}-N concentrations were not significantly greater than runoff concentrations, however, for 10 of 14 events, exfiltrate concentrations were greater than runoff concentrations. All exfiltrate concentrations of NH_4-N were less than the MDL. Exfiltrate concentrations of TKN were significantly ($p \leq 0.05$) lower than runoff concentrations. Aerobic conditions may have facilitated nitrification of NH_4-N to NO_{2+3}-N, which could explain higher NO_{2+3}-N exfiltrate concentrations. The pave-

Table 8. Mean Pollutant Concentrations, Corresponding p values, and Events Analyzed from the Goldsboro PICP Site

	Runoff exfiltrate				
Pollutant analysis	Samples	(mg/L)	(mg/L)	p value	Events
Total nitrogen calculation mg N/l (TN)	14	1.33	0.77	0.0511[a]	1–14
Nitrate–nitrite in water mg N/l (NO_{2+3}-N)	14	0.30	0.44	0.1668	1–14
Total Kjeldahl nitrogen/water mg N/l (TKN)	14	1.03	0.41	**0.0074**[a,b]	1–14
Ammonium-N (NH_4^+-N), mg/L	6	0.31	0.05	**0.0003**[a,b]	9–14
Organic nitrogen mg/L (ON)	6	0.75[c]	0.48[c]	0.6875[d]	9–14
Total phosphorus/water mg P/L (TP)	14	0.134	0.049	**0.0017**[a,b]	1–14
Orthophosphate mg P/L (PO_4)	6	0.038	0.022	0.2730[a]	9–14
Particle bound phosphorus mg P/L (PBP)	6	0.077	0.057	0.2752	9–14
Total suspended solids mg/L (TSS)	13	12[c]	8[c]	0.5811[d]	1–12,14
Copper mg Cu/L (Cu)	8	0.013[c]	0.005[c]	0.2188[d]	1–8
Zinc mg Zn/L (Zn)	8	0.067	0.008	**0.0001**[b]	1–8

[a]Log-transformed data used in Student t-test.

[b]Significant difference ($p \leq 0.05$) between exfiltrate and runoff concentration populations (SAS 2003).

[c]Medians reported when compared populations were neither normal nor lognormal distributions.

[d]Sign test.

J. Irrig. Drain Eng., 2007, 133(6): 583-592

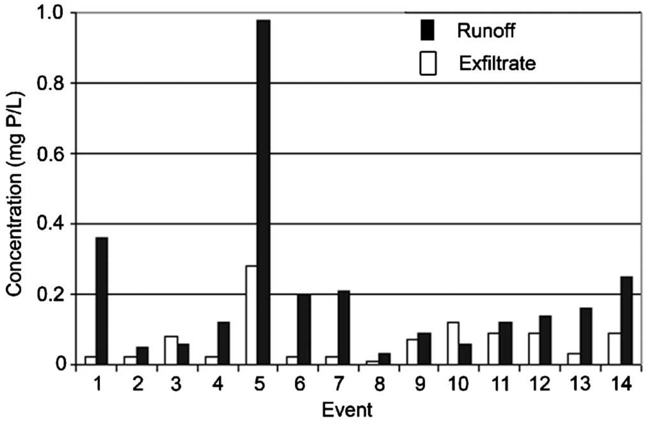

Fig. 8. Total phosphorus concentrations from PICP exfiltrate and asphalt runoff samples collected from the Goldsboro PICP site

ment system was designed to be aerobic. However, as the asphalt runoff could not be assumed to have the same pollutant concentrations as water that infiltrated the PICP cell, it can only be hypothesized that aerobic conditions were present.

Exfiltrate concentrations of TP were significantly ($p \leq 0.05$) lower than runoff concentrations; PICP exfiltrate concentrations ranged from 0.01 to 0.28 mg/L, whereas asphalt runoff concentrations ranged from 0.03 to 0.98 mg/L. However, concentrations of PBP and PO_4 were not significantly different between exfiltrate and runoff. Particle bound phosphorus may have been filtered, whereas PO_4 may have been retained by surface exchange sites within the drainage cell. Runoff concentrations of TP spiked for two events (Fig. 8), which may have resulted from fertilizer contamination from adjoining landscape beds.

Swansboro PICP exfiltrate concentrations are summarized in Table 9. As no runoff was produced from the Swansboro PICP site, no pollutants left the site by runoff. Any pollutant removal would be due to postinfiltration chemical, biological, and any other physical processes. As in Goldsboro, concentrations of NH_4-N for all 16 events were all below the MDL, supposedly resulting from designed aerobic conditions in the gravel storage layer.

Annual loadings of TN and TP were estimated from exfiltrate concentrations and rainfall totals. Loadings were determined for each event from exfiltrate sample concentration and site rainfall volume, assuming complete infiltration of rainfall. Annual loadings were then extrapolated by the ratio of total rainfall for sampled events to total annual rainfall. During monitoring, 0.31 kg of TN infiltrated the Swansboro PICP site. A retention rate of 3.8 kg/ha/year was estimated, which was slightly less than the 5.09 kg/ha/year lost from minimally disturbed watersheds in the United State as determined by Lewis (2002).

