HYDROLOGIC AND WATER QUALITY COMPARISON OF FOUR TYPES OF PERMEABLE PAVEMENT AND STANDARD ASPHALT IN EASTERN NORTH CAROLINA

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EXECUTIVE SUMMARY

A parking lot in eastern North Carolina consisting of four types of permeable pavement and standard asphalt was monitored from June 2006 to July 2007 for hydrologic and water quality differences among pavement types. The four permeable sections were pervious concrete (PC), two types of permeable interlocking concrete pavement (PICP) with small-sized aggregate in the joints and having 12.9% (PICP1) and 8.5% (PICP2) open surface area, and concrete grid pavers (CGP) filled with sand. The site was located in poorly drained soils, and all permeable sections were underlain by a crushed stone base with a perforated pipe underdrain. The effects of rainfall depth, rainfall intensity, antecedent dry period, season, and lot age were evaluated for all pavement types.

Hydrologic differences among pavements were evaluated for surface runoff volume, total outflow volume, peak flow rate, and peak delays. All permeable pavements significantly and substantially reduced surface runoff volumes and peak flow rates when compared to standard asphalt ($p<0.01$), but of the permeable pavements, CGP generated the greatest surface runoff volumes ($p<0.01$). The PICP1 and CGP generated significantly lower outflow volumes than asphalt and the other permeable pavement sections evaluated ($p<0.01$). These two sections were able to store up to 6mm of rainfall, a volume equivalent to roughly 30% of the median rainfall event that occurred during the study. Further, these sections had the lowest peak flows and the longest peak delays. The response of the PICP1 cell was likely due to an increased base storage volume resulting from an elevated pipe underdrain; whereas, the CGP cell response was attributed to water retention in the sand fill layer. Permeable pavement surface runoff and peak flow delay appeared to be most dependent on rainfall intensity, whereas outflow volume and peak flow reductions were most dependent on rainfall depth.

Rainfall and asphalt runoff water quality samples were compared to permeable pavement subsurface drainage samples for pH and concentrations of total nitrogen (TN), nitrite-nitrate as nitrogen ($NO_{2,3}$-N), total Kjeldahl nitrogen (TKN), ammonia as nitrogen (NH_4-N), organic nitrogen (ON), total phosphorus (TP), orthophosphate (OPO_4), and total suspended solids (TSS). Due to problems with initial laboratory results, analyses of water quality parameters were only performed on samples collected from January 2007 through July 2007. All pavements were effective in buffering acidic rainfall pH ($p<0.01$). The pH of permeable

pavement subsurface drainage was higher than that of asphalt runoff ($p<0.01$) and the PC cell had the highest pH values of all pavement sections ($p<0.01$). Further, permeable pavement subsurface drainage tended to have lower NH_4-N and TKN concentrations than asphalt runoff and rain. With the exception of the CGP cell, permeable pavements had higher $NO_{2,3}$-N concentrations than asphalt, a probable result of nitrification occurring within the permeable pavement profile. The CGP cell had lower $NO_{2,3}$-N concentrations than other permeable pavements ($p<0.01$), and also had the lowest mean TN concentrations, although these TN results were not significantly different from those of asphalt runoff. The possible N removal exhibited by the CGP cell is similar to that observed in sand filter research, not surprising considering the composition of CGP. TP and TSS concentrations were not different among various pavement sections. Because the permeable pavement cells were not lined with an impermeable material, it is possible, and likely, that TSS and TP were leached from the underlying soils. The pollutant concentrations and loads measured in this study were typical of those found in parking lot runoff, but lower than pollution levels generally reported from roadway runoff, particularly with respect to nitrogen constituents.

Overall, different permeable pavement sections performed similarly to one another with respect to both hydrology and water quality. The permeable pavement sections did, however, function differently than asphalt. Subtle differences in the performance of CGP were noticed relative to other permeable pavements; this was primarily due to the characteristics of the sand filled media compared to small stones typically used in PICP joints and bedding. The CGP cell appears to improve nitrogen concentrations. Based upon this study, it is recommended to regulators that:

(1) various permeable pavement types be treated similarly with respect to runoff reduction.

(2) no direct nitrogen or phosphorous removal credit be assigned to permeable pavements at this time, beyond those corresponding to runoff reduction. Further research on the nutrient removal capabilities of permeable pavements is needed.

INTRODUCTION

Permeable pavements are regarded as an effective tool in managing stormwater. When compared to traditional, impervious asphalt, permeable pavements can reduce runoff quantity, lower peak runoff rates, and delay peak flows due to their high surface infiltration rates (Pratt *et al*., 1989; Hunt *et al*., 2002; Brattebo and Booth, 2003; Bean *et al*., 2007a). Even in locations where the underlying soil is not ideal for complete infiltration, the installation of underdrain pipes in the permeable pavement base has yielded reductions in outflow volume and peak flow rate, and delayed the time to peak flow (Pratt *et al*., 1989). Further, permeable pavement outflow has been shown to reduce concentrations of several heavy metals and suspended solids (Pratt *et al*., 1989; Pratt *et al*., 1995; James and Shahin, 1998; Brattebo and Booth, 2003).

The base course layer of permeable pavements supports traffic loads and serves to retain a portion of the infiltrated rainfall. The permeability, evaporation rate, drainage rate, and retention properties of permeable interlocking concrete pavements have been found to be largely dependent on the percent of surface openings and the particle size distribution of the aggregate joint filling and bedding material (Andersen *et al.*, 1999; James and Shahin, 1998). A laboratory study by Andersen *et al.* (1999), using a 15mm/hr, one hour duration storm, found, on average, that 55% of the simulated rainfall event was retained by a completely dry pavement with a base course depth ranging from 30-70 cm. Pavements that were initially wet retained 30 % of the rainfall, on average. Another study by Pratt *et al*. (1989) examining permeable pavement stalls lined with an impermeable liner found that parking stalls having various subbase materials displayed subsurface outflow volume reductions from rainfall. This phenomenon was attributed to storage of stormwater on the subbase material surfaces. Rainfall events up to 5 mm produced no subsurface outflow from any pavements evaluated, which were underlain by pea gravel, blast furnace slag, limestone, or granite. The pavements with blast furnace slag were able to retain the greatest amount of runoff, due to the increased surface area of the material.

Pratt *et al.* (1989) also observed peak flow reductions and delays for permeable pavement fitted with underdrains and an impervious liner. For a rainfall event characterized by 22 mm of rainfall depth and peak rainfall intensity just under 25 mm/hr, permeable pavement peak outflows were roughly 30% of rainfall peak intensities. Permeable pavement subsurface drainage time to peak flows were delayed approximately 5-10 minutes from the peak of rainfall intensity, compared to a 2-3 minute peak flow delay for asphalt runoff. Further, permeable pavement outflows were attenuated to greater extents than what would be expected from traditional asphalt.

Heavy metal pollutant removal rates are variable depending on the material used for the concrete pavers and base, as well as the joint spaces in the surface (Fach and Geiger, 2005; Pratt *et al*., 1989). Dierkes *et al.* (2002) evaluated heavy metal reduction efficiencies of four pavements: solid concrete block pavers with open infiltration joints, concrete block pavers with greened joints (topsoil fill with planted grass), pervious concrete pavers, and pervious concrete pavers with greened joints. While all four pavements retained some amount of cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn), systems with pervious concrete or greened joints demonstrated higher pollution retention capacities. The pervious concrete pavers with greened joints had the highest pollutant trapping efficiency. Pb and Cu were retained more effectively than Cd and Zn. Specific removal values were not published by the authors of the study.

Another laboratory study by Fach and Geiger, (2005) examined pollution removal rates of Cd, Zn, Pb, Cu for pervious concrete pavers, as well as for three variations of solid concrete block pavers; one with wide infiltration joints (29mm), another with narrow infiltration joints (3mm), and a third with narrow joints filled with crushed brick substrate. Pervious concrete pavers had the highest heavy metal removal rate (96.5% average) followed by the solid concrete block pavers with brick substrate infill (92.9% average). No significant differences between the narrow joint spaces and the wide joints spaces were observed for the solid concrete block pavers (63.1% and 78.6% average removal rates, respectively) When set over a 4 cm thick crushed basalt or brick substrate roadbed and a 40 cm thick open-graded limestone base course, average pollution removal rates for all pavements and substructures were very high, ranging from 96 to 99.8 percent.

Nutrient removal capabilities of permeable pavements are much less understood. A laboratory water pollution study of various types of concrete grid pavers included analyses on nitrogen and phosphorus removal (Day *et al.*, 1981). The CGP openings were filled with sod, and underlain with sand and open-graded No. 57 stone limestone aggregate. For 10 simulated rainfall events, the study concluded that there were high phosphorus removal rates, most likely from adsorption to the sand and aggregate. Nitrate-nitrite removal rates were minimal, and high leaching rates to the pavement drainage were observed. In most trials, ammonia, organic nitrogen, and total organic carbon had low to minimal removal rates.

At two sites in North Carolina, water samples from PICP subsurface drainage were evaluated (Bean, 2005; Bean *et al.*, 2007b). In Goldsboro, NC, nutrient concentrations from PICP subsurface drainage were compared to those in adjacent asphalt runoff. Total phosphorus (TP), zinc, ammonia-nitrogen (NH_4-N), and total kjeldhal nitrogen (TKN) were all significantly lower in the subsurface drainage. On average, nitrate-nitrogen (NO_3-N) in the subsurface drainage was higher than the asphalt runoff. Total suspended solid levels appeared to be reduced, without significant results. In Cary, NC, PICP subsurface drainage was compared to rainfall. NH_4-N and bound phosphate were significantly lower in the subsurface drainage. Ortho-phosphate concentrations were significantly greater in the subsurface drainage, and TP, TN, and NO_3-N concentrations in the subsurface drainage were greater on average than the rainfall concentrations. At both sites, the higher concentrations of NO_3-N in the PICP subsurface drainage were attributed to the probability that aerobic conditions occurred throughout the pavement that nitrified NH_4-N to NO_3-N. The studies did not test any differences in nutrient removal among permeable pavement types.

A similar laboratory study by James and Shahin (1998) compared the quantity and quality of runoff from PICP and rectangular concrete pavers to runoff from a standard asphalt block. The study determined that water infiltrating through permeable pavements tended to cause an increase in NO_3-N and a decrease in TKN due to oxidation within the pavement subbase. Little change in phosphorus concentrations was observed. For the three pavement types evaluated, the runoff volume from PICP was the lowest due to a large percentage of open surface area and high void space in the subsurface base. PICP runoff also contained the lowest concentrations of heavy metal, oils, grease, and bacteria, likely from adsorption or filtering by PICP open-graded aggregate base materials.

Permeable pavements demonstrate lower total pollution loadings than standard pavements because the overall volume of runoff is much lower (Day *et al.*, 1981; NCDENR, 2005). Rushton (2001) compared asphalt runoff to runoff from pervious concrete pavement with a swale and found pollutant loads for metals and total suspended solids to be reduced by 75 percent. Load reductions were observed for ammonia, nitrate, and total nitrogen; however, there was an increased loading for phosphorus, attributed to landscaping practices on the vegetated swale adjacent to the pervious concrete pavement.

There is reason to suspect that permeable pavements with sand layers could provide additional water quality benefits due to increased filtration provided by the sand media. However, the use of sand in the joints or bedding is not standard industry practice due to lower infiltration rates through sand than through open-graded aggregate. Sand filters can be applied below the base materials to achieve additional filtration.

Henderson *et al.* (2007) compared the performance of sand, sandy loam and aggregate fill medias for different bio-infiltration systems and concluded that sand and sandy loam were the most effective filtering medias for N and P, due to increased surface areas on which microbes could colonize. Benefits of sand filters have been well documented. Barrett (2003) evaluated the performance of Austin sand filters and found them to be effective in sequestering TSS, TKN, and TP ($p<0.01$). OPO_4 removal was low, and not significant, and an increase in nitrate was observed. Overall, an average 22% removal of TN was observed (not significant).

An investigation of Danish sand filters estimated 30-45% nitrogen removal and 40-60% phosphorous sequestration. 70-90% phosphorous sequestration rates were achieved by sands containing natural iron compounds (Nielsen *et al*., 1993). Removal of P was determined to be the result of chemical precipitation.

Currently, various types of permeable pavement are treated similarly with respect to runoff reduction and water quality. In several states, no runoff reduction credit is assigned for permeable pavements in impermeable soils applications (i.e. infiltration rates less than 0.5 in/hr). In North Carolina, state regulators treat permeable pavement as if it is 60% grass lawn and 40% impermeable surface, under certain *in-situ* soil conditions, and permeable pavements receive no direct pollutant removal credit (NCDENR, 2006). Other states do give pollutant removal credit to these systems. Pennsylvania, for example, credits permeable pavements with 85% TSS and TP removal, and 30% NO_3 removal (DEP, 2006).

A study in Renton, Washington examined the effectiveness of four different permeable pavements: PICP with open-graded aggregate base, CGP with grass, plastic grid pavers with grass, and plastic grid pavers with aggregate (Brattebo and Booth, 2003). Due to the geographical location of the study, rainfall intensities were lower than those of the Southeast USA, with a maximum 15 minute intensity of 7.4 mm/hr (0.29 in/hr). Most storms had intensities less than 5 mm/hr (0.2 in/hr). Additionally, the in-situ soils underlying the lot were permeable and deep, allowing for rapid exfiltration from the pavement system. The study concluded that with respect to infiltration capabilities and runoff reduction, all permeable pavements performed substantially better than asphalt; however, no substantial differences between permeable pavement types were found. Hardness and conductivity levels increased significantly in both the PICP and CGP subsurface drainage as compared to asphalt runoff. Compared to that of the asphalt runoff, concentrations of Zn, Cu, and motor oil were significantly lower in the subbase drainage from all permeable pavement sections.

In many regions, including the eastern coast of the United States, rainfall intensities are much higher than those observed in Washington State. In Kinston, North Carolina, for example, the peak 1 year, 15 minute rainfall intensity is 93.5 mm/hr (3.67 in/hr) (NOAA, 2004). Further, permeable pavements are not always sited in highly permeable soils.

The objectives of this study were to evaluate and compare (1) hydrologic differences between permeable pavements and standard asphalt, (2) hydrologic differences among various types of permeable pavements, (3) water quality differences between permeable pavements and standard asphalt, and (4) water quality differences among various types of permeable pavements for a permeable pavement parking lot sited in clayey soils in Eastern North Carolina. Hydrologic responses of pavement surface runoff, total outflow volume, peak flow, and time to peak were examined. Water quality analyses focused specifically on nutrients and total suspended solid concentration and load. reductions within permeable pavements.

SITE DESCRIPTION

A 20-stall employee parking lot was constructed in January 2006 at the City of Kinston Public Service Complex in Eastern North Carolina. The lot consisted of six 6 m by 18 m pavement sections, two of which were standard asphalt, each containing two parking stalls. The four remaining sections had four parking stalls and were comprised of the following types of permeable pavement (Figures 1 and 2):

- Pervious concrete (PC),
- Permeable interlocking concrete pavers with 12.9% open surface area and openings filled with No. 78 stone (PICP1)
- Concrete grid pavers with 28% surface open areas and opening filled with sand (CGP)
- Permeable interlocking concrete pavers with 8.5% surface open areas and openings filled with No. 78 stone (PICP2).

On the ends of both asphalt sections, 3 m x 6 m asphalt entranceways were hydraulically disconnected from the rest of the lot. The lot was surrounded by a concrete curb to prevent any run on from areas surrounding the lot.

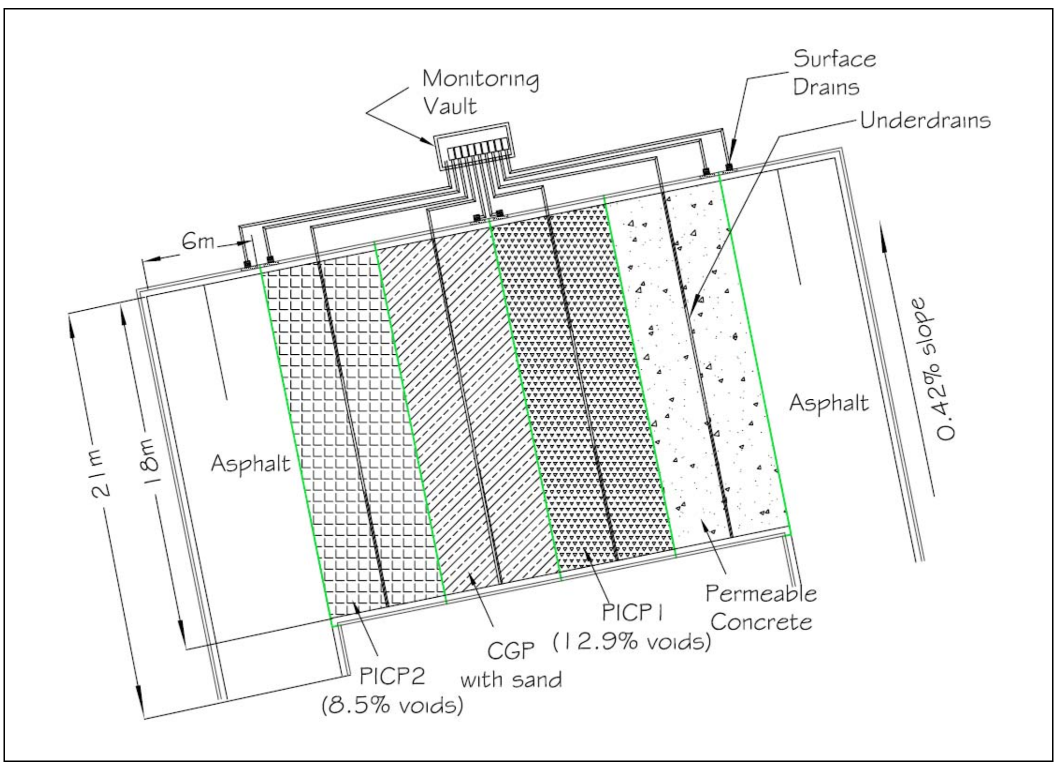


Figure 1. Permeable pavement parking lot design (plan view).

Figure 2. Permeable pavement sections surfaced with (left to right) pervious concrete, permeable interlocking concrete pavers with 12.9% open surface area (PICP1), concrete grid pavers, and permeable interlocking concrete pavers with 8.5% open surface area (PICP2).

The site investigation revealed that at a depth of approximately 50 cm, the in-situ soil type changed from sandy loam to sandy clay loam. This depth varied slightly across the lot; however, the change in texture was consistent over the site area. The lower soil horizons had a Unified Soil Classification of CL, SC, and SC-SM (USDA, 2007). In several locations, iron deposits were observed starting at a depth of 85 cm, likely indicative of a high water table elevation and a confining feature of the lot design. The bottom of the pavement was designed to be above the suspected seasonal high water table.

All permeable sections overlaid a washed ASTM No. 78 stone aggregate bedding layer and a washed ASTM No. 5 stone base course layer, the depths of which varied slightly based on the product specifications of the overlying pavement types (Figure 3). The base course layer was designed to support the expected parking lot traffic loading, estimated as 60 vehicle passes per day. For ease of installation, the excavation depth beneath the permeable pavements was kept consistent, so the aggregate storage layer was adjusted for all sections to meet the strength requirements for the section which limited pavement design.

Each pavement section was designed to be hydraulically separate from the other sections. Thirty mil thick (0.75 mm) LLDPE plastic sheeting was trenched between each pavement section to prevent any subsurface flow from one pavement section to the next. The plastic sheet extended from the soil underlying each pavement aggregate base layer to the parking lot surface, where 6.5 cm high asphalt berms were placed to prevent surface flow migration from one pavement section to another.

Due to the low permeability of the in situ soils, perforated corrugated plastic pipe (CPP) underdrains (d=10cm) were installed at the bottom of the each permeable pavement aggregate base course layer to drain water from the system, thereby creating separate "cells."

The aggregate subbase of each permeable pavement section sloped toward the corrugated underdrains in the center of each pavement section at a 30:1 side slope. The pavement cells were unlined, to allow for some potential exfiltration of water into the subsoil.

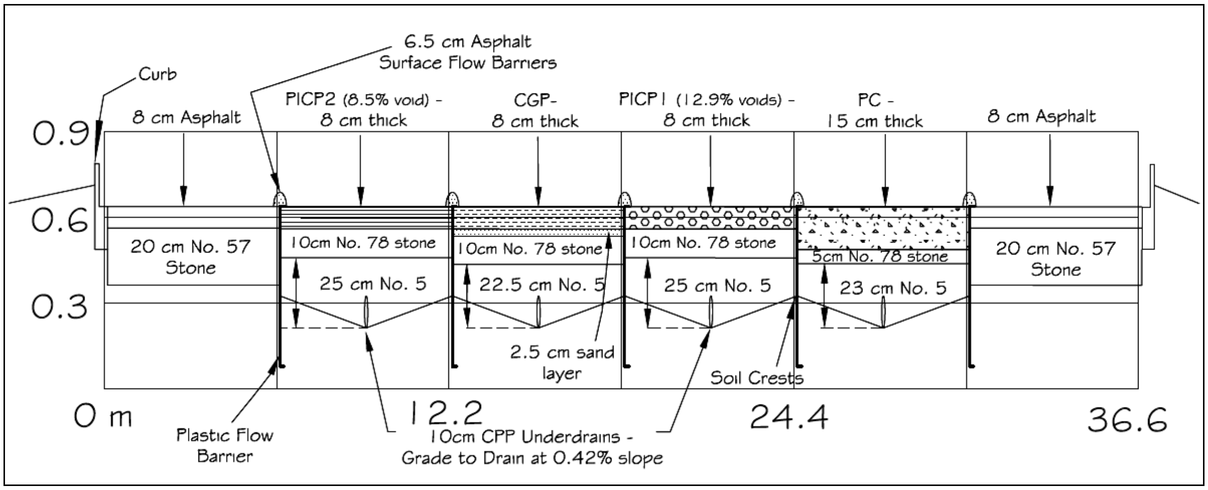


Figure 3. Parking Lot Cross Section (measurements in meters)

Because design configurations of various permeable pavements differed slightly, the pavements are referred to as cells rather than individual pavement types. Excluding surface runoff, the hydraulic and water quality responses of each permeable pavement section were not solely dependent on the pavement type, but rather the entire configuration of the pavement cell (pavement type, structural/storage layer design, and outlet configuration).

The entire parking lot, excluding the entrance ways, was designed with a 0.42% surface and sub-grade slope to provide drainage and allow for monitoring. Surface runoff from each of the six pavement sections drained to a partitioned gutter and then to a monitoring vault, where flow was measured over 30 degree, galvanized steel v-notch weirs. The underdrains from the four permeable sections also flowed to the monitoring vault where four additional weir boxes measured subsurface drainage flow rates.

MONITORING METHODS

A concrete monitoring vault (4 x 2 x 1 m) was located down slope of the parking lot, approximately 3 m from the edge of the parking lot curb (Figure 4). The vault was placed so that positive drainage occurred from all monitored sections of the parking lot into the vault.

All water measurements and sampling occurred within this vault, from where the water then drained via two 25 cm (10 in) culverts to a nearby stream.

The rate of flow from each of the surface drains and underdrains was calculated by measuring the head of water above the weir v-notch opening. The standard equation for flow through a 30 degree weir, which accurately describes flow for head readings above 0.06 m, or flows greater than 0.329 l/s, is defined as:

$$Q=373.2*H^{2.5} \qquad \text{Where Q = flow rate (l/s) and H= head (m)} \qquad (1)$$

For lower flows, the standard weir equation is not applicable, as water adhesion to the crest of the weir increases the resistance of flow (Grant and Dawson, 2001). By mounting the weir plates in a laboratory scale flume, weirs were calibrated by measuring the head of water above the weir for various low flow rates. Averaging the calibration results for the ten weirs yielded the following equation relating low flow rates to head above the weir:

$$Q = 981.76*H^{2.86} \qquad \text{Where Q = flow rate (l/s), H= head (m)} \qquad (2)$$

Figure 4. Monitoring vault

Head measurements for each weir were recorded at 5 minute intervals using ten separate pulley-float systems equipped with Sargent data loggers. Flow was calculated using the calibrated weir equation for head values less than 0.06 m (Equation 2), and the standard weir equation for values 0.06 m or greater (Equation 1). Backup level measurements of asphalt runoff and permeable pavement subsurface drainage were recorded using ISCO® 4230 flow meters.

Precipitation quantity and intensity were measured on site using an automatic ISCO® 674 tipping bucket rain gauge and backup manual rain gauge, which were installed adjacent to the parking lot 1.6 m (5 ft) above the ground, clear of any overhead vegetation. Precipitation data from the automatic gauge, which tipped at a 0.25mm (0.01 in) frequency, were recorded by an ISCO® 4230 flow meter.

During precipitation events, composite, flow-weighted water quality samples of the surface runoff from each of the two asphalt regions, along with subsurface drainage from each permeable pavement section, were collected. Six total sections were sampled individually using Sigma 900™ or Sigma 900Max ™ automatic samplers, all of which were housed in a monitoring shed located adjacent to the vault. Runoff and subsurface drainage samples for precipitation events from 0.25 cm to 5.0 cm (0.1-2.0 in) in size were collected. ISCO® 4230 flow meters, also located within the shed, used a sensor to continuously measure water elevations in the weir boxes for each of the sections being evaluated for water quality. Changes in head level above the weir, indicating flow through the system, triggered water quality sampling via the Sigma 900's and 900Max's to begin. Sampling continued at specific volume intervals until head levels dropped back to the level of the weir nappe. For each asphalt section, 200ml of runoff was sampled after every 60 liters of water passed over the weir. For the permeable sections, 200ml of subsurface drainage was sampled after every 40 liters. Composite samples were temporarily stored in an 11.3 liter (3 gal) glass jar stored underneath the sigma sampling units. The samplers and flow meters were all individually powered by Trojan® 12v marine deep-cycle batteries, which, in turn, were charged via five Free Energy America® 14-watt amorphous solar panels that had been mounted to the roof of the monitoring shed. Precipitation samples were collected in a 5 liter oil pan and analyzed for background rainfall quality data.

Table 1. List of monitoring equipment.

Purpose	Equipment	Quantity
Level recorders	Sargent pully-float system data loggers	10
Water quality samplers	Sigma 900 ™ / Sigma 900Max ™	6
Level recorders	ISCO® 4230 flow meters	5
Rainfall data	ISCO® 674 tipping bucket rain gauge	1
pH measurement	Oakton® Instruments handheld probe	1
Power	Trojan® 12v marine deep-cycle batteries	11
Power	Free Energy America® 14-watt amorphous solar panels	6

SAMPLING PROTOCOL

Within 24 hours of a monitored precipitation event, water quality samples were collected from each Sigma sampler along with the rainfall sample from the oil pan. The 11.3 liter sampling jars that stored the composite runoff and subsurface drainage samples were first shaken to ensure proper mixing of the water sample. pH was measured using a handheld pH probe. Once pH was recorded, the sample was again shaken and then distributed among multiple sampling bottles to facilitate the various water quality laboratory tests. First, 20 ml of the sample was drawn through a syringe and filtered through a Whatman® 0.45 μm pore sized filter into a glass bottle for analysis of orthophosphate. The remainder of the unfiltered sample was distributed proportionally into a 250 ml pre-acidified bottle with 0.25 ml of sulfuric acid, and a 1 liter plastic bottle. The acidified bottle was used for nutrient analyses and the 1 liter bottle was used for TSS measurement. The sampling jars were then emptied of any remaining sample, rinsed with deionized water, scrubbed, and placed back in the sampler from which they were taken. A similar procedure was followed for the rainwater samples. Rainfall pH was measured and recorded prior to being poured or filtered into smaller sampling bottles. The oil pan was then rinsed with DI water and placed back on the ground.

The collected samples were chilled in a cooler filled with ice and transported back to NCSU for immediate laboratory analysis at the Center for Applied Aquatic Ecology Water Quality Laboratory. Table 3-2 details the parameters analyzed and testing methods used.

Table 2. Laboratory analysis methods.

Parameter	LAB2
Total Kjeldahl Nitrogen (TKN)	EPA Method 351.1 (1993)
Nitrate-Nirtite ($NO_{2,3}N$)	EPA Method 353.2 (1993) or SM 4500-NO3 F (1998).
Ammonia (NH_4N)	EPA Method 350.1 (1993) or SM 4500-NH3 H (1998)
Total Nitrogen (TN)	Calculation =TKN + NO2,3N
Total Phosphorus (TP)	EPA Method 365.3 (1993) or SM 4500-P F (1998).
Orthophosphorus (OPO_4)	EPA Method 365.1(1993) or SM 4500-P F (1998).
Total Suspended Soilds (TSS)	SM 2540 D (1998)

Modifications

During initial monitoring stages, it was noticed that the PICP1 cell was not properly draining. A 2.24 cm rainfall event on 5 May 2006 yielded very little surface runoff and no subsurface drainage volume. A water hose was placed on the PICP1 surface and verified that water was being stored and eventually leaking out of the adjacent sections. All other sections functioned as intended. The PICP1 cell underdrain pipe was unearthed and discovered to be 10 cm higher than the underdrain pipes of the adjacent sections, thus creating a subsurface storage volume in the PICP1 cell. The elevation of the PICP1 underdrain was lowered, and water hose tests soon indicated proper drainage from each section, even after long periods of flow. Further analyses indicated that the PICP1 cell outlet still remained slightly higher than adjacent sections; however, adjacent sections did not appear to be affected. It is likely that the PICP1 section contained a greater aggregate subbase layer storage volume than the other permeable sections. As a result, PICP1 total outflow measurements and peak rates were expected, and often found, to be lower than other permeable sections.

In September 2006, problems associated with flooding from Tropical Storm Ernesto forced changes in the measurement of asphalt and permeable pavement drainage levels. From this point on, data were complied from the backup ISCO® 4230 flow meters, which recorded at 2 minute intervals. Only data recorded after 20 September 2006 were analyzed for peak flow responses.

Finally, due to quality control concerns, a laboratory change was implemented in January 2007. With the exception of nitrate-nitrite data, all water quality results prior to this date were discarded. Results from January 2007 to July 2007 are discussed herein, and long term $NO_{2,3}$-N results are described in the Appendix.

Soil Characteristics

On December 15, 2006, several soil samples were collected from the site and analyzed at the NCDA&CS Agronomic Division Laboratory, located on Reedy Creek Road in Raleigh, NC. The sampling locations were scattered around the parking lot in areas both disturbed and undisturbed during lot construction. Results of the background soil tests are detailed in the Appendix.

Overall, site cation exchange capacity (CEC) values were low, and the percent base saturation (%BS) was high, indicating that the soil had low potential for adsorption of positively charged cations, such as iron (Fe). Phosphorous, a negatively charged ion, can bind to soil by coupling with Fe cations. The high %BS indicates that little P-Fe binding to soil is likely to occur within the site soils. The phosphorus index (P-I), zinc index (Zn-I) and copper index (Cu-I) reflect the amounts of these elements in the soil. In general, the higher the index value, the greater the availability of these elements in the soil, and the greater the risk of leaching. While Cu-I and Zn-I were generally in the low-medium range, P-I ranged from high to very high with values from 53 to 133 and a mean index of 78. The average pH of all soil samples analyzed was 5.36.

Surface Infiltration Rates

Four times over the course of the study, infiltration tests on the parking lot were performed using a modified ASTM D 3385 double ring infiltration testing method (ASTM, 2003). Tests were preceded by a minimum dry period of three days. Due to the hard nature of the pavement surfaces, rings were placed directly on the pavement surface and sealed with putty. For most trials, the infiltration rates of the pavements were very high (>150 cm/hr), so a single ring infiltration test was used. For the single ring test, the time to completely drain a measured level of water from the inner ring was recorded. The infiltration rate for the trial was determined by averaging the water level drop over each recorded time interval. Even in cases where a double ring test was possible, the infiltration rates were such that a falling head test was used in place of a constant head test. If feasible, the rings were filled with 6 inches of water and the time elapsed was recorded for each half inch change in head. Water in the outer ring was kept at the same level as the inner ring. Measurements continued until all water drained from the inner ring.

For each section, trials were repeated twice at three different locations on the pavement surface. The infiltration rates were then averaged to determine the overall infiltration rate of the pavement. No substantial clogging was noticed over the course of the 18 month study (Table 1). Surface infiltration rate trends were as follows: PC>PICP1>PICP2>CGP.

Table 3. Average permeable pavement surface infiltration rates.

DATE	PC	PICP1	CGP	PICP2
	-----Surface Infiltration Rate (cm/hr)-----			
06/2006	3087	771	91	457
09/2006	6152	1027	89	171
03/2007	4466	1299	87	376
07/2007	4941	1536	101	267

<u>Storm Characteristics</u>

For a total of 56 storm events, occurring June 2006 through July 2007, data on pavement surface runoff volumes, total outflow volumes, peak flows and peak delays were collected and compiled. Individual storms were defined as precipitation events exceeding 2.5 mm with an antecedent dry period of 24 hours or more, meeting the minimum storm selection criteria as specified in the Urban Stormwater BMP Monitoring Manual (USEPA, 2002). Over the entire monitoring period, all precipitation events occurred in the form of rainfall, and complete drainage of the permeable sections was observed within 24 hours of the termination of rainfall. During the study, two storms, Tropical Storm Ernesto and the 22 November 2006 Storm, had rainfall depths of 183 mm and 135 mm, respectively. These large storms events exceeded the pavement storage design, and in one case, inundated the monitoring infrastructure. These storms were excluded from the overall statistical analysis and are discussed independently. Excluding these two events, monitored rainfall depths ranged from 3.1 to 88.9 mm, with mean and median rainfall depths of 20.6 mm and 14.7 mm, respectively.

Statistical Analyses

To compare the hydrologic and water quality responses of various pavement sections, a one-way analysis between pavements was performed using a multiple linear regression (MLR) procedure for unbalanced designs in which pavements were blocked by storm (α=0.05). Hydrologic data were square-root transformed to produce normal residuals with constant variance. All concentration data was distributed log-normally. The surface runoff data did not consist of normal residuals with constant variance, and a suitable transformation for the data did not exist. As a result, a nonparametric Wilcoxon signed rank test was used to evaluate differences in surface runoff among pavement types. The effects of independent variables – rainfall depth, rainfall intensity, antecedent dry period (ADP), lot age, and season – were evaluated for each pavement response. A Pearson correlation test procedure was used to identify significant correlations between continuous independent variables, and a multiple linear regression (MLR) forward selection procedure was used to determine which independent variables were significant predictors of surface runoff volume (α=0.05). All statistical analyses were run using SAS® 9.1 software.

RESULTS AND DISCUSSION

HYDROLOGY

Figure 5 illustrates the typical response of a permeable pavement section following a rainfall event. The majority of the stormwater left the permeable pavement cells as subsurface drainage from the underdrains. This is also where permeable pavement peak outflows were observed. Total permeable pavement outflow was defined as the sum of surface runoff and cell subsurface drainage for a particular section. Exfiltrate, which was not monitored, referred to water that entered the soil underlying the permeable sections.

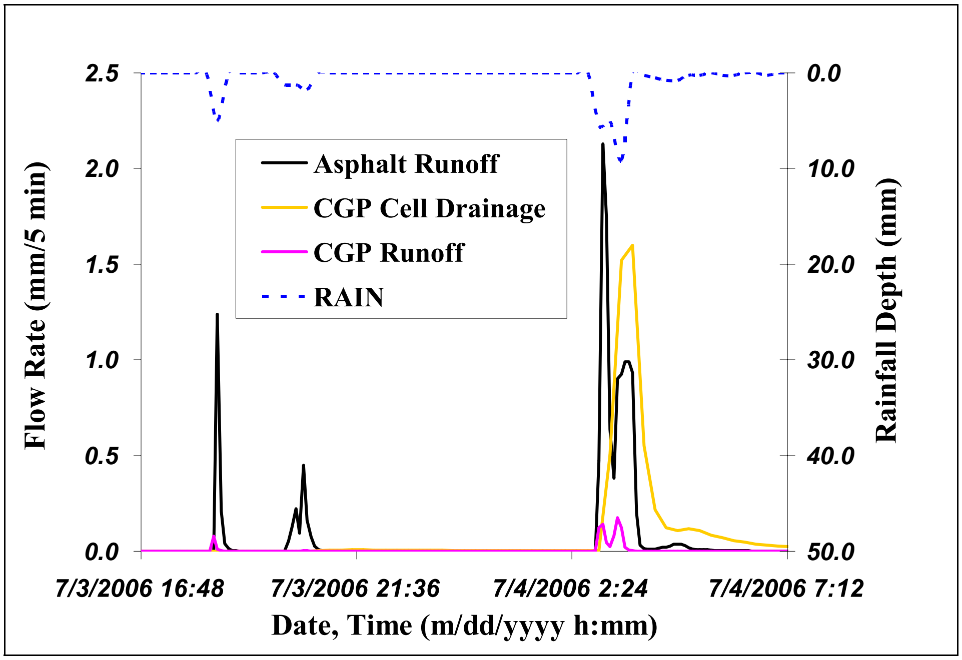


Figure 5. Asphalt runoff and CGP runoff and drainage for 32.8 mm event on 7/3/2006.

Over the entire study period, correlations between rainfall depth and rainfall intensity were observed ($r=0.57$, $p<0.001$).

Surface Runoff

When compared to asphalt, all four permeable pavement sections dramatically reduced surface runoff volumes. The marked reductions in permeable pavement surface runoff were similar to results found by Hunt *et al*. (2002), Bean *et al*. (2007b), Brattebo and Booth (2003), and Valavala *et al.* (2006) on unclogged pavement sites. Mean runoff reductions from rainfall depth were 34.7, 99.9, 99.3, 98.2, and 99.5% for asphalt, PC, PICP1, CGP, and PICP2, respectively (Table 4). Surface runoff volumes of all pavements were statistically different from one another ($p<0.01$). Expressed in order of highest runoff generation, pavements performed as follows: Asphalt>>CGP>PICP1>PICP2>PC. All pavement surface runoff volumes were positively correlated to rainfall depth and intensity ($p<0.05$). Asphalt, PC and PICP2 were more strongly correlated to rainfall depth, whereas stronger correlations to intensity were observed for PICP1 and CGP (Table 5). PICP2 runoff was positively correlated to the age of the parking lot, although not significantly ($p=0.059$), reflecting potential clogging of this pavement surface during the study.

Table 4. Percent surface runoff reductions from rainfall depth

Parameter	Asphalt (n=44)	PC (n=40)	PICP1 (n=41)	CGP (n=40)	PICP2 (n=40)
	-------Percent Runoff Reduction from Rainfall (%)-------				
MEAN	34.65	99.86	99.33	98.17	99.51
MEDIAN	29.43	99.94	99.37	98.67	99.68
MIN	-2.73	99.03	97.76	91.11	96.94
MAX	84.80	100.00	100.00	100.00	100.00
STDEV	18.71	0.22	0.58	1.83	0.65

The curb and gutters along each pavement section were hydraulically connected to the parking lot, so runoff from these areas likely contributed some volume of runoff to each pavement section. The estimated runoff volume associated with the gutters was subtracted from the runoff volumes from each pavement to calculate surface runoff coming solely from a pavement surface during a rainfall event (USDA-SCS, 1972).