Swansboro exfiltrate TP concentrations were slightly higher than those from the Goldsboro PICP site, ranging from 0.14 to 0.57 mg/L. In total 0.04 kg of TP from runoff were retained by the PICP lot during monitoring. Annual retention rates were estimated to be 0.53 kg/ha/year for the PICP monitoring site.

Table 9. Maximum, Mean, Median, and Minimum Exfiltrate Pollutant Concentrations from the Swansboro PICP Site, $n=16$

Pollutant	Maximum (mg/L)	Mean (mg/L)	Median (mg/L)	Minimum (mg/L)
TN	0.93	0.36	0.36	0.1
NO_{2+3}-N	0.36	0.17	0.18	0.05
TKN	0.65	0.13	0.17	0.05
ON	0.6	0.05	0.12	0
NH_4^+-N	0.05	0.05	0.05	0.05
TP	0.14	0.057	0.06	0.005
PO_4	0.08	0.025	0.005	0.005
PBP	0.135	0.011	0.03	0

Conclusions

Previous research has found permeable pavements to be effective at reducing runoff and associated pollutants for other areas around the United States (Brattebo and Booth 2003; Rushton 2001; Sansalone and Buchberger 1997). Data presented in this study show the monitored permeable pavement lots located in Eastern North Carolina also reduced, and at times eliminated, runoff. The Swansboro PICP monitoring site infiltrated all rainfall that occurred at the site during the monitoring period. Three main reasons for its effectiveness were (1) being sited over sandy in situ soils; (2) being designed with a large storage volume; and (3) having a surface free from fines. The Kinston CGP site also reduced or eliminated runoff from multiple rainfall events over 25 mm, compared to what a typical impervious surface would produce. For rainfall events less than 30 mm, a maximum of 4 mm of runoff occurred at the Wilmington PC site.

Calculated CNs from these sites ranged from 37 to 89. Permeable pavement sites that are constructed on sandy soils with high hydraulic conductivities, designed with large storage basins, and are maintained to prevent sediment accumulation on the surface may perform similarly to the Swansboro PICP site.

Water quality results from this study seem to support previous research that permeable pavements can reduce Zn. Although these findings did not compare inflow concentrations to outflow concentrations, results did show that discharge from a permeable pavement cell had lower concentrations of Zn than adjacent asphalt runoff. No exfiltrate sample from either the Swansboro PICP site or the Goldsboro PICP sites had NH_4-N concentrations above the minimum detectable level. In addition, NH_4-N and TKN were significantly ($p \leq 0.05$) higher in asphalt runoff than in exfiltrate from the Goldsboro PICP site. This may have been the result of nitrification, as NO_{2+3}-N concentrations in exfiltrate were higher than those found in asphalt runoff. To reduce NO_{2+3}-N loadings, secondary stormwater treatment devices which perform denitrification should be used if solely aerobic conditions exist in permeable pavements.

Exfiltrate concentrations of TP from the Goldsboro PICP site were significantly ($p \leq 0.05$) less than asphalt runoff concentrations and were similar to the Swansboro PICP exfiltrate concentrations. In watersheds where phosphorus is a concern, permeable pavements may be implemented to reduce TP loadings and concentrations.

The Swansboro PICP site was estimated to retain TN at a rate of 3.8 kg/ha/year and TP at a rate of 0.4 kg/ha/year from runoff. Sites constructed similarly to the Swansboro PICP site may experience comparable pollutant retention through total infiltration. Using permeable pavement in series with a secondary treatment down gradient, such as riparian buffers, would help reduce nutrient loadings reaching target water courses.

J. Irrig. Drain Eng., 2007, 133(6): 583-592

Acknowledgments

The writers would like to thank the employees from Mickey's Pastry Shop in Goldsboro, the Town of Swansboro, the City of Kinston, and the City of Wilmington for assisting with data collection and construction. Grant funds to conduct the study were provided by North Carolina State University Extension, NCDENR and EPA 319. This research is in memoriam of Michael E. Regans (1946–2004), who helped obtain research sites and funding in Goldsboro and Kinston, N.C.

Notation

The following symbols are used in this paper:

A = area of contributing watershed (L^2);
C = rational coefficient (unitless);
I, P = total event rainfall (L);
K_{sat} = saturated hydraulic conductivity (L/T);
Q = total runoff depth (L);
Q_T = total runoff volume (L/T^3); and
S = storage depth (L).

References

American Society for Testing and Materials (ASTM). (2003). "Standard classification for sizes of aggregate for road and bridge construction." *ASTM D448*, West Conshohocken, Pa.

Barrett, M. E., Irish, L. B., Malina, J. F., and Charbeneau, R. J. (1998). "Characterization of highway runoff in Austin, Texas area." *J. Environ. Eng.*, 124(2), 131–137.

Bean, E. Z., Hunt, W. F., and Bidelspach, D. A. (2007). "A field survey of permeable pavement surface infiltration rates." *J. Irrig. Drain. Eng.*, 133(3), 249–255.