Table 5. Pearson's correlation coefficients for pavement hydrologic responses and continuous variables. Numbers in **bold** are statistically significant (α=0.05)

Pavement	*Rainfall Depth*	*Rainfall Intensity*	*ADP*	*Lot Age*
	---------------- Surface Runoff (Curb Adjusted)---------------			
Asphalt	**0.976**	**0.408**	0.062	-0.049
PC	-	-	-	-
PICP1	0.244	0.021	0.081	0.086
CGP	**0.474**	**0.352**	-0.166	-0.194
PICP2	-0.136	-0.246	0.325	0.291
	------------------------- Total Volume --------------------------			
Asphalt	**0.950**	**0.500**	-0.090	0.067
PC	**0.894**	**0.388**	0.011	-0.053
PICP1	**0.939**	**0.460**	-0.071	0.051
CGP	**0.918**	**0.408**	-0.158	0.154
PICP2	**0.921**	**0.415**	-0.099	-0.044
	--------------------------- Peak Flow ----------------------------			
Asphalt	**0.536**	**0.900**	-0.322	**0.526**
PC	**0.780**	**0.855**	-0.299	**0.339**
PICP1	**0.770**	**0.825**	-0.290	0.328
CGP	**0.855**	**0.676**	-0.235	0.251
PICP2	**0.741**	**0.872**	-0.300	**0.355**
	--------------------------- Peak Delay ----------------------------			
Asphalt	-	-	-	-
PC	-0.327	**-0.364**	0.157	-0.173
PICP1	-0.355	**-0.411**	0.024	-0.011
CGP	-0.341	**-0.365**	-0.017	-0.176
PICP2	-0.297	**-0.368**	0.086	-0.172

Simultaneous runoff from all five pavements was generated during only two rainfall events: Tropical Storm Ernesto and the 22 November 2006 Storm. As stated previously, rainfall depth during these events exceeded 180 mm and 130 mm, respectively. Statistically, asphalt runoff was greater than all permeable pavement surface runoff ($p<0.001$), and CGP generated more surface runoff than all other permeable sections ($p<0.001$). No differences between PC, PICP1 and PICP2 were observed. Rainfall depth was the best predictor of asphalt runoff; whereas, rainfall intensity was the best predictor of CGP runoff (Table 6).

As shown in Figure 5, runoff from CGP occurred during intense periods of rainfall, indicating that the runoff was proportional to the intensity, not accumulating rainfall. This phenomenon was observed for all runoff producing events, and is similar to results found by Hunt *et al*. (2002) on CGP and Valavala *et al.* (2006) on permeable concrete systems.

Table 6. Significant predictor variables of MLR analysis for pavement hydrologic responses (α=0.05).

Pavement	Significant Predictor Variables *	R^2
SURFACE RUNOFF (Curb Adjusted)		
Asphalt	Rainfall Depth	0.900
PC	-	
PICP1	-	
CGP	Rainfall Intensity	0.240
PICP2	-	
TOTAL VOLUME		
Asphalt	Rainfall Depth	0.850
PC	Rainfall Depth, Season	0.900
PICP1	Rainfall Depth, Season	0.860
CGP	Rainfall Depth, Season, Dry Period	0.890
PICP2	Rainfall Depth, Season	0.900
PEAK FLOW		
Asphalt	Rainfall Intensity	0.780
PC	Rainfall Intensity, Rainfall Depth	0.830
PICP1	Rainfall Intensity, Rainfall Depth	0.800
CGP	Rainfall Depth, Rainfall Intensity	0.750
PICP2	Rainfall Intensity, Rainfall Depth	0.860
PEAK DELAY		
Asphalt	-	
PC	Rainfall Intensity	0.160
PICP1	Rainfall Intensity	0.190
CGP	Rainfall Intensity	0.160
PICP2	Rainfall Intensity	0.230

* Variables ranked in order of decreasing weight

Pavement surface infiltration rate and geometry appeared to affect the amount of surface runoff. In general, the surface infiltration rate of the permeable pavements, which was largely dependent on physical properties of the fill media of the various pavements, was a good predictor of surface runoff volumes. Because of the larger grain size of aggregate and PC material, the sizes of the individual pore spaces in these pavements are much larger than those in the sand fill. Aggregate, (K_{sat}=10^2-10^4 m/d) allowed for more rapid infiltration and flow of water through the fill material than sand (K_{sat}=10^0-10^2 m/d) (Heath, 1983). As a result, more runoff was generated from CGP than the aggregate filled and PC sections during intense rainfall events.

More runoff was generated from PICP1 than PICP2, despite PICP1 having a higher void area of the pavement surface, a higher surface infiltration rate, and similar joint filling material. The reason may be that the surface configuration and geometries of the paving blocks differed (Figure 6). Although PICP2 had a smaller fraction of surface open void space, the area between individual pavers was depressed, which directed water into the voids. In addition, water could not travel down-slope without passing over a channel. Conversely, the PICP1 did not contain a grid of surface channels, and these pavers only infiltrated water that passed directly over the voids. For the PICP1 section, surface runoff was theoretically able to avoid open surface voids, or at least travel a distance before infiltrating.

(a) **(b)**

Figure 6. (a) Surface geometry of PICP1. **(b)** Surface geometry of PICP2.

PICP1 surface infiltration rates (Table 1) were higher than those of PICP2, yet more runoff was generated from PICP1. The surface infiltration rate measured how fast a falling head of water was able to completely infiltrate into the permeable pavements. The infiltration rate of PICP2 was lower because water was passing through a smaller open void area. During rainfall events, rainfall rate was much lower compared to surface infiltration tests, and water was able to infiltrate into the smaller PICP2 surface voids. Thus, the surface infiltration differences observed between PICP1 and PICP2 during the infiltrations tests were not observed under natural conditions.

Although subtle differences in surface runoff did exist among pavements, runoff was both substantially and statistically significantly lower than that of asphalt for all permeable pavement types evaluated.

Total Volumes

The majority of the total outflow for all permeable pavement sections occurred as subsurface drainage. Table 7 details the percentage of outflow volume which occurred as surface runoff for each permeable section. For every measured storm except the 22 November 2006 Storm, surface runoff comprised only 6% of the total outflow volume for CGP, and less than 2% for all other permeable pavements. Two large storms were not accurately monitored due to equipment inundation or malfunction.

Table 7. The percentage of surface runoff resulting from total outflow volumes.

STORM EVENT	PC	PICP1	CGP	PICP2
(P=Rainfall Depth)	-------Percentage of Surface Runoff (%)------			
6 mm<P<50 mm*	0.2	1.7	6.0	0.7
22 Nov 2006 (P=135 mm)	9.2	30.6	34.8	14.1

*Storms less than 6 mm in size were not averaged, due to the absence of subsurface drainage generated from PICP1 and CGP cells.

Because of the poor infiltration exhibited by the underlying *in-situ* soils, the permeable pavement cells were designed with underdrains to facilitate subsurface drainage in between storm events. As a result, these sections generated greater outflow than would typically be expected in a sandy soil application where in-situ soils were highly permeable.

The PICP1 and CGP cells generated significantly less outflow volumes than the other pavement sections ($p<0.001$) and no statistical difference between these cells was observed. The total outflow volumes of the PC cell, PICP2 cell and asphalt were not statistically different from one another. Average percent volume reductions from rainfall volume were 35.7, 43.9, 66.3, 63.6, and 37.7% for asphalt, PC, PICP1, CGP, and PICP2 cells, respectively

(Table 8). There were several storms during the fall and winter months where the total outflow volumes from some or all the permeable pavement cells were greater than the volume of asphalt runoff.

Table 8. Percent outflow volume reductions from rainfall depth

Parameter	Asphalt (n=54)	PC (n=51)	PICP1 (n=50)	CGP (n=50)	PICP2 (n=46)
	------Percent Outflow Reduction from Rainfall (%)------				
MEAN	35.70	43.88	66.29	63.63	37.68
MEDIAN	30.20	49.30	65.55	67.24	35.55
MIN	-2.73	-9.44	20.70	10.48	-9.13
MAX	92.33	92.09	100.00	99.96	84.02
STDEV	21.76	23.68	23.22	26.46	23.85

There were several cases where neither subsurface drainage volume nor surface runoff was generated from the PICP1 and CGP cells. In general, these events were associated with rainfall depths less than 6 mm. Mean rainfall depth during the study was approximately 21 mm. By storing 6 mm, these two pavements captured nearly 30% of the mean rainfall depth. The response of the PICP1 cell was likely attributed to an increased subsurface storage volume in the bottom of the pavement, and a consequential increase in exfiltration, due to an elevated underdrain outlet. However, the hydrologic response of the CGP cell is presumed due to water retention within the pore spaces of the sand filling the pavement surface openings. It is unlikely that this cell had an increased subbase storage volume because observations made during infiltration tests showed immediate subsurface drainage from the CGP cell[1]. During these tests, the sand in the testing area was quickly saturated and gave up excess water once pore spaces filled.

Due to its smaller grain size, sand is able to retain a greater water volume than crushed stone aggregate. The small sized sand grains have a greater specific retention of water (capillary action) versus aggregate because of their larger surface area per volume of material to which water molecules can adsorb (Heath, 1983). The captured moisture eventually evaporates or slowly leaks into the storage area for subsequent infiltration. It is likely that a small portion of the outflow volume reductions of permeable pavements without sand fill was due to some water retention in the No. 78 stone and coarse aggregate layers.

[1]During infiltration tests, the sand in the testing area was quickly saturated and gave up excess water once pore spaces filled.

The sand fill appeared to have a more substantial impact on volume retention. These findings are similar to those found by Andersen *et al*. (1999) and Pratt *et al*. (1989).

Unlike surface runoff, total outflow volume was more influenced by rainfall depth than rainfall intensity. Total volume for all pavements was positively correlated to rainfall depth ($p<0.001$). The effects of rainfall intensity were lost as water traveled through the coarse aggregate layer, as the aggregate layer had a dampening effect on the stormwater runoff flows. Greater volumes of rainfall caused saturation of the voids, resulting in more drainage and outflow.

Negative correlations between antecedent dry period and outflow volumes were noticed, but were not significant. Dry period was, however, a significant predictor of the CGP cell outflow volume (Table 6). A longer dry period presumably allowed for evaporation or leakage of the sand-retained water between rainfall events, which then allowed for runoff from subsequent rainfalls to be retained in the pavement pore spaces. For all permeable pavements, strong seasonal trends in total outflow volume were observed. In general, greater outflow volumes occurred during the fall and winter months.

It is unknown why permeable pavement outflow volumes were sometimes greater than asphalt runoff volumes. Asphalt initial abstraction (puddles) was a noticeable factor, but probably not enough to cause the substantial differences that were observed. Combining the results of all 4 pavement types and treating the permeable pavement lot as a single system also yielded instances of greater outflow volume than asphalt runoff, although to a lesser magnitude than the individual pavement types. Comparing the entire permeable system outflow to asphalt runoff, most negative reductions (more outflow than asphalt runoff) occurred during winter months (Figure 7). A partial explanation is a decrease in evaporation from the pavement surfaces during these colder months; however, it is likely that there were additional groundwater inputs to the system that resulted from a seasonal high water table. Soil survey data for the *in-situ* soils identified the upper limit of the water table at a depth of 0-3 feet, with the shallowest depths occurring from December to April (USDA, 2007). A strong relationship between season and percent reductions was also observed.

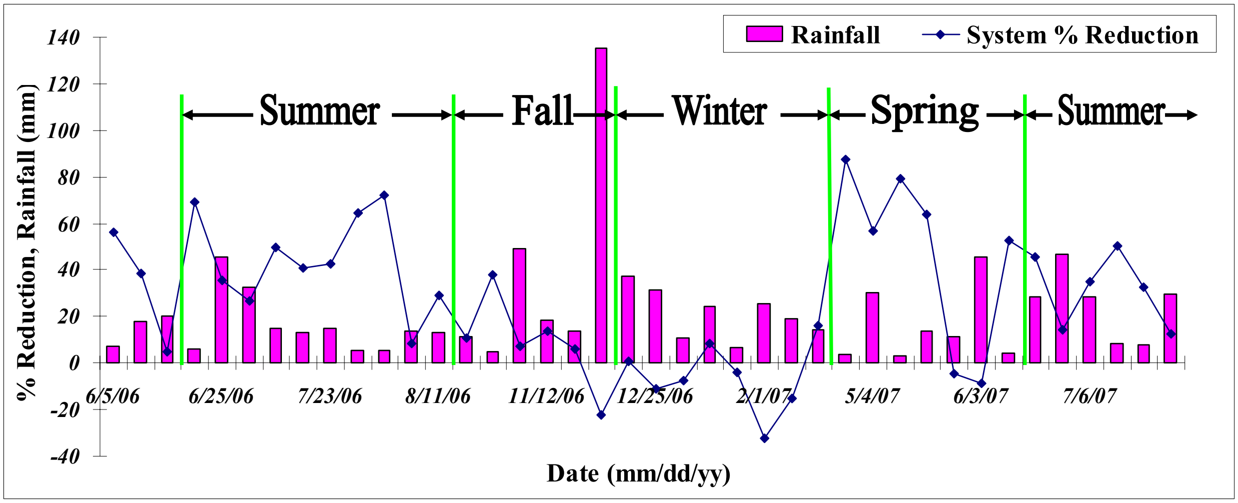


Figure 7. Permeable pavement system total outflow volume reductions over those of asphalt.

Outflow volume reductions for the permeable system that did occur can be attributed to retention within the pavement void fill media and aggregate subbase and some small degree of subsoil infiltration. Because the system was designed to drain, the degree of infiltration was likely limited. The one exception was the PICP1 cell, in which an elevated underdrain left some water ponded in the system after each storm event, allowing more time for infiltration.

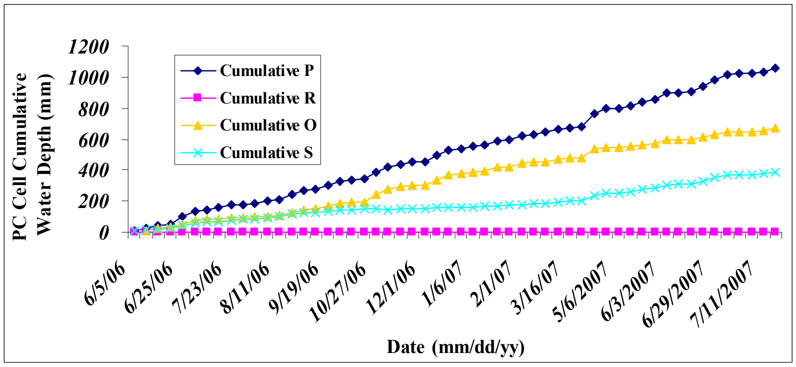
The following equations were used to estimate a water mass balance for each individual pavement section:

$$Q_{in} = Q_{out} + \Delta Q \quad (6)$$

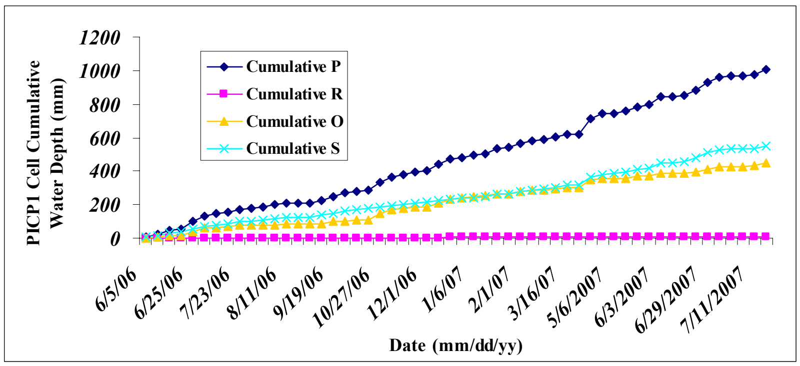
$$Q_{in} = P \quad (7)$$

$$Q_{out} = R + O \quad (8)$$

where P = rainfall depth (mm), R = runoff depth (mm), and O = subsurface drainage outflow depth (mm). ΔQ, the storage depth, accounted for evaporation losses, subsurface infiltration, and pavement storage. Figure 8 shows cumulative water balance graphs for each permeable pavement section. Storm event data containing recording errors for individual pavement sections were excluded from the cumulative graphs of that particular section. Storage was greater in the PICP and CGP cells than the PC and PICP2 cells. A decrease in storage (decreasing line slope), and a related increase in outflow (increasing line slope), was observed for all permeable pavements during the fall and winter months, the likely result of decreased evapo-transpiration and a high water table.



(a)



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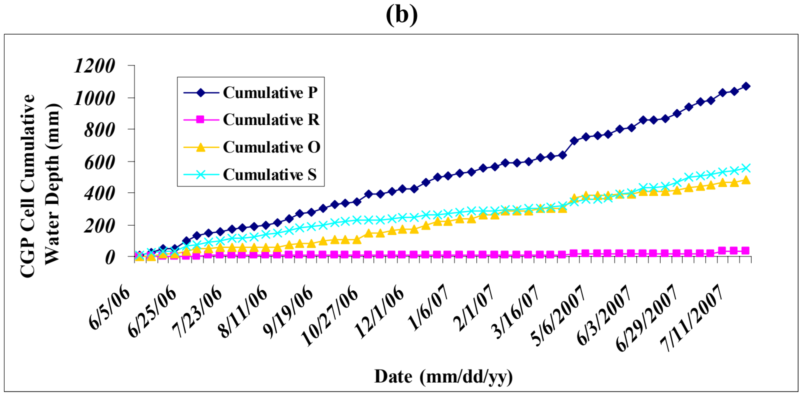

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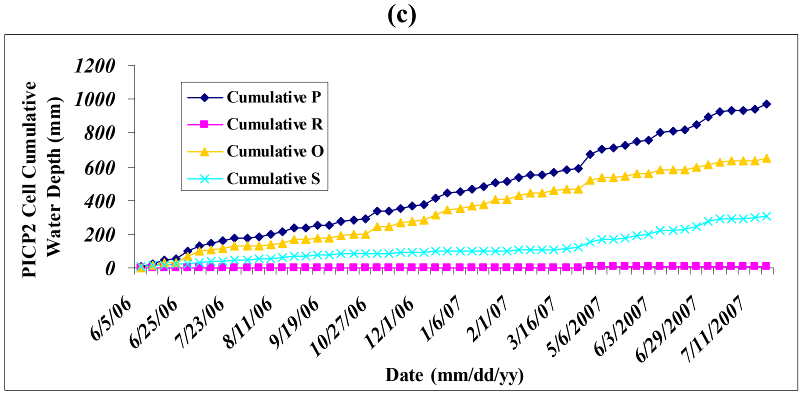


(d)

Figure 8. Cumulative outflow graphs for each permeable section: **(a)** PC cell **(b)** PICP1 cell **(c)** CGP cell and **(d)** PICP2 cell.

Peak Flows and Time to Peak

All permeable pavement sections reduced and delayed peak outflow rates from asphalt. Peak outflow rates from all permeable pavement sections were lower than the peak runoff flow rates from asphalt ($p<0.001$). Of the permeable pavements, the CGP and PICP1 cells had the lowest mean and median peak outflow values (Table 9). Peak outflows from the CGP cell were significantly less than those from the PICP2 and PC cells, and the PICP1 cell peak outflows were significantly less than those from the PICP2 cell ($p<0.01$).

Table 9. Permeable pavement peak flow reductions and time to peak[1].

Parameter	PC (n=36)	PICP1 (n=36)	CGP (n=36)	PICP2 (n=34)
	-----Peak Flows Reductions (%)-----			
MEAN	67.1	73.5	77.1	60.3
MEDIAN	69.5	78.5	83.0	63.0
MIN	17.0	17.0	20.5	12.5
MAX	99.4	100.0	100.0	100.0
STDEV	22.8	23.6	22.6	24.5
Parameter	**PC (n=30)**	**PICP1 (n=29)**	**CGP (n=30)**	**PICP2 (n=28)**
	---------Time to Peak (min)---------			
MEAN	31	46	50	28
MEDIAN	10	12	28	6
MIN	0	0	0	0
MAX	262	294	312	260
STDEV	102	70	94	88

[1]compared to asphalt

During smaller storms, the permeable pavement sections often produced no subsurface drainage, and, therefore, a peak outflow rate of 0 l/s. These storms were excluded from time to peak analyses. This occurred more frequently for the PICP1 and CGP cells.

Time to peak was estimated as the time delay (in minutes) from the asphalt peak runoff rate to the peak outflow rate for all permeable sections. For 34 of the 35 storms analyzed for peak delays, peak outflow rates of the permeable pavement sections occurred after peak runoff rates of asphalt. For all permeable sections, no delay in peak was observed for the 88.9 mm rainfall event on 16 April 2007. The CGP cell had the longest mean and median time to peak (Table 9). Peak delays from the PICP1 and CGP cells were significantly longer than those from the PICP2 cell ($p<0.001$). Compared to peak delays in the PC cell, CGP cell delays were significantly longer ($p<0.001$) and PICP1 cell delays were not significant ($p=0.052$).

Unlike asphalt runoff, which traveled directly to the gutter, rainfall infiltrated through each pavement, and then exited via the underdrain. The aggregate subbase functioned to slow and delay the transport of water by dissipating the rainfall energy. The sand layer of the CGP cell, which had a lower hydraulic conductivity and a lower surface infiltration rate than the PC and PICP sections, provided additional dissipation of rainfall intensity. The CGP and PICP1 cells also stored a larger runoff volume relative to the other permeable sections, which further attenuated peak outflows.

For all pavements, peak flow rates were positively correlated to both rainfall depth and rainfall intensity ($p<0.001$). Rainfall intensity was the best predictor variable of peak flow rates for all pavements except the CGP, for which rainfall depth was the best predictor (Table 6). However, when comparing permeable pavement peak outflow reductions from those of asphalt runoff, rainfall depth was the only significant predictor variable and demonstrated a strong negative correlation to percent peak reduction for all permeable pavements ($p<0.001$). Thus, as rainfall depth increased, the permeable pavements had a smaller peak flow reduction relative to asphalt peak flows. No correlations between peak reductions and rainfall intensity were significant.

It was likely that rainfall depth distinguished permeable pavement peak outflow response from that of asphalt runoff. Intensity was both a strong and the only significant predictor variable for asphalt; whereas, both rainfall and intensity tended to be significant predictors of permeable pavement peak flows. A greater rainfall depth likely resulted in the saturation of the retaining voids within the permeable pavements, particularly those surrounding the underdrain. Once these voids are filled, water that entered the pavements would flow more readily through the pavement and exit as subsurface drainage. During higher intensity but low rainfall events, water would still be retained in these void spaces.

Time to peak delays for each pavement were negatively correlated to rainfall intensity ($p<0.05$). A high rainfall intensity produced a greater volume of rain in a shorter period of time, which resulted in a faster time to peak outflow. Antecedent dry period, lot age, and season were not significant predictors of peak flow or peak flow reductions.

Large Storm Events

Tropical Storm Ernesto and the 22 November 2006 storm generated permeable pavement hydrologic responses that were different from the typical storms recorded with rainfall depths less than 50 mm. The 183 mm of rainfall that fell from 31 August 2006 to 1 September 2006 during Tropical Storm Ernesto resulted in unquantifiable results due to the overtopping of all outflow (surface runoff and subsurface drainage) v-notch weirs in the monitoring vault. During the 22 November 2006 Storm, reductions in surface runoff were still observed, but were not as great the surface runoff reductions observed for smaller rainfall events (Table 10). Despite the larger amounts of surface runoff, the highest outflow volumes and outflow rates occurred in permeable pavement subsurface drainage. Total outflow volumes of all permeable pavements were greater than that of asphalt runoff, a probable result of a high water table which may have been present during the large storm event. Peak outflow rates of the permeable pavements were slightly less than, but not statistically different from asphalt. During these larger storm events, differences among permeable sections were less evident than during smaller storm events.

Table 10. Hydrologic responses of pavement sections as a function of rainfall depth

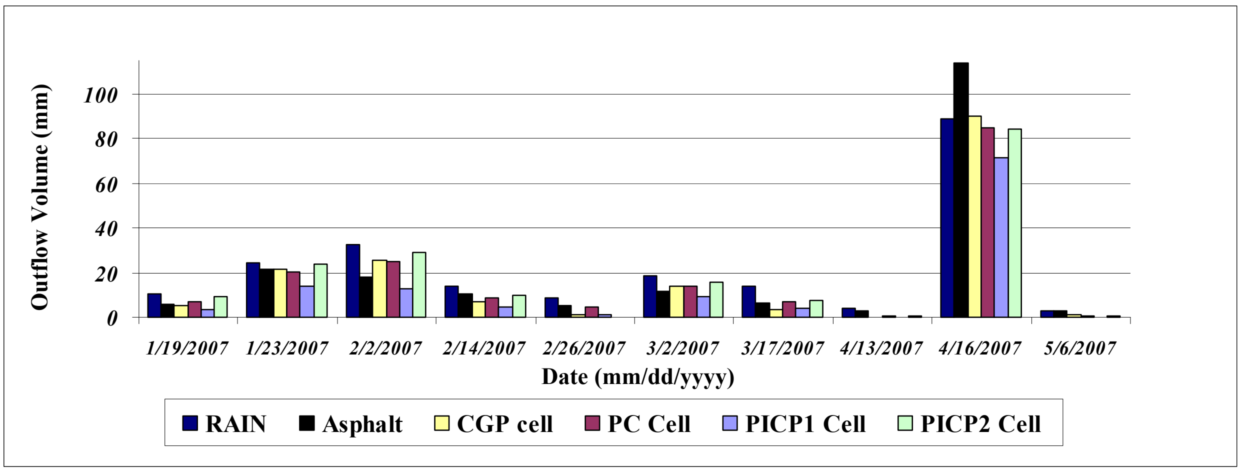
Rainfall	# storms	Asphalt	PC	PICP1	CGP	PICP2
			Mean Surface Runoff[1] (mm)			
P<13 mm	16	3.72	0.00	0.00	0.08	0.01
13 mm<P<25 mm	17	11.39	0.00	0.00	0.11	0.01
25 mm<P	15	25.77	0.00	0.03	1.18	0.00
22 Nov 2006 (P=135 mm)	1	371.19	34.60	147.51	177.11	57.84
*OVERALL MEAN**	48	13.24	0.00	0.01	0.46	0.01
			Mean Outflow Volumes (mm)			
	# storms	**Asphalt**	**PC**	**PICP1**	**CGP**	**PICP2**
P<13 mm	19	3.62	3.29	1.34	1.34	3.56
13 mm<P<25 mm	16	11.66	10.49	6.65	7.13	12.25
25 mm<P	19	28.38	23.45	21.06	21.21	27.23
22 Nov 2006 (P=135 mm)	1	373.44	399.50	488.68	515.52	426.02
*OVERALL MEAN**	54	14.65	11.84	8.89	9.99	13.67
			Mean Peak Flows (l/s)			
	# storms	**Asphalt**	**PC**	**PICP1**	**CGP**	**PICP2**
P<13 mm	14	0.496	0.068	0.042	0.023	0.115
13 mm<P<25 mm	9	0.930	0.330	0.297	0.243	0.421
25 mm<P	12	1.662	0.784	0.742	0.561	0.915
22 Nov 2006 (P=135 mm)	1	6.536	6.177	6.275	6.535	6.271
*OVERALL MEAN**	35	1.008	0.381	0.348	0.264	0.465
			Mean Peak Delays (min)			
	# storms	**Asphalt**	**PC**	**PICP1**	**CGP**	**PICP2**
P<13 mm	14	-	102	97	113	80
13 mm<P<25 mm	9	-	34	36	46	33
25 mm<P	12	-	15	18	24	11
22 Nov 2006 (P=135 mm)	1	-	0	0	0	0
*OVERALL MEAN**	35	-	55	47	61	44

[1] Curb adjusted surface volumes

* Overall mean values exclude results of 11/22/2006 Storm

WATER QUALITY

From January 2007 to July 2007, composite, flow-weighted water quality samples for 20 storm events were collected and analyzed from seven locations; rainfall, runoff from both asphalt runoff sections, and subsurface drainage from all four permeable pavement sections. Figure 9 shows the outflow volumes from each section from all sampled rainfall events. On average, rainfall events producing less than 6 mm of rainfall generated no outflow from the CGP and PICP1 cells. For these events, the concentrations for all parameters were recorded as zero, since no pollutants left the pavements. For all parameters reported, data from the two asphalt sections were not statistically different. Where represented graphically, a mean of the data from the two sections is depicted.



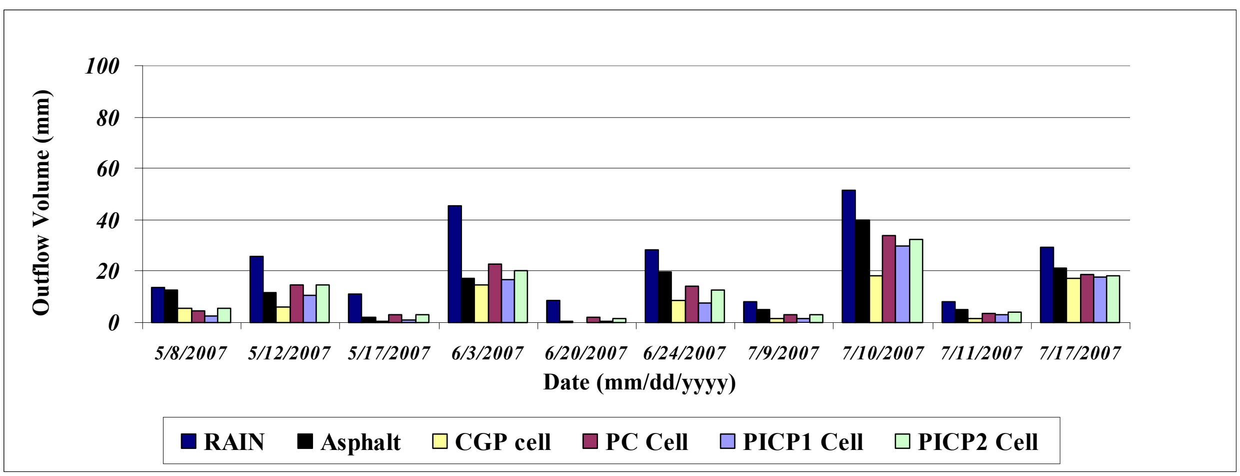


Figure 9. Outflow volumes for sampled rainfall events for each sampling site.

The Kinston parking lot received light traffic over the course of the study, so the many of the pollutant inputs to the lot were believed to be atmospherically deposited, resulting from rainfall or wind blown particles. Studies have determined that atmospheric deposition contributes to a large portion of the nitrogen found in stormwater (Line *et al*., 2002, Wu *et al.*, 1998). A study in Charlotte, North Carolina, found that 70-90% of the TN, 10-30% of both TP and TSS pollutant loadings were attributed to rainfall (Wu *et al*., 1998). Since the permeable pavement subbase layers had direct contact with the underlying soils, it is possible, and likely, that additional pollutant inputs were contributed from soil leaching and construction impacts.

Permeable pavement subsurface drainage pollutant concentrations were compared to rainfall and asphalt runoff. Since the rain collection pan was located on the ground, occasional debris from grass clippings were collected with rainfall samples. It is likely that this contributed to an increase in TSS and, although the grassed area nearby was not fertilized during the study period, higher nutrient levels in the rain samples. The comparison of permeable pavement drainage samples to asphalt runoff samples allowed for consideration of additional inputs of pollutant deposition on the parking surfaces from traffic or wind.

Parameter statistical summaries for each sampling site, along with graphs of all parameter concentrations and loads, are contained in the Appendix.

<u>pH</u>

All pavements displayed pH buffering capacities of the influent acidic rainfall. Figure 10 shows the pH measurements for each pavement and rain. On average, all permeable pavement drainage had a higher pH than asphalt runoff ($p<0.001$). The PC cell had higher pH values than all other permeable pavement cells ($p<0.001$). Rain pH was lower than asphalt and all permeable pavement sections ($p<0.01$). No correlations were observed between rain pH and any pavement pH. Further, no significant pH correlations to any climate variables were observed for any pavement sections (Table 11).

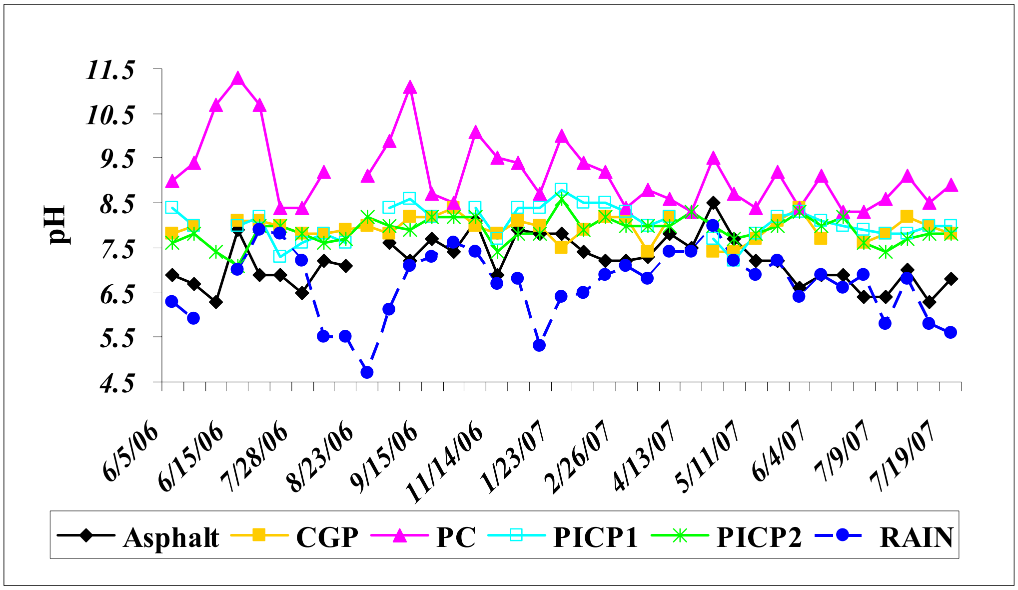


Figure 10. pH measurements for all sampling sites.

Pavement buffering capacity was likely due to the presence of calcium carbonate and magnesium carbonate in the pavement and aggregate materials. The hardness of pavement effluents was not measured in this study, but it is likely that an increase in hardness would have been related to the increased pH values observed, due to the precipitation of calcium and magnesium. Permeable pavements had a greater buffering capacity than asphalt, attributable to the greater surface area provided by contours in the pavement geometry and the additional coarse aggregate layer through which water migrated. Similar buffering capacities of permeable pavements have been observed by James and Shahin (1998), and Pratt *et al*. (1995). James and Shahin found that the deeper water percolated through permeable pavement subbases, the more the pH of water alkalinized, due to the greater interaction with metal carbonates. The PC cell provided the most contact time with cemetitious material, explaining the higher pH generated from this section. It is unlikely that the *in situ* soils provided significant additional buffering of pH due to the low organic matter content.

At lower pH values, metals become soluble, and thus more mobile. (Sparks *et al*, 2003; Mikkelsen *et al*, 1994). James and Shahin (1998) reported that acidic rainwater will more readily dissolve metal pollutants. A number of experiments have yielded higher effluent metal concentrations in lower pH environments (Wong and Yang, 1997,

Table 11. Pearson's correlation coefficients for water quality parameter concentrations and continuous variables. Values in **bold** were significant for α=0.05.

VARIABLE	A1	A2	PC	PICP1	CGP	PICP2	RAIN
				pH			
Rainfall Depth	**0.36**	0.38	**0.39**	0.06	-0.26	0.06	**0.35**
Rainfall Intensity	-0.17	-0.08	0.14	-0.26	-0.14	-0.29	-0.01
ADP	0.11	0.17	-0.29	0.33	0.17	**0.39**	0.48
Lot Age	-0.08	-0.01	**-0.53**	-0.08	-0.21	0.18	0.01
				TN			
Rainfall Depth	-0.34	-0.31	-0.20	-0.22	**0.50**	-0.17	-0.29
Rainfall Intensity	0.23	0.30	-0.01	-0.13	0.32	0.15	0.07
ADP	0.20	0.21	0.34	**0.47**	0.03	0.13	0.40
Lot Age	**0.57**	**0.70**	**0.60**	0.41	0.41	**0.67**	**0.41**
				$NO_{2,3}$-N			
Rainfall Depth	-0.38	-0.40	-0.22	-0.20	**0.56**	-0.22	-0.36
Rainfall Intensity	-0.21	-0.06	-0.03	-0.15	0.09	0.00	-0.10
ADP	0.20	0.01	0.04	**0.47**	0.02	0.19	0.27
Lot Age	0.22	0.46	**0.54**	0.38	0.09	**0.55**	0.43 (p=0.0575)
				NH_4-N			
Rainfall Depth	-0.11	-0.28	0.19	-0.21	-0.12	0.13	-0.08
Rainfall Intensity	**0.54**	0.46	**0.65**	0.00	0.05	**0.50**	0.43
ADP	-0.32	-0.33	-0.16	0.14	0.30	-0.30	0.02
Lot Age	0.40	**0.55**	0.18	-0.05	0.11	0.33	**0.50**
				TKN			
Rainfall Depth	-0.31	-0.26	-0.08	-0.30	0.25	0.00	-0.25
Rainfall Intensity	0.31	0.36	0.02	-0.05	**0.47**	0.38	0.10
ADP	0.18	0.24	**0.57**	0.42	0.03	-0.02	0.39
Lot Age	**0.60**	**0.71**	0.39	**0.53**	**0.65**	**0.68**	0.36
				ON			
Rainfall Depth	-0.26	-0.04	-0.02	-0.20	0.27	-0.04	-0.29
Rainfall Intensity	0.17	0.45	0.17	0.02	**0.48**	0.32	-0.32
ADP	0.14	0.22	0.34	0.38	-0.01	0.04	0.35
Lot Age	**0.62**	**0.87**	**0.59**	**0.48**	**0.66**	**0.69**	0.13
				TP			
Rainfall Depth	-0.31	-0.24	0.05	0.32	-0.13	0.45 (p=0.0564)	-0.25
Rainfall Intensity	-0.29	-0.17	0.21	**0.56**	-0.27	**0.64**	-0.24
ADP	0.13	0.38	-0.05	-0.11	0.29	-0.18	**0.49**
Lot Age	0.09	0.05	0.21	0.24	-0.31	0.28	0.30
				OPO_4			
Rainfall Depth	-0.25	-0.19	-0.12	-0.06	-0.25	0.07	-0.27
Rainfall Intensity	-0.29	-0.38	-0.28	0.24	-0.38	0.43	-0.22
ADP	0.01	-0.10	0.08	-0.28	0.35	-0.23	0.34
Lot Age	0.03	-0.43	-0.33	**0.46**	**-0.53**	0.41	0.19
				TSS			
Rainfall Depth	-0.14	0.24	0.25	0.08	0.18	0.34	**-0.51**
Rainfall Intensity	**0.46**	**0.77**	**0.82**	0.43	0.27	**0.66**	**-0.50**
ADP	0.10	0.20	-0.21	-0.10	0.12	-0.23	**0.49**
Lot Age	**0.56**	**0.67**	**0.73**	0.17	0.45	0.34	-0.38

Aulenbach and Chan, 1988). Aulenbach and Chan (1988) performed studies on sand filtration systems under various pHs. Under neutral pH, sand filters were effective, sequestering 35-40% of Zn and Pb, and 20% of Cu; however, an increase in pH above 11 or below 2.4 led to an increase in the effluent concentration of metals. Although metals were not analyzed, the pH of the permeable pavements was such that leaching of metals was not expected.