Brattebo, B. O., and Booth, D. B. (2003). "Long-term stormwater quantity and quality performance of permeable pavement systems." *Water Res.*, 37(18), 4369–4376.

Davis, A. P., Shokouhian, M., and Ni, S. (2001). "Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources." *Chemosphere*, 44(5), 997–1009.

Gerritts, C., and James, W. (2002). "Restoration of infiltration capacity of permeable pavers." *Proc., Global Solutions for Urban Drainage*, ASCE, Portland, Ore., 1–16.

He, W., Odnevall Wallinder, I., and Leygraf, C. (2001). "A laboratory study of copper and zinc runoff during first flush and steady-state conditions." *Corros. Sci.*, 43(1), 127–146.

Hunt, W., Stevens, S., and Mayes, D. (2002). "Permeable pavement use and research at two sites in eastern North Carolina." *Proc., Global Solutions for Urban Drainage*, ASCE, Portland, Ore., 1–10.

Lee, J. H., and Bang, K. W. (2000). "Characterization of urban stormwater runoff." *Water Res.*, 34(6), 1773–1780.

Lewis, W. M., Jr. (2002). "Yield of nitrogen from minimally disturbed watersheds of the United States." *Biochemistry*, 57(1), 375–385.

National Ocean and Atmospheric Administration (NOAA). (2004). "NOAA Atlas 14. Vol. 2. Ver. 2." Precipitation Data Frequency Server, National Weather Service, Silver Spring, Md. ⟨http://hdsc.nws.noaa.gov/hdsc/pfds/orb/nc_pfds.html⟩ (July 5, 2005).

National Ocean and Atmospheric Administration, National Climate Data Center (NOAA NCDC). (2005). "Wilmington International Airport." *Precipitation data, hourly*, ⟨http://www.ncdc.noaa.gov/oa/ncdc.html⟩ (July 5, 2005).

North Carolina Dept. of Environment and Natural Resources (NCDENR). (1995). "Design of stormwater management measures." *15A NCAC 2H.1008*, Raleigh, N.C.

North Carolina Dept. of Environment and Natural Resources (NCDENR). (1998). "Neuse River Basin—Nutrient sensitive waters management strategy: Basinwide stormwater requirements." *15A NCAC 2B.0235*, Raleigh, N.C.

North Carolina Dept. of Environment and Natural Resources (NCDENR). (1999). *Stormwater best management practices*, Raleigh, N.C.

North Carolina Dept. of Environment and Natural Resources (NCDENR). (2001). "Tar-Pamlico River Basin—Nutrient sensitive waters management strategy: Basinwide stormwater requirements." *15A NCAC 02B.0258*, Raleigh, N.C.

Pagotto, C., Legret, M., and Le Cloirec, P. (2000). "Comparison of the hydraulic behavior and the quality of highway runoff water according to the type of pavement." *Water Res.*, 34(18), 4446–4454.

Ponce, V. M., and Hawkins, R. H. (1996). "Runoff curve number: Has it reached maturity?" *J. Hydrol. Eng.*, 1(1), 11–19.

Pratt, C. J., Mantle, J. D. G., and Schofield, P. A. (1995). "UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality." *Water Sci. Technol.*, 32(1), 63–69.

Rushton, B. (2001). "Low-impact parking lot design reduces runoff and pollutant loads." *J. Water Resour. Plann. Manage.*, 127(3), 172–179.

SAS. (2003). *SAS user's guide: Statistics*, Ver. 8.2, SAS Institute, Inc., Cary, N.C.

Sansalone, J. J., and Buchberger, S. G. (1997). "Partitioning and first flush of metals in urban roadway stormwater." *J. Environ. Eng.*, 123(2), 134–143.

United States Dept. of Agriculture, Natural Resource Conservation Service (USDA, NRCS). (1986). "Urban hydrology for small watershed, TR-55." *Rep. No. PB87-101580*, 2nd Ed., Springfield, Va.

United States Dept. of Agriculture, Natural Resource Conservation Service (USDA, NRCS). (2005). "Physical soil properties." *Web soil survey*, ⟨http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx⟩ (July 12, 2005).

USEPA. (1972). "Federal water pollution control act." *Clean Water Act*, ⟨http://www.epa.gov/region5/water/pdf/ecwa.pdf⟩ (July 5, 2005).

USEPA. (1983). "Methods for chemical analysis of water and wastes." *EPA 600/4-79- 020*, Washington, D.C.

USEPA. (1993). "Methods for the determination of inorganic substances in environmental samples." *EPA 600/R-93-100*, Washington, D.C.

USEPA. (1996). "Overview of the stormwater program." *EPA 833/R-96-008*, Washington, D.C.

USEPA. (1999). "Economic analysis of the final phase II stormwater rule." Washington, D.C.

USEPA. (2000). "Stormwater phase II final rule: Small MS4 stormwater program overview. Factsheet 2.0." *EPA 833/F-00-002*, Washington, D.C.

USEPA. (2001). "Protecting the nation's waters through effective NPDES permits: A strategic plan, FY 2001 and beyond." *EPA 833/R-01-001*, Washington, D.C.

J. Irrig. Drain Eng., 2007, 133(6): 583-592