Nitrogen

Generally, permeable pavement subsurface drainage tended to have lower NH_4-N and TKN concentrations than asphalt runoff and rain. With the exception of the CGP cell, permeable pavement subsurface drainage had higher $NO_{2,3}$-N concentrations. The CGP cell produced the lowest TN concentrations. Nitrogen loads leaving the PICP1 cell were generally low due to the outflow volume reductions provided by this section. Detailed results are discussed by parameter.

Ammonia as Nitrogen

Pavement and rain NH_4-N concentrations are shown in Figure 11. All permeable sections had significantly lower NH_4-N concentrations and loadings than both asphalt and rain ($p<0.001$). No significant difference in NH_4-N concentration was observed between asphalt and rain, or among permeable pavements.

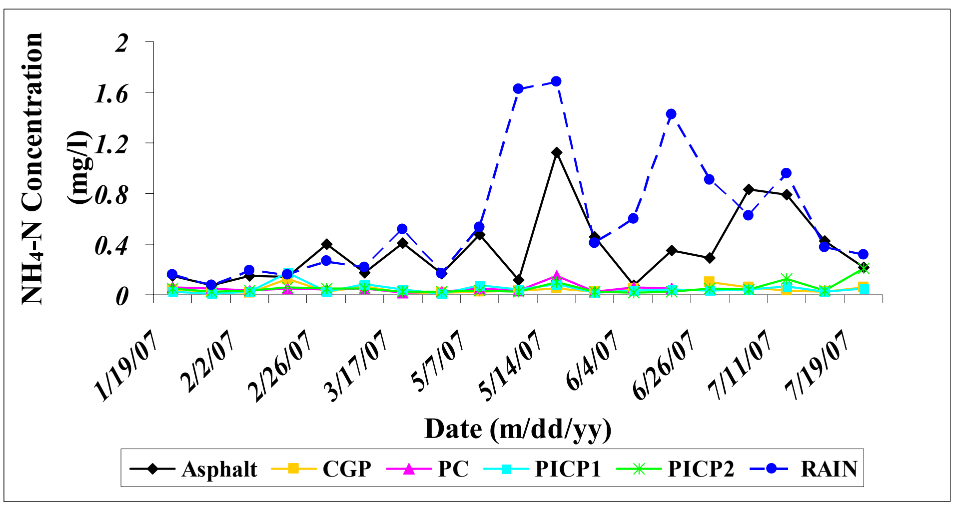


Figure 11. NH_4-N concentrations for all sampling sites.

Rain and asphalt NH_4-N loads were significantly greater than NH_4-N loads from all permeable pavement sections. Rain NH_4-N loads were significantly greater than those of asphalt ($p<0.001$). For all pavements, NH_4-N loads were positively correlated to rainfall depth ($p<0.01$).

Total Kjeldahl Nitrogen

TKN is the sum of organic nitrogen and NH_4-N. Pavement and rain TKN concentrations are shown in Figure 12. Asphalt and rain had highest mean and median TKN values. Statistically, asphalt TKN concentrations were higher than all other pavement sections ($p<0.01$). Rain TKN concentrations were greater than those from all permeable pavement cells ($p<0.05$) except the PC cell ($p=0.0604$). Rain and asphalt TKN concentrations were positively correlated ($r= 0.74$, $p<0.001$).

All permeable pavement TKN loads were significantly lower than asphalt ($p<0.05$) and rain ($p<0.001$) TKN loads. TKN loads from the PICP1 cell were lower than PC and PICP2 cells ($p<0.05$). For all sampling sites, TKN loads were positively correlated to rainfall depth ($p<0.001$).

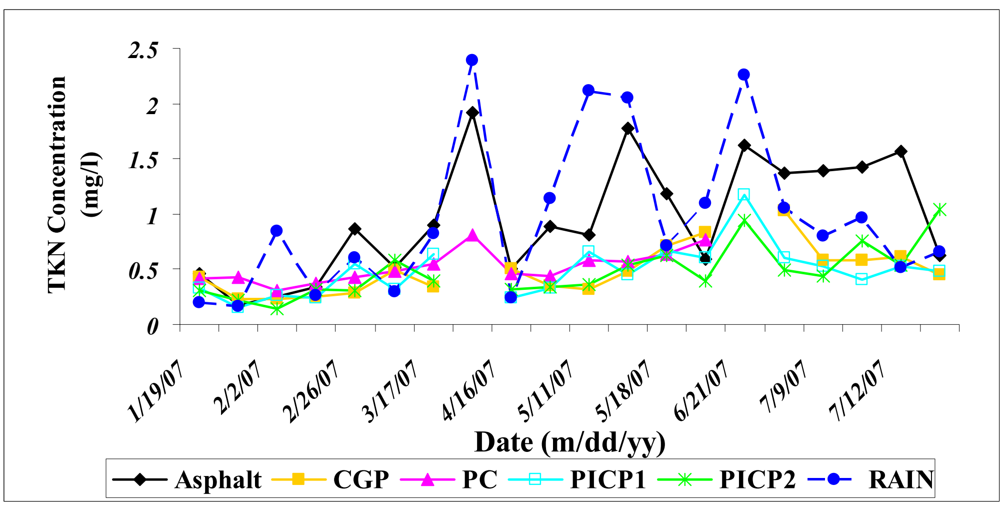


Figure 12. TKN concentrations for all sampling sites.

Nitrate-Nitrite as Nitrogen

Figure 13 shows pavement and rain $NO_{2,3}$-N concentrations. $NO_{2,3}$-N concentrations from the PICP1 cell were significantly higher than all other pavement sections and rainfall samples ($p<0.05$). Asphalt, rain, and the CGP cell $NO_{2,3}$-N concentrations were significantly lower than all other pavement sections ($p<0.05$). No differences among asphalt, rain, or CGP cell $NO_{2,3}$-N concentrations were observed. All $NO_{2,3}$-N pavement concentrations, except those from the CGP cell, were positively correlated to rainfall $NO_{2,3}$-N concentration ($p<0.01$).

Asphalt and CGP cell $NO_{2,3}$-N loads were significantly lower than those from rain, the PC cell, and the PICP2 cell ($p<0.01$). For all sampling sites, $NO_{2,3}$-N loads were positively correlated to rainfall depth ($p<0.001$).

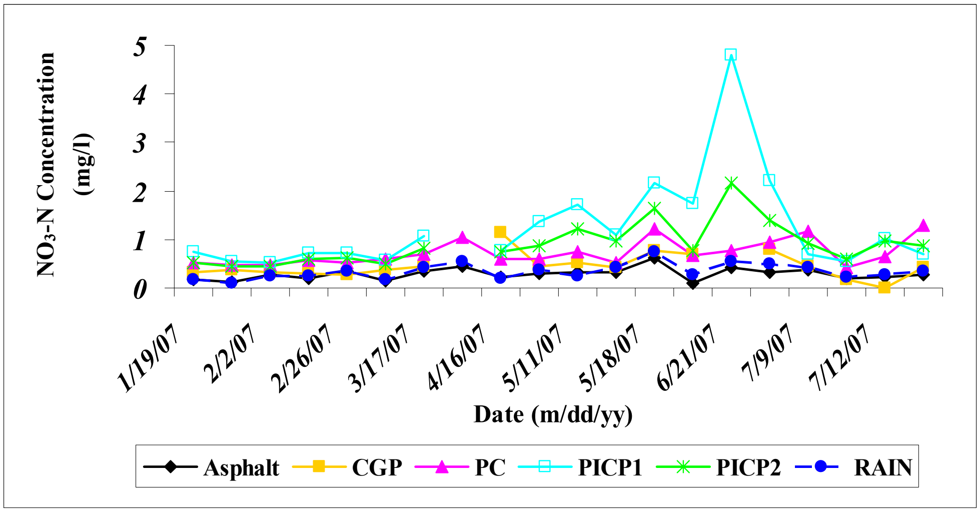


Figure 13. $NO_{2,3}$-N concentrations for all sampling sites.

Organic Nitrogen

Organic nitrogen (ON) concentrations were calculated by subtracting NH_4-N concentrations from TKN concentrations. No significant differences in ON concentrations were observed among pavements. All pavement ON concentrations were greater than those of rain ($p<0.01$). Positive correlations between asphalt and each permeable pavement ON concentrations were observed ($p<0.01$).

PICP1 cell ON loads were significantly lower than PC cell and rain ON loads ($p<0.05$). ON loads for all pavements were positively correlated to rainfall depth ($p<0.001$).

Total Nitrogen

Total nitrogen concentration (Figure 14) was calculated by summing $NO_{2,3}$-N and TKN concentrations. Overall, the CGP cell had the lowest mean and median TN concentrations, and PICP1 had the highest. The PICP1 cell TN concentrations were greater than asphalt, rain, and the CGP cell TN concentrations ($p<0.01$). Additionally, the CGP cell had lower TN concentrations than those of the PICP2 cell ($p<0.05$). TN concentrations in the Asphalt, PC, PICP1 and PICP2 cells were positively correlated to rain TN concentrations ($p<0.001$).

Rain and the PICP2 cell had the highest mean and median TN loads (Figure 15), while the CGP cell had lowest median TN loads. The TN loads leaving the CGP cell were significantly less than those leaving asphalt, and the PC and PICP2 cells ($p<0.05$). TN loads leaving the PC, PICP1, and CGP cells were significantly less than rain TN loads ($p<0.001$). For all sampling sites, TN loads were positively correlated to rainfall depth ($p<0.001$).

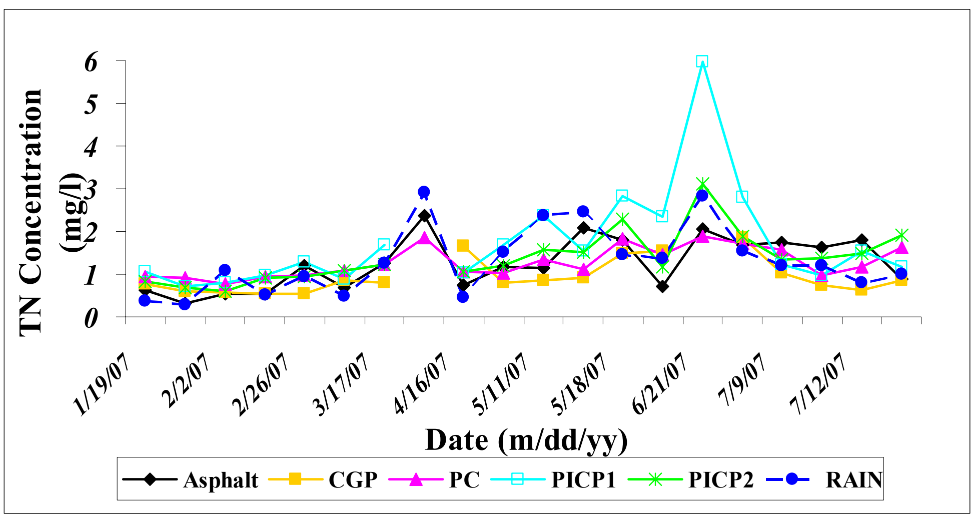


Figure 14. TN concentrations for all sampling sites.

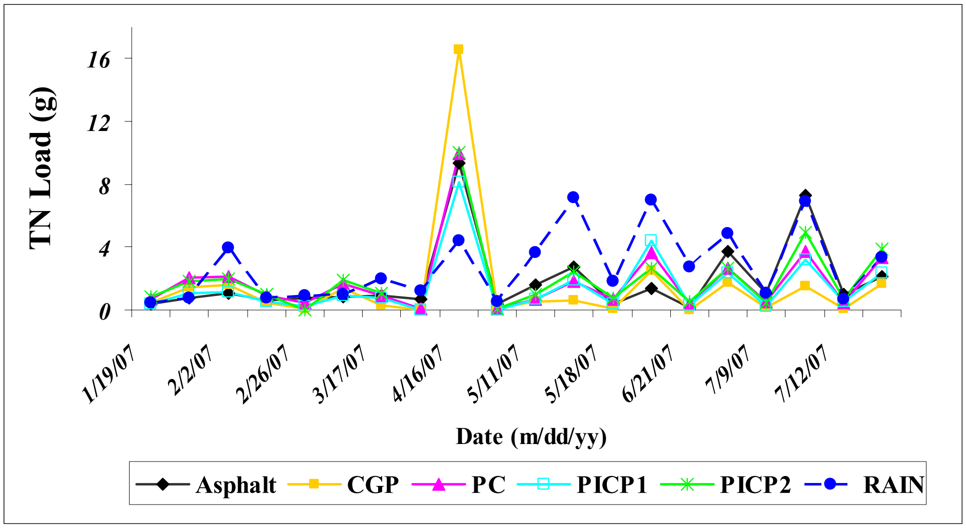


Figure 15. TN loads for all sampling sites.

Nitrate (NO_3^-) is a highly mobile anion which leaches readily through soils and other media. In an aerobic environment, NH_4^+ can be converted to NO_3^- in a two step microbial process. The first step of the process involves the formation of nitrite from ammonia, and is mediated by bacteria in the *Nitrosomonas* genus. The second step forms nitrate from nitrite, and is mediated by bacteria in the *Nitrobacter* genus (Kadlec and Knight, 2006). Nitrification occurs most rapidly in neutral to alkaline environments (Coyne, 1999), such as those observed in the permeable pavement sections during this study. The optimum pH ranges for growth of these bacteria are listed in Table 12. Average permeable pavement subsurface drainage pH values ranged from 7.9-9.4. Microorganisms also take up nitrogen for cell growth in the processes of assimilation. Because of its highly reduced nitrogen state, NH_4^+ is most commonly assimilated (Kadlec and Knight, 2006).

Table 12. Table pH allowing growth (adapted from Coyne, 1999).

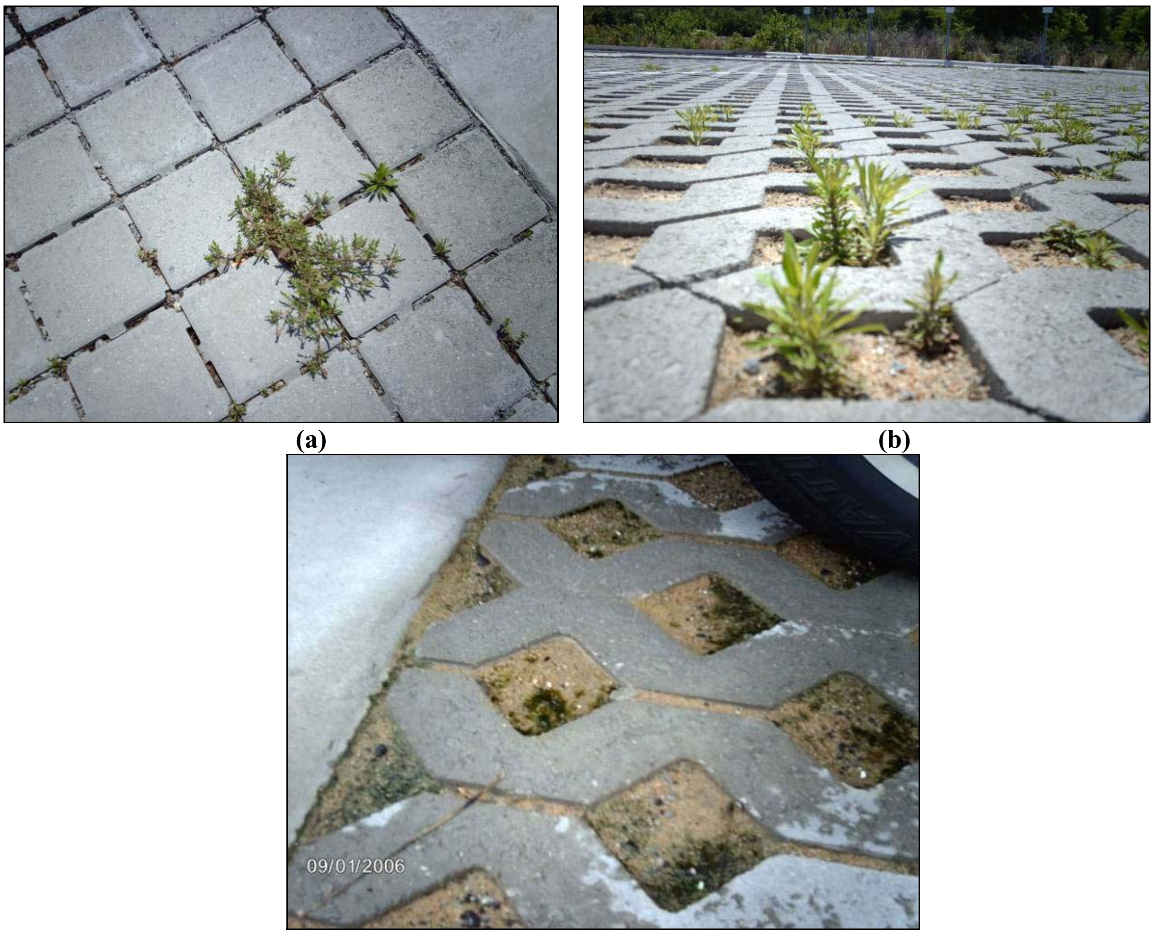
Bacteria	Minimum	Optimum	Maximum
Nitrosomonas	7-7.6	8-8.8	9.4
Nitrobacter	6.6	7.6-8.6	10

The aggregate base course and fill media of the permeable pavement sections provided a habitat for many microorganisms, which have been shown to naturally establish themselves in permeable pavement systems (Newman *et al.*, 2002). By draining the permeable pavements via underdrains, an aerobic environment was created within the upper subsurface aggregate layers of these systems. This allowed for nitrification of NH_4^+ to NO_3^-, as evidenced from the comparison of rain and asphalt concentrations of these parameters to the permeable pavement concentrations. Similar trends have been observed by Bean *et al.,* (2007b) and James and Shahin (1998). Sand media has a higher surface area than aggregate media, which likely provided more area for microorganisms to colonize. Further, it is possible that some assimilation of NH_4-N occurred in the sand-filled pavers before the nitrification process began. This phenomenon could partially explain the lower concentrations of $NO_{2,3}$-N and TN in the CGP cell effluent as compared to other permeable pavements.

Bean *et al.,* (2007b) and James and Shahin (1998) both found a significant decrease in TKN of permeable pavement drainage from inflow concentrations. Results from the Kinston lot were similar for all permeable pavement sections monitored. Assuming no substantial additions of ON, lower TKN concentrations in the permeable pavement drainage is likely due to the observed decrease in NH_4-N concentrations.

For some storms, the concentrations of ON and TN were higher in the permeable pavement cell subsurface drainage than in asphalt runoff or rain. It is unlikely that additional N inputs came from the underlying soils, as the site soils tests revealed low organic matter content. Nitrogen increases in the permeable sections could have resulted from biomass decay in the voids of the permeable pavement or algal nitrogen fixation. Throughout the summer and fall months of 2006, sparse growth of vegetation in the PICP1, CGP, and PICP2 pavement surface voids was observed. Vegetation died during the winter months, but reappeared in late March 2007, and as of July 2007 covered a greater extent of the PICP1, CGP, and PICP2 surfaces than at any time prior. Vegetative growth in PC was not observed at any time during the study. For monitoring purposes, none of the pavements were vacuum swept during this study, which is recommended by the permeable pavement industries. Surface vacuuming might have reduced or eliminated vegetative growth in the PICP surfaces. CGP typically have vegetation (grass) planted in their openings. However, this study examined the hydrologic and water quality response to using only sand in the openings.

Through a visual inspection using surface photographs, coverage was estimated to be 0, 1, 6, and 2% of the total surface area for PC, PICP1, CGP, and PICP2, respectively. Images are shown in Figure 16. Additionally, noticeable algal growth was observed in the CGP section beginning in late summer, 2006. Although vegetation would likely uptake some nutrients for growth, decay of this vegetation would cause some nutrients to be leached back into the system. This phenomenon be most prevalent during winter months (dormant season), but could occur in the summer, particularly during periods of drought.



(a) (b)

(c)

Figure 16. (a) Vegetative growth in PICP2, May 2007. **(b)** Vegetative growth in CGP, May 2007. **(c)** Algal growth in CGP, Sept. 2007

For all sampling sites except the PICP1 and CGP cells, TN concentrations were positively correlated to lot age ($p<0.05$). ON concentrations from all pavement sections were also positively correlated to lot age ($p<0.05$) (Table 11). This correlation is likely related to the increasing growth of vegetation in the cell voids that was observed during the monitoring period, and the associated accumulation of organic matter.

Orthophosphate, Total Phosphorus, and Total Suspended Solids

No significant differences were observed among OPO_4, TP, and TSS concentrations for any samples. The TSS concentrations from the PC, PICP1, and PICP2 cells were positively correlated to asphalt TSS concentrations ($p<0.05$), but no other correlations between similar parameters were observed. For many storms, TP concentrations for the permeable sections were higher than those from asphalt or rain. On three occasions in the winter and early spring months, CGP cell drainage yielded very high concentrations of TP (Figure 17).

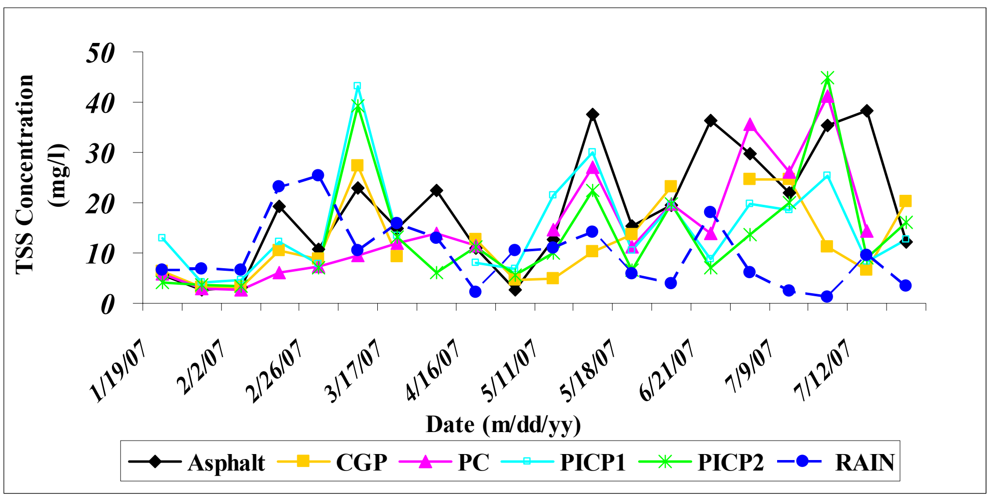


Figure 17. TSS concentrations for all sampling sites.

PICP1 and CGP cell TSS loads were lower than asphalt and rain TSS loads ($p<0.01$). No differences in TP and OPO_4 loads among pavements and rain were observed. TP and TSS loads were positively correlated to rainfall depth for all pavement and rain samples ($p<0.001$).

Unlike nitrogen, phosphorous is relatively immobile in soils because it easily precipitates and binds to soil minerals and organic matter. In saturated conditions, if iron is reduced, phosphorous will be released and become more available (Coyne, 1999). The iron content of the *in situ* soils was not analyzed, but iron deposits were noticed during manual soil sampling at depths of 30 cm. During rainfall events, particularly during winter months when a high water table may have existed, it is suspected that reduced conditions occurred within the lower depths of the permeable pavement aggregate base and subbase layers. As a result, leaching of P from the soil was likely, and an increase in TP concentrations of the permeable pavement subsurface drainage would be expected.

As mentioned previously, an analysis of the phosphorus index of the nearby site soils yielded high values, indicating high P levels in the in-situ soil. In an examination of bioretention cell exfiltrate, Hunt *et al.* (2006) found a significant positive correlation between the P-index of the cell fill media and exfiltrate TP concentrations, and recommended that media with a low P-index be used to reduce effluent phosphorous concentrations. In Kinston, cell drainage was not filtered through the soil; however, soil-water contact did occur along the bottom of the permeable pavement subbases. It is likely that a similar correlation between P-index and subsurface drainage TP concentration may have been observed; however, due to the lack of information regarding the particular soils underlying each pavement section, the relationship could not be explored. The P-index of the sand fill media was never analyzed, but it is possible that additional phosphorus would leach from the sand fill if the sand environment experienced anaerobic conditions. This phenomenon would likely be a temporal effect.

Phosphorous binds readily to soil particles, thus, a relationship between TP and TSS was expected at this site. Significant positive correlations ($p<0.001$) between TP and TSS concentrations did exist in the PICP1 and PICP2 cells ($r=0.85$, $r=0.94$, respectively). Figure 18 details the relationship between TSS and TP concentration for the PICP sections. Conversely, no correlation between TSS and TP parameters was observed in the PC or CGP cells. In general, no differences in TSS were observed among pavements and rain samples. However, due to the observed vegetation establishment in the surface voids of several permeable sections, it is probable that solids were captured in the permeable pavement surface voids, particularly for the CGP and PICP sections. Bean *et al.* (2007b) showed significantly lower TP concentrations in the subsurface drainage of PICP compared to asphalt runoff. Reductions were attributed to precipitation and filtering of soluble phosphorous; however, no significant difference in TSS concentrations was observed. A similar study by

James and Shahin (1998) found little change in TP concentration in runoff passing through permeable pavements.

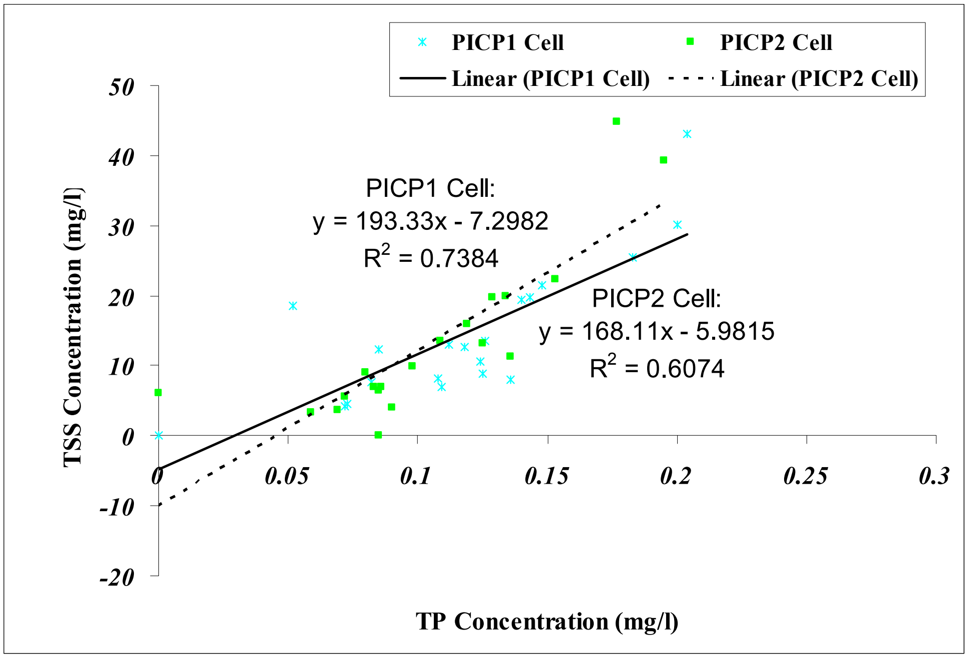


Figure 18. Relationship of TSS and TP concentrations for permeable pavement sections.

Studies have shown removal of TSS by permeable pavements via filtration of solids in the upper layer of the pavements (Pratt *et al*., 1989; Pratt *et al*., 1995). At the Kinston parking lot, the potential for increases in TSS concentrations was present due to drainage contact with the underlying soils, since no barrier was placed between the underdrain and aggregate subbase, and the underlying soils. For all pavement samples except CGP, TSS concentrations were positively correlated to rainfall intensity ($p<0.05$) (Table 11). Higher rainfall intensities could have caused more solids to be disturbed and then drained from the permeable pavement subbases and underlying soils.

A 3.8 mm event occurred on 13 April 2007 that was preceded by 20 days of antecedent dry weather. This event generated the highest TKN and TN concentrations for asphalt, rain, and the PC cell, signifying some relationship between the antecedent dry period and concentrations of these constituents. Further, a 8.6 mm rainfall event on 21 June 2007 preceded by 17 days of dry weather generated the highest $NO_{2,3}$-N concentrations for both the PICP1 and PICP2 cells. Statistically, only PICP1 cell $NO_{2,3}$-N concentrations were positively correlated to antecedent dry period ($p<0.05$) (Table 11). This relationship could be further explored; however, it is expected that a long antecedent dry period would result in greater deposition of pollutants on the pavement surfaces. Smaller rainfall events would produce a first flush of nutrients, resulting in runoff with higher pollutant concentrations to enter the drainage system. The first flush phenomenon has been well documented in studies for heavy metals (He *et al*., 1999, Kim *et al*., 2005), phosphate (Lee and Bang, 2000) and suspended solids concentrations (Lee and Bang, 2000, Wu *et al.*, 1998). Several models have shown that antecedent dry period was an important predictor of first flush concentrations for heavy metals and suspended solids (Kim *et al.*, 2005, Robien *et al.*, 1997, Hewitt and Rashed, 1992).

With respect to water quality, permeable pavements tend to release more pollution during the winter months than in warmer months. During the winter, microbial populations and vegetation cover decrease, both of which affect nutrient filtration and uptake. Additionally, evapo-transpiration rates are considerably lower in the winter, which is expected to decrease retention of water, consequently causing higher nutrient loadings in pavement outflow. For some monitored storm events, permeable pavement outflow was greater than the asphalt runoff volume. As previously discussed, this was possibly the result of a seasonal high water table. If a high water table did exist, leaching of pollutants from the underlying soils would likely occur, leading to increased effluent concentrations of TSS and TP.

The pollutant concentrations observed during this study were typical of parking lot runoff pollutant concentrations measured in previous studies (Table A10 in the appendix). However, stormwater runoff pollutant levels typically reported for impervious areas are often based on measurements from highway and roadway runoff. Studies by Passeport (2005) found, particularly for nitrogen constituents, that pollutant concentrations of parking lot runoff were lower than pollutant levels from highway and roadway runoff. Therefore, the pollutant concentrations reported in this study may be lower than those typically reported for stormwater runoff from impervious areas.

<u>Sand Filtration</u>

As previously mentioned, nitrogen sequestration and removal has been documented in several sand filter studies (Nielsen *et al*., 1993; Barrett 2003). The CGP cell works similarly to a large sand filter by filtering stormwater through a sand media, although characterized by a different geometry and different loading rate per cubic foot of sand. Of all permeable pavements evaluated, the CGP cell subsurface drainage had the lowest mean TN concentrations, and significantly lower $NO_{2,3}$-N concentrations ($p<0.05$). These reductions were not reflected for TP concentrations, and spikes in TP concentration were observed from the CGP cell, particularly in winter and spring months. Phosphorous was likely leached from the underlying soils, where as nitrogen inputs likely came from the pavement surface (rainfall or biomass decay), which were filtered through the sand fill media. With the likely addition of phosphorus to the subsurface drainage through phosphorus leaching from the soil, any filtration of phosphorus in the CGP sand fill was not distinguishable.

Pollutant Mass Balance.

TN, TP, and TSS cumulative pollutant mass balance graphs were generated for each permeable pavement section. Graphs for the PICP1 cell are shown in Figures 19-21, and all other permeable pavement sections are included in the Appendix. For all parameters, pollutant inflow was assumed to be the asphalt runoff loads. Pollutant storage was calculated by subtracting permeable pavement outflow loads from inflow loads. A positive storage slope indicated pollutant storage, where a negative storage slope indicated pollutant export. TN storage was greatest in the PICP1 cell, followed by the CGP cell, but seemed to be negligible in all other permeable sections. TP was exported from all sections. All permeable pavement sections were effective in storing TSS.

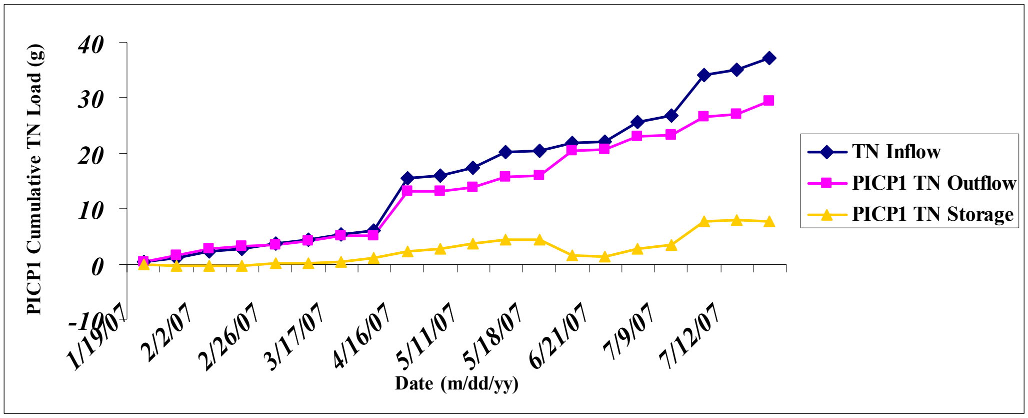


Figure 19. Cumulative TN mass balance for PICP1 cell.

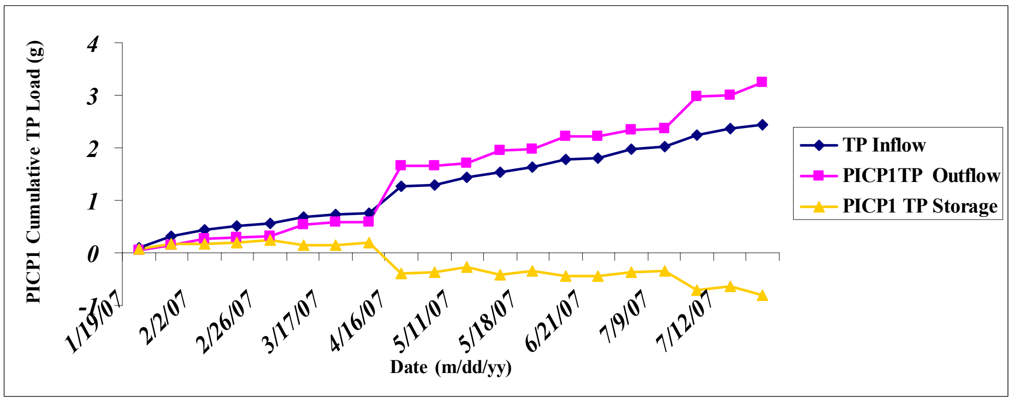


Figure 20. Cumulative TP mass balance for PICP1 cell.

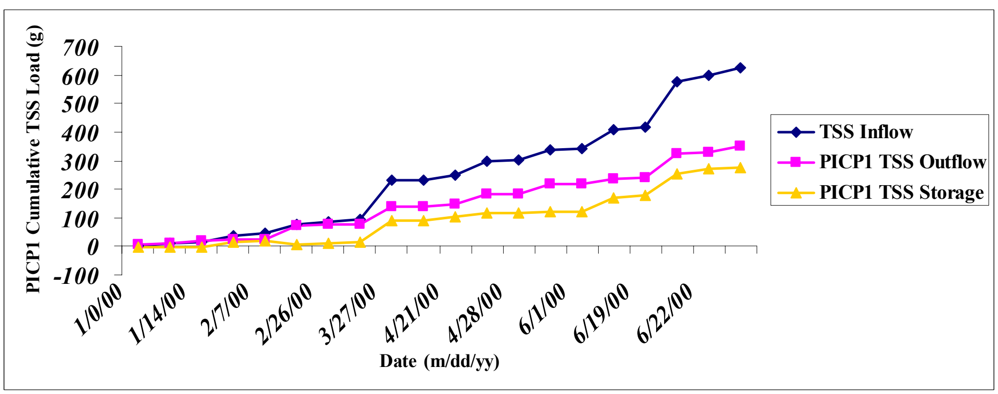


Figure 21. Cumulative TSS mass balance for PICP1 cell.

The PICP1 section had the highest rate of TSS storage. Over the 7 month water quality monitoring period, the PICP1 section stored roughly 45% of the estimated influent TSS. At this rate, assuming bulk density of 2.65 g/cm^3, the permeable pavement coarse aggregate layer in this section would clog roughly 0.003% over ten years.

At this time, few differences among permeable pavements with respect to pollutant reduction performance can be identified. Overall, similar trends among permeable pavement subsurface drainage quality were observed. The CGP cell appears to demonstrate the greatest TN improvements. PICP1 often had lower loadings, due to decreased volume (additional storage).

CONCLUSIONS

Hydrology

- With respect to runoff reduction and peak flow mitigation, all pavements performed substantially and significantly better than asphalt ($p<0.001$). Although hydrologic differences among the permeable pavements did exist, they were small in comparison to the overall improvements from asphalt.
- The PICP1 and CGP cells were able to store up to 6 mm of rainfall without yielding any outflow. Further, outflow from these two pavements exhibited the lowest total volumes of stormwater, the greatest peak flow reductions, and longest times to peak. It is likely that the response of the PICP1 cell was due to an increased subsurface storage volume resulting from an elevated outlet pipe; whereas, the CGP cell response was likely an effect of the sand fill media.
- The sand fill of the CGP cell likely retained the greatest amount of runoff, and was most effective in mitigating peak rainfall intensities. Sand fill, which has been viewed as a detriment because of increased surface runoff, appears to have the benefit of holding additional water, which then slowly leaks or evaporates.
- Although it functioned well with regard to total stormwater volume reduction, CGP yielded the greatest volume of surface runoff among permeable pavements ($p>0.01$). This is likely due to the relatively low hydraulic conductivity of the sand fill media compared to aggregate fill, and the resulting lower surface infiltration rate of the CGP section.
- Paver geometry appeared to influence surface runoff generation more than the percent of open surface void space. The PICP2 section, with a an 8.5% open surface void

space generated less surface runoff that the PICP1 section with 12.9% open surface void space.

- The majority of outflow resulting from the permeable pavement sections was in the form of subsurface drainage. For storms with rainfall depths less than 50 mm, surface runoff comprised less than 6% of the total outflow volume from the CGP cell, and less than 2% for all other permeable pavement types. It is likely that a seasonal high water table contributed to the total outflow volumes of several permeable pavement sections, particularly during the winter months.
- From a design perspective, subsurface flow rates can be relatively easy to control (by creating a sump or restricting flow). Thus, the vast majority of flow leaving a permeable pavement cell is subject to design modification.
- Rainfall intensity was the best predictor variable of permeable pavement surface runoff generation and time to peak. Rainfall depth was the best predictor of permeable pavement total outflow volumes and peak flow reductions relative to asphalt.
- During large rainfall events (>50 mm), permeable pavement sections acted similarly with respect to hydrology. In general, hydrologic differences among pavements were small; each type performed similarly.

Water Quality

- All pavements were effective in buffering acidic rainfall pH, with permeable pavements providing a greater buffering capacity than asphalt ($p<0.01$). The PC cell had the highest pH of all pavements ($p<0.01$). Permeable pavement pH values were such that the leaching of metals through the pavements would not be expected.
- Permeable pavement drainage tended to have lower NH_4-N and TKN concentrations than asphalt runoff and rain. With the exception of CGP cell drainage, permeable pavements had higher $NO_{2,3}$-N concentrations, a probable result of nitrification.
- The CGP cell had lower $NO_{2,3}$-N concentrations than other permeable pavements ($p<0.01$). CGP also had the lowest mean TN concentrations, although results were not significantly lower than those of asphalt. The possible N removal is similar to that of sand filter research, not surprising considering the composition of CGP. CGP

appears to improve TN concentrations and may be considered for consideration for concentration reduction credit (removal efficiency) by states like North Carolina.

- TP and TSS concentrations were not different among various pavement sections. Because the permeable pavement cells were not lined, it is possible, and likely, that TSS and TP were leached from the underlying soils.

RECOMMENDATIONS AND FURTHER RESEARCH

Presented in the following are recommendations that pertain to both future research and permeable pavement design. The recommendations are listed by content area and are not separated by whether they target design or research.

Monitoring limitations prevented some hydrologic factors from being studied in depth. In particular, analyses of permeable pavement total outflow volumes were affected. Despite efforts to characterize the drainage systems associated with the sections, the exact configuration of the permeable pavement subbase drainage system was unknown; therefore, the extent to which stormwater was stored in each permeable pavement section, the degree to which leaking occurred between permeable pavements, and the impact of groundwater intrusion into the cells via a high water table were unknown.

When designing permeable pavements, a designer has little control over the climate profile and the *in situ* soils. However, the designer does have flexibility in the design and layout of the subbase and underdrain configuration (if necessary). Based on the results of this study, consideration could be given to modifying the permeable pavement design to suit a given location. When the installation of underdrains is recommended or necessary, (e.g. a low pre-construction infiltration rate of the *in situ* soils), design of the subbase can be altered to increase detention time within the pavement subbase by raising the perforated underdrain pipe elevations. This could allow for pre-development infiltration to be more closely mimicked and decrease total outflow volumes. Further, time to peak can be delayed during small to medium rainfall events by creating an internal storage zone. Although unintentional, the elevated outlet design of the PICP1 section resulted in lower outflow volumes and reduced peak flow rates. The opportunity to incorporate sumps at the bottom of permeable pavement cells should be further investigated.

In future experiments, separating the permeable pavement subbase from the *in situ* soils would isolate the effects of the permeable pavement system by eliminating any influence of the soils on water quality. The design of this particular experiment limited the full understanding of water quality and hydrologic response, because the exact mechanisms occurring at the aggregate base/soil interface were unknown. The monitoring design was similar to what is typically installed in many applications, and therefore represents processes that practically occur.

Due to the fact that interaction between the permeable pavement aggregate subbase layer and the *in-situ* soils existed, it is suspected that TP and TSS leached from the permeable pavement cells. In order to reduce TSS and TP concentrations, a liner should be installed between the permeable pavement subbase and the underlying soils if minimal or no infiltration is expected. An impermeable liner would eliminate the possibility of infiltration into the underlying soils, but would be less susceptible to clogging than a permeable liner. If a high water table existed, the impermeable liner would prevent groundwater flow into the system. Another option would be to raise the drainage pipe a few inches above the underlying soils, encasing it in a washed aggregate layer. This would potentially allow TSS and TP to settle out in the lower regions of the subbase.

If possible, more data should be collected on the lot's response to larger rainfall events, such as the 10- or 25-year storms. Assuming no exfiltration, the lot was capable of storing 90 mm of rainfall, but the monitoring design was set up to capture 50 mm of rainfall depth or less. The lot performed well with respect to surface runoff and peak flow reductions during small- to medium-sized storms, and results indicate that these reductions were reflected for even larger storm events, although to a lesser magnitude. It would be of interest to monitor performance during larger flooding events to see if results change. Several large events did occur during the period of study; however, errors in equipment often prevented collection of accurate data.

Further research should be performed to better understand the mechanisms of phosphorus leaching through this system. Currently, analyses are being conducted on the site soils and pavement materials in an attempt to identify additional sources of phosphorus in the pavement systems. Due to setbacks with the initial laboratory analysis, initial water quality responses could not be fully understood. In order to better understand the water quality effects of the four different types of permeable pavements, samples from more storm events are necessary.

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APPENDIX

SOIL TESTS

Soil sampling locations surrounded the parking lot in areas both disturbed (Fill1, Fill2, and Fill3) and undisturbed (Kins1-6) during lot construction (Figure A1).

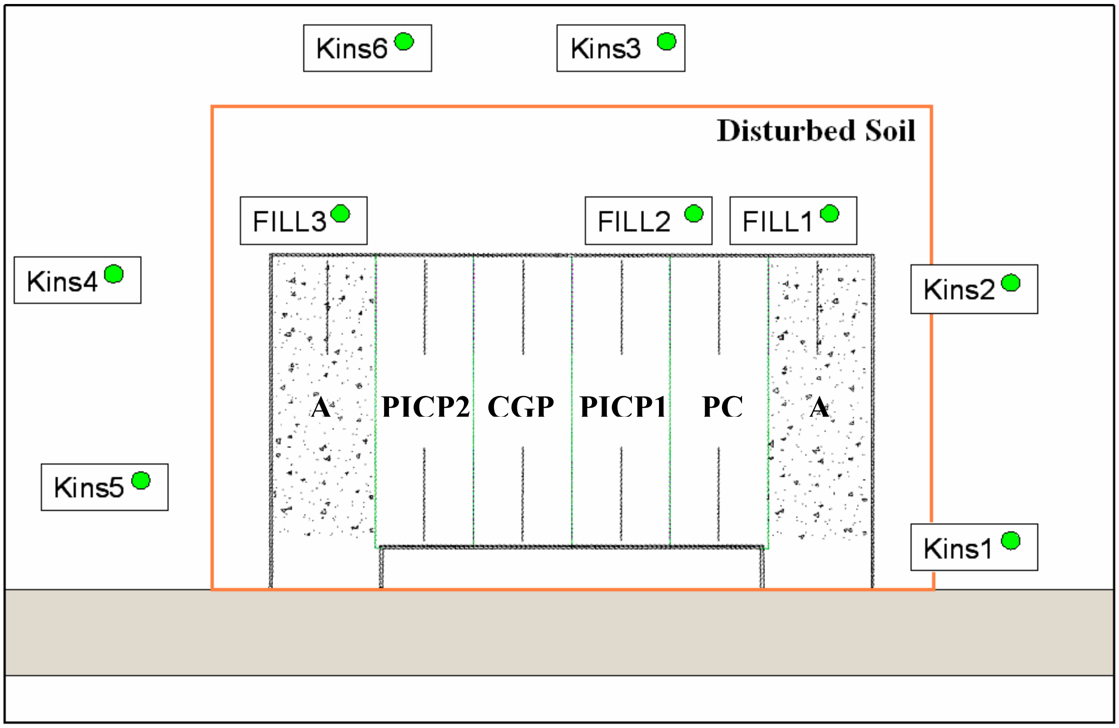


Figure A1. Soil test locations.

A summary of the results are listed in Table A1. The percent humic matter (%HM) describes the organic content of the soil. The weight-to-volume ratio (W/V) can be a good indicator of soil texture, with sands typically weighing more than 1.5 g/cm^3, and silts and clays near 1 g/cm^3 (Hardy, 2003). Samples collected from the undisturbed soils furthest from the Public Service Complex Building (Kins4, Kins5, Kins6) had the highest organic matter contents (%HM>3%) and lowest W/V ratios. Cation exchange capacity (CEC) is a measure of sites available in the soil for cation exchange, and the percent base saturation (%BS) describes how many of these available sites are filled by Ca and Mg and K ions.

Table A1. Soil test results.

Sample ID	Soil Type	pH	HM%	W/V	CEC	BS%	P-I	Zn-I	Cu-I
Kinston 1	MIN	6.3	0.6	1.26	6.9	88	77	18	23
Kinston 2	MIN	5	1.25	1.18	4.6	57	68	11	16
Kinston 3	MIN	5	1.94	1.16	3.6	44	63	15	13
Kinston 4	M-O	5	4.95	1.05	4.8	58	133	16	17
Kinston 5	M-O	4.9	3.98	1.06	4.9	35	71	7	12
Kinston 6	MIN	4.8	3.19	1.08	5.4	44	53	12	13
Fill 1	MIN	6.1	1.31	1.15	7.2	89	61	61	28
Fill 2	MIN	5.1	1.55	1.20	4.3	53	111	25	45
Fill 3	MIN	6	0.66	1.13	4.3	91	66	28	22
AVG	-	**5.36**	**2.16**	**1.14**	**5.11**	**62.11**	**78.11**	**21.44**	**21.00**

MIN – *mineral soil class*, M-O- *mineral organic soil class*, %HM – *percent humic matter,* W/V- *weight per volume ratio*, CEC – *cation exchange capacity expressed in meq/100 cm³,* BS% - *percentage of CEC occupied by the basic cations calcium (Ca), magnesium (Mg), and potassium (K),* P-I – *phosphorus (P) index,* Zn-I – *zinc (ZN) index,* Cu-I – *copper (Cu) index* (Hardy, 2003)

STORM CHARACTERISTICS

Table A2. Characteristics of storm events.

DATE	Rainfall (mm)	Peak Intensity (mm/hr)	Dry period (hr)	Age of Lot (days)	Season
6/5/2006	7.4	6	63.5	118	Spring
6/11/2006	18	20	65.5	124	Spring
6/14/2006	20.3	13	28.25	127	Spring
6/21/2006	6.1	12	165.25	135	Summer
6/25/2006	45.7	20	87.5	139	Summer
7/3/2006	32.8	37	147.25	146	Summer
7/6/2006	14.7	17	52.5	149	Summer
7/15/2006	13.2	40	213.75	159	Summer
7/23/2006	14.7	39	173.75	167	Summer
7/25/2006	5.6	9	34.25	168	Summer
7/27/2006	5.6	8	45.25	170	Summer
8/5/2006	13.5	18	202.5	180	Summer
8/11/2006	13	11	107	185	Summer
8/21/2006	30	33	206.25	195	Summer
8/31/2006 [a]	182.6	44	171.25	205	Summer
9/5/2006	25.9	33	89.5	211	Summer
9/13/2006	10.2	3	128	218	Summer
9/19/2006	26.9	46	122	225	Summer
10/7/2006	20.6	21	183.5	242	Fall
10/17/2006	11.4	7	185	253	Fall
10/22/2006	4.6	3	104	258	Fall
10/27/2006	49.3	22	114.25	263	Fall
11/7/2006	30.2	10	246	274	Fall
11/12/2006	18.5	5	76.25	278	Fall
11/16/2006	14	2	79	283	Fall
11/22/2006 [b]	135*	-	76	288	Fall
12/1/2006	4.1	1	145.25	297	Fall
12/22/2006	37.3	21	240	319	Winter
12/25/2006	31.5	17	69.25	322	Winter
1/1/2007	11.7	18	158	329	Winter
1/6/2007	15.2	28	79.5	333	Winter
1/18/2007	12	4	192.5	345	Winter
1/22/2007	24.4	7	58.75	349	Winter
1/28/2007	6.9	3	138	355	Winter
2/1/2007	25.7	8	86.75	359	Winter
2/13/2007	13.7	2	268.5	372	Winter
2/25/2007	8.6	3	260.75	383	Winter
3/1/2007	18.8*	12	93	387	Winter
3/16/2007	14.2	8	144	402	Winter
4/12/2007	3.81	5	480	429	Spring
4/16/2007	88.9	34	38.5	433	Spring
5/4/2007	30.48	19	440.25	451	Spring
5/6/2007	3.05	5	33	453	Spring
5/8/2007	13.72	18	46	455	Spring
5/12/2007	25.9	45	71.25	459	Spring

Table A2. (continued).

DATE	Rainfall	Peak Intensity	Dry period	Age of Lot	Season
5/17/2007	11.18	7	85.75	464	Spring
6/3/2007	45.7	20	358	481	Spring
6/5/2007	4.06	16	49.5	483	Spring
6/20/2007	8.64	6	346.5	498	Spring
6/24/2007	28.19	35	95	502	Summer
6/29/2007	46.74	47	93	507	Summer
7/6/2007	28.45	35	136.75	514	Summer
7/9/2007	8.13	21	41.5	517	Summer
7/10/2007	51.56	60	24	518	Summer
7/11/2007	7.87	24.384	24	519	Summer
7/17/2007	29.46	29.464	24	525	Summer

[a] Tropical Storm Ernesto. Storm excluded from overall analyses

[b] Late November 2006 storm. Storm excluded from overall analyses

* Rainfall estimated from manual rain gage

HYDROLOGIC DATA

Table A3. Surface runoff volumes.

DATE	Rainfall (mm)	Peak Intensity (mm/hr)	Runoff Depth (mm)				
			Asp	*PC*	*PICP1*	*CGP*	*PICP2*
6/5/2006	7.4	6	2.27	0.00	0.05	0.14	0.00
6/11/2006	18	20	7.85	0.03	0.09	1.11	0.06
6/14/2006	20.3	13	8.08	0.02	0.13	0.91	0.07
6/21/2006	6.1	12	1.53	0.00	0.04	0.05	0.00
6/25/2006	45.7	20	26.28	0.08	0.30	0.91	0.26
7/3/2006	32.8	37	13.43	0.05	0.22	0.85	0.26
7/6/2006	14.7	17	4.63	0.01	0.05	0.18	0.06
7/15/2006	13.2	40	6.31	0.04	0.11	0.18	0.07
7/23/2006	14.7	39	6.74	0.09	0.11	0.22	0.21
7/25/2006	5.6	9	0.87	0.00	0.01	0.05	0.01
7/27/2006	5.6	8	0.97	0.00	0.01	0.04	0.00
8/5/2006	13.5	18	5.17	0.01	0.10	0.18	0.04
8/11/2006	13	11	4.74	0.00	0.08	0.13	0.04
8/21/2006	30	33	14.82	0.04	-	0.58	0.14
8/31/2006 [a]	182.6	44	-	-	-	-	-
9/5/2006	25.9	33	11.86	0.08	-	0.92	-
9/13/2006	10.2	3	3.31	0.00	0.02	0.29	-
9/19/2006	26.9	46	14.82	0.05	0.22	0.60	-
10/7/2006	20.6	21	6.88	0.01	0.09	-	0.04
10/17/2006	11.4	7	5.40	0.00	0.04	0.02	0.03
10/22/2006	4.6	3	2.32	0.00	0.05	0.03	0.00
10/27/2006	49.3	22	33.26	0.05	0.44	1.42	0.04
11/7/2006	30.2	10	28.43	0.09	0.63	-	0.28
11/12/2006	18.5	5	4.62	0.00	0.08	0.02	0.00
11/16/2006	14	2	3.78	0.09	-	0.15	0.04
11/22/2006 [b]	135	-	274.35	36.85	149.75	179.36	60.08
12/1/2006	4.1	1	1.35	0.00	0.00	0.11	0.00
12/22/2006	37.3	21	12.51	0.36	0.60	1.09	0.21
12/25/2006	31.5	17	10.83	0.05	0.65	0.74	0.18
1/1/2007	11.7	18	3.83	0.00	0.12	0.32	-
1/6/2007	15.2	28	4.43	0.01	0.12	-	0.22
1/18/2007	12	4	1.29	0.00	0.00	0.00	0.32
1/22/2007	24.4	7	5.65	0.03	0.13	0.02	0.06
1/28/2007	6.9	3	0.73	0.00	0.04	0.02	0.00
2/1/2007	25.7	8	5.44	-	0.13	0.28	0.22
2/13/2007	13.7	2	5.26	-	0.12	-	0.33
2/25/2007	8.6	3	2.97	0.00	0.02	0.01	0.00
3/1/2007	18.8	12	11.62	0.03	0.08	0.31	0.13
3/16/2007	14.2	8	6.60	0.00	0.00	0.03	0.04
4/12/2007	3.81	5	1.81	-	0.00	0.00	0.00
4/16/2007	88.9	34	76.14	-	0.00	0.87	0.98
5/4/2007	30.48	19	28.79	-	0.00	0.14	-
5/6/2007	3.05	5	3.11	-	0.00	0.00	-
5/8/2007	13.72	18	12.63	-	0.00	0.14	-
5/12/2007	25.9	45	11.54	-	-	1.78	-
5/17/2007	11.18	7	1.89	-	-	0.05	-

Table A3. (continued).

DATE	Rainfall (mm)	Peak Intensity (mm/hr)	Runoff Depth (mm)				
			Asp	*PC*	*PICP1*	*CGP*	*PICP2*
6/3/2007	45.7	20	17.41	-	-	0.38	0.25
6/5/2007	4.06	16	1.39	-	-	0.05	0.02
6/20/2007	8.64	6	0.66	-	-	0.00	-
6/24/2007	28.19	35	19.58	-	-	0.06	-
6/29/2007	46.74	47	22.53	-	-	1.57	-
7/6/2007	28.45	35	20.99	-	-	1.14	-
7/9/2007	8.13	21	5.30	-	-	0.43	-
7/10/2007	51.56	60	39.89	-	-	12.60	-
7/11/2007	7.87	24.384	4.93	0.00	0.02	0.70	0.01
7/17/2007	29.46	29.464	21.12	0.17	0.66	1.17	0.21

[a] Tropical Storm Ernesto. Storm excluded from overall analyses
[b] Late November 2006 storm. Storm excluded from overall analyses
* Rainfall estimated from manual rain gage

Table A4. Adjusted surface runoff volumes (values subtracted for gutters).

DATE	Rainfall (mm)	Peak Intensity (mm/hr)	Runoff Depth (mm) *Asp*	*PC*	*PICP1*	*CGP*	*PICP2*
6/5/2006	7.4	6	3.87	0	0	0.03	0
6/11/2006	18	20	12.48	0	0	0.82	0
6/14/2006	20.3	13	14.16	0	0	0.57	0
6/21/2006	6.1	12	2.90	0	0	0	0
6/25/2006	45.7	20	41.28	0	0	0.15	0
7/3-4/2006	32.8	37	28.42	0	0	0.31	0
7/6/2006	14.7	17	11.42	0	0	0	0
7/15/2006	13.2	40	9.21	0	0	0	0
7/23/2006	14.7	39	10.54	0	0	0	0
7/25/2006	5.6	9	2.45	0	0	0	0
7/27/2006	5.6	8	3.45	0	0	0	0
8/5/2006	13.5	18	4.61	0	0	0	0
8/11/2006	13	11	6.83	0	0	0	0
8/21/2006	30	33	21.26	0	-	0.08	0
9/5/2006	25.9	33	17.74	0	-	0.49	-
9/13/2006	10.2	3	2.82	0	0	0.12	-
9/19/2006	26.9	46	21.32	0	0	0.16	-
10/7/2006	20.6	21	14.75	0	0	-	0
10/17/2006	11.4	7	5.47	0	0	0	0
10/22/2006	4.6	3	2.41	0	0	0	0
10/27/2006	49.3	22	46.89	0	0	0.60	0
11/12/2006	18.5	5	14.72	0	0	0	0
11/16/2006	14	2	10.94	0	0	0	0
11/22/2006	135	-	371.19	34.60	147.51	177.11	57.84
12/1/2006	4.1	1	0.56	0	0	0.04	0
12/22/2006	37.3	21	28.26	0	0	0.48	0
12/25/2006	31.5	17	25.03	0	0.12	0.21	0
1/1/2007	11.7	18	7.24	0	0	0.13	-
1/6/2007	15.2	28	11.00	0	0	-	0
1/18/2007	10.7	4	5.63	0	0	0	0.15
1/22/2007	24.4	7	21.33	0	0	0	0
1/28/2007	6.9	3	2.64	0	0	0	0
2/1/2007	25.7	8	15.03	0	0	0	0
2/13/2007	13.7	2	10.18	0	0	-	0.10
2/25/2007	8.6	3	5.30	0	0	0	0
3/1/2007	18.8	12	11.31	0	0	0	0
3/16/2007	14.2	8	6.37	0	0	0	0
4/12/2007	3.81	5	1.75	-	0	0	0
5/4/2007	30.48	19	28.29	-	0	0	-
5/6/2007	3.05	5	3.06	-	0	0	-
5/8/2007	13.72	18	12.41	-	0	0	-
5/12/2007	25.9	45	11.11	-	-	1.35	-
6/29/2007	46.74	47	21.75	-	-	0.80	-
7/6/2007	28.45	35	20.52	-	-	0.67	-
7/9/2007	8.13	21	5.17	-	-	0.30	-
7/10/2007	51.56	60	39.03	-	-	11.74	-
7/11/2007	7.87	24.384	4.81	0	0	0.57	0
7/17/2007	29.46	29.464	20.63	0	0.17	0.68	0

Table A5. Outflow volumes.

DATE	Rainfall	VOLUME RAIN (l)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)
	(mm)	(l)	*Asphalt*	*----PC Cell-----*		*---- PICP1 Cell ---*		*----CGP Cell)---*		*----PICP2 Cell----*	
6/5/2006	7.4	825	3.99	3.02	0.00	1.26	0.05	0.02	0.14	2.48	0.00
6/11/2006	18	2007	12.78	11.67	0.03	4.77	0.09	3.52	1.11	10.13	0.06
6/14/2006	20.3	2263	14.50	17.29	0.02	9.87	0.13	10.62	0.91	16.29	0.07
6/21/2006	6.1	680	3.00	1.43	0.00	0.19	0.04	0.00	0.05	1.96	0.00
6/25/2006	45.7	5096	42.05	23.04	0.08	23.02	0.30	18.67	0.91	41.76	0.26
7/3/2006	32.8	3657	28.97	21.09	0.05	19.75	0.22	17.11	0.85	25.79	0.26
7/6/2006	14.7	1639	11.66	5.77	0.01	5.16	0.05	3.06	0.18	9.26	0.06
7/15/2006	13.2	1472	9.43	7.54	0.04	4.65	0.11	1.17	0.18	8.66	0.07
7/23/2006	14.7	1639	10.78	6.42	0.09	4.92	0.11	1.55	0.22	11.18	0.21
7/25/2006	5.6	624	2.55	1.00	0.00	0.00	0.01	0.11	0.05	2.45	0.01
7/27/2006	5.6	624	3.53	1.52	0.00	0.00	0.01	0.00	0.04	2.34	0.00
8/5/2006	13.5	1505	4.83	4.53	0.01	4.03	0.10	1.26	0.18	7.52	0.04
8/11/2006	13	1450	7.04	4.77	0.00	4.42	0.08	1.76	0.13	8.74	0.04
8/21/2006	30	3345	21.76	18.97	0.04	13.89	-	11.31	0.58	20.83	0.14
8/31/2006	182.6		-	-	-	-	-	-	-	-	-
9/5/2006	25.9	2888	18.17	19.12	0.08	14.32	-	14.16	0.92	21.62	-
9/13/2006	10.2	1137	2.99	4.68	0.00	0.68	0.02	0.71	0.29	4.93	-
9/19/2006	26.9	2999	21.76	21.47	0.05	14.88	0.22	13.00	0.60	21.65	-
10/7/2006	20.6	2297	15.09	12.40	0.01	6.47	0.09	6.79	-	15.00	0.04
10/17/2006	11.4	1271	5.65	7.19	0.00	2.89	0.04	2.36	0.02	7.66	0.03
10/22/2006	4.6	513	2.48	2.48	0.00	0.00	0.05	0.55	0.03	3.08	0.00
10/27/2006	49.3	5497	47.71	48.77	0.05	38.12	0.44	41.01	1.42	47.45	0.04
11/7/2006	30.2	3367	31.02	32.96	0.09	22.50	0.63	25.63	-	-	0.28
11/12/2006	18.5	2063	15.02	15.44	0.00	8.98	0.08	10.57	0.02	16.69	0.00
11/16/2006	14	1561	11.18	12.15	0.09	6.72	-	10.29	0.15	12.55	0.04
11/22/2006[b]	135*	15053*	373.44	362.65	36.85	338.92	149.75	336.16	179.36	365.93	60.08
12/1/2006	4.1	457	0.62	2.15	0.00	0.00	0.00	0.43	0.11	2.56	0.00

Table A5. (continued)

DATE	Rainfall	VOLUME RAIN (l)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)	Drainage Vol (mm)	Runoff Vol (mm)
	(mm)	(l)	*Asphalt*	*----Cell 1 (PC)-----*		*----Cell 2 (PICP1)---*		*----Cell 3 (CGP)---*		*----Cell 4 (PICP2)----*	
12/22/2006	37.3	4159	28.88	31.41	0.36	25.85	0.60	24.52	1.09	30.66	0.21
12/25/2006	31.5	3512	25.55	30.14	0.05	24.33	0.65	26.03	0.74	31.29	0.18
1/1/2007	11.7	1305	7.44	8.90	0.00	5.26	0.12	3.94	0.32	10.94	-
1/6/2007	15.2	1695	11.25	14.93	0.01	10.55	0.12	9.44	-	16.36	0.22
1/18/2007	10.7	1193	5.81	6.74	0.00	3.28	0.00	5.30	0.00	9.34	0.32
1/28/2007	6.9	769	2.75	3.45	0.00	0.22	0.04	2.76	0.02	5.00	0.00
2/1/2007	25.7	2866	15.45	21.43	-	12.61	0.13	22.73	0.28	24.20	0.22
2/13/2007	13.7	1528	10.40	8.79	-	4.80	0.12	6.93	-	9.78	0.33
2/25/2007	8.6	959	5.44	4.36	0.00	1.33	0.02	1.35	0.01	-	0.00
3/1/2007	18.8	2096	11.62	14.10	0.03	9.31	0.08	14.21	0.31	15.53	0.13
3/16/2007	14.2	1583	6.60	6.82	0.00	3.96	-	3.76	0.03	7.61	0.04
4/12/2007	3.81	425	1.81	0.30	0.00	0.00	0.00	0.00	0.00	0.61	0.00
4/16/2007	88.9	9912	76.14	57.57	-	48.09	0.00	61.38	0.87	57.21	0.98
5/4/2007	30.48	3399	28.79	13.30	0.00	10.09	0.00	12.87	0.14	13.54	0.00
5/6/2007	3.05	340	3.11	0.49	0.00	0.00	0.00	1.28	0.00	0.78	0.00
5/8/2007	13.72	1530	12.63	4.36	0.05	2.57	0.00	5.56	0.14	5.57	0.05
5/12/2007	25.9	2888	11.54	14.63	-	10.79	-	6.04	1.78	14.64	-
5/17/2007	11.18	1247	1.89	3.15	0.00	1.18	0.00	0.47	0.05	3.06	0.00
6/3/2007	45.7	5096	17.41	22.59	0.30	16.67	0.30	14.75	0.38	20.35	0.25
6/5/2007	4.06	453	1.39	1.21	0.00	0.00	0.00	0.34	0.05	1.01	0.02
6/20/2007	8.64	963	0.66	1.89	0.00	0.41	0.00	0.00	0.00	1.51	0.00
6/24/2007	28.19	3143	19.58	13.95	0.05	7.53	0.05	8.36	0.06	12.75	0.05
6/29/2007	46.74	5212	22.53	22.14	0.50	18.22	0.50	13.57	1.57	20.42	0.50
7/6/2007	28.45	3172	20.99	13.72	0.70	10.92	0.70	14.00	1.14	12.96	0.70
7/9/2007	8.13	906	5.30	3.10	0.30	1.55	0.30	1.52	0.43	3.02	0.30
7/10/2007	51.56	5749	39.89	33.92	-	29.81	-	17.98	12.60	32.25	-
7/11/2007	7.87	878	4.93	3.63	0.00	3.26	0.02	1.38	0.70	4.26	0.01
7/17/2007	29.46	3285	21.12	18.45	0.17	17.90	0.66	17.22	1.17	18.06	0.21

Table A6. Peak flows and delays.

DATE	A1	PCE Cell		PICP1 Cell		CGP Cell		PICP2 Cell	
	Peak (l/s)	Peak (l/s)	Delay (hr)	Peak (l/s)	Delay (hr)	Peak (l/s)	Delay (hr)	Peak (l/s)	Delay (hr)
9/25/2006	0.037	0.001	1.87	0.000		0.000		0.000	
10/8/2006	1.304	0.357	0.20	0.285	0.20	0.273	0.27	0.483	0.17
10/17/2006	0.281	0.052	0.23	0.037	0.40	0.018	0.50	0.077	0.17
10/22/2006	0.085	0.009	2.63	0.000		0.001	7.13	0.016	1.10
10/28/2006	0.916	0.691	0.02	0.653	0.02	0.562	0.02	0.701	0.02
11/8/2006	0.533	0.360	0.43	0.309	0.40	0.355	0.50		
11/12/2006	0.523	0.147	0.17	0.081	0.30	0.096	0.27	0.174	0.10
11/16/2006	0.564	0.183	2.30	0.133	2.33	0.166	2.40	0.208	2.30
12/1/2006	0.192	0.005	8.07	0.000		0.001		0.018	7.00
1/1/2007	1.094	0.223	0.13	0.221	0.13	0.148	0.23	0.404	0.07
1/6/2007	1.240	0.799	0.03	0.805	0.03	0.467	0.20	0.985	0.03
1/18/2007	0.064	0.039	0.83	0.030	1.00	0.026	1.10	0.056	0.27
1/22/2007	0.298	0.168	1.83	0.143	1.87	0.168	1.90	0.171	1.80
1/28/2007	0.090	0.017	0.70	0.002	3.13	0.013	0.63	0.038	0.50
2/1/2007	0.248	0.154	0.10	0.094	0.30	0.133	0.20	0.183	0.10
2/13/2007	0.584	0.167	0.17	0.123	0.17	0.084	0.33	0.195	0.13
2/25/2007	0.342	0.052	0.00	0.010	3.07	0.005	3.50		
3/1/2007	1.418	0.827	0.10	0.844	0.07	0.735	0.20	1.097	0.07
3/16/2007	0.971	0.117	0.17	0.083	0.20	0.017	0.97	0.158	0.13
4/12/2007	0.170	0.001	5.00	0.000		0.000		0.002	2.50
4/16/2007	1.686	1.399	0.00	1.399	0.00	1.340	0.00	1.446	0.00
5/4/2007	1.111	0.397	0.07	0.368	0.07	0.338	0.50	0.422	0.07
5/6/2007	0.344	0.007	0.80	0.000		0.004	1.10	0.013	0.53
5/8/2007	1.472	0.203	0.20	0.177	0.20	0.185	0.30	0.321	0.17
5/12/2007	1.936	0.817	0.17	0.672	0.17	0.340	0.50	1.004	0.03
5/17/2007	0.208	0.052	4.37	0.022	4.90	0.004	5.20	0.065	4.33
6/3/2007	1.349	0.457	0.07	0.432	0.13	0.433	0.07	0.588	0.03
6/5/2007	0.740	0.029	0.27	0.000		0.002	0.43	0.053	0.20
6/20/2007	0.116	0.048	0.60	0.008	1.37	0.000		0.043	0.63
6/24/2007	1.949	0.655	0.10	0.473	0.57	0.437	0.63	0.710	0.10
6/29/2007	1.691	0.729	0.17	0.677	0.17	0.505	0.30	0.898	0.17
7/6/2007	2.613	0.907	1.47	0.918	1.47	0.695	1.53	1.007	1.47
7/9/2007	1.855	0.224	0.10	0.054	0.33	0.075	0.30	0.321	0.00
7/10/2007	4.391	1.948	0.27	1.937	0.27	0.718	0.43	2.142	0.00
7/11/2007	1.362	0.196	0.10	0.199	0.20	0.029	0.60	0.393	0.10
7/17/2007	1.525	0.89	0.07	0.974	0.07	0.876	0.13	0.960	0.07

WATER QUALITY RESULTS

Table A7. Statistical summary of parameter concentrations

Variable	N	Mean	Median	Std Dev	Minimum	Maximum
			TKN (mg/l)			
A1	14	0.793	0.664	0.508	0.192	1.847
A2	12	0.828	0.737	0.594	0.166	1.992
PC	14	0.517	0.467	0.145	0.303	0.809
PICP1	14	0.389	0.331	0.208	0.000	0.667
CGP	14	0.390	0.343	0.212	0.000	0.838
PICP2	13	0.374	0.342	0.138	0.148	0.628
RAIN	14	0.924	0.767	0.757	0.168	2.391
			$NO_{3,2}$-N (mg/l)			
A1	17	0.298	0.306	0.126	0.099	0.581
A2	15	0.313	0.329	0.147	0.109	0.666
PC	17	0.713	0.599	0.238	0.468	1.208
PICP1	17	1.264	0.783	1.095	0.000	4.792
CGP	17	0.455	0.423	0.284	0.000	1.150
PICP2	16	0.918	0.800	0.479	0.449	2.165
RAIN	17	0.354	0.352	0.167	0.104	0.744
			NH_4-N (mg/l)			
A1	14	0.289	0.170	0.276	0.061	1.119
A2	12	0.350	0.299	0.299	0.069	1.134
PC	14	0.049	0.047	0.031	0.017	0.147
PICP1	14	0.048	0.035	0.043	0.008	0.171
CGP	14	0.035	0.025	0.030	0.000	0.124
PICP2	14	0.039	0.031	0.022	0.015	0.100
RAIN	14	0.574	0.336	0.570	0.075	1.687
			TN (mg/l)			
A1	14	1.074	0.909	0.604	0.329	2.268
A2	12	1.126	1.025	0.706	0.275	2.479
PC	14	1.177	1.064	0.333	0.771	1.846
PICP1	14	1.375	1.177	0.766	0.000	2.837
CGP	14	0.853	0.798	0.446	0.000	1.656
PICP2	13	1.159	1.076	0.442	0.597	2.278
RAIN	14	1.250	1.172	0.846	0.272	2.928
			ON (mg/l)			
A1	13	0.418	0.451	0.213	0.116	0.808
A2	11	0.384	0.374	0.221	0.095	0.765
PC	13	0.446	0.426	0.122	0.272	0.710
PICP1	13	0.370	0.306	0.196	0.072	0.649
CGP	13	0.382	0.327	0.191	0.125	0.791
PICP2	13	0.334	0.305	0.134	0.114	0.604
RAIN	13	0.302	0.304	0.212	0.046	0.654

Table A7. (continued)

Variable	N	Mean	Median	Std Dev	Minimum	Maximum
------------------------------- **OPO4 (mg/l)** -------------------------------						
A1	19	0.093	0.040	0.165	0.005	0.732
A2	15	0.028	0.021	0.029	0.005	0.113
PC	19	0.053	0.032	0.047	0.012	0.184
PICP1	19	0.046	0.044	0.028	0.000	0.145
CGP	19	0.061	0.026	0.102	0.000	0.421
PICP2	18	0.035	0.032	0.015	0.022	0.086
RAIN	18	0.090	0.036	0.121	0.005	0.434
------------------------------- **TP (mg/l)** -------------------------------						
A1	16	0.149	0.093	0.181	0.025	0.782
A2	14	0.077	0.064	0.041	0.032	0.162
PC	16	0.143	0.133	0.059	0.063	0.268
PICP1	16	0.117	0.125	0.050	0.000	0.204
CGP	16	0.195	0.124	0.235	0.000	0.964
PICP2	15	0.105	0.090	0.037	0.059	0.195
RAIN	16	0.172	0.077	0.290	0.012	1.204
------------------------------- **TSS (mg/l)** -------------------------------						
A1	19	19.77	19.60	12.61	2.70	39.80
A2	14	14.47	12.25	10.50	2.00	35.30
PC	18	15.31	12.85	10.82	2.80	41.30
PICP1	19	14.50	12.30	10.41	0.00	43.10
CGP	19	10.77	9.30	8.46	0.00	27.40
PICP2	18	13.69	9.50	11.83	3.30	44.80
RAIN	19	10.16	9.50	6.79	1.30	25.30
------------------------------- **pH** -------------------------------						
A1	36	7.2	7.2	0.5	6.3	8.5
A2	23	7.3	7.4	0.5	6.4	8.1
PC	36	9.2	9.1	0.8	8.3	11.3
PICP1	33	8.1	8.0	0.4	7.2	8.8
CGP	34	7.9	8.0	0.3	7.4	8.4
PICP2	37	7.9	7.9	0.3	7.1	8.6
RAIN	36	6.7	6.9	0.8	4.7	8.0

Table A8. Statistical summary of parameter loads

Variable	N	Mean	Median	Std Dev	Minimum	Maximum
			TKN (mg/l)			
A1	14	0.961	0.565	1.071	0.269	4.291
A2	12	1.322	0.476	2.317	0.230	8.404
PC	14	0.830	0.390	1.122	0.024	4.311
PICP1	14	0.385	0.215	0.522	0.000	1.898
CGP	14	0.691	0.224	1.315	0.000	5.065
PICP2	12	0.689	0.414	0.773	0.030	2.940
RAIN	14	1.863	0.948	1.919	0.241	5.905
			$NO_{3,2}$-N (mg/l)			
A1	17	0.430	0.217	0.694	0.037	3.034
A2	15	0.438	0.229	0.719	0.027	2.958
PC	17	0.953	0.527	1.312	0.032	5.663
PICP1	17	1.013	0.467	1.577	0.000	6.244
CGP	17	1.019	0.237	2.729	0.000	11.512
PICP2	15	1.328	0.757	1.697	0.075	7.111
RAIN	17	0.704	0.388	0.554	0.131	2.022
			NH_4-N (mg/l)			
A1	14	0.355	0.180	0.464	0.016	1.440
A2	12	0.498	0.180	0.819	0.035	2.806
PC	14	0.074	0.047	0.076	0.003	0.240
PICP1	14	0.036	0.015	0.039	0.000	0.103
CGP	14	0.045	0.027	0.052	0.000	0.180
PICP2	13	0.065	0.050	0.065	0.003	0.216
RAIN	14	1.216	0.596	1.392	0.182	4.872
			TN (mg/l)			
A1	14	1.419	0.834	1.791	0.390	7.325
A2	12	1.787	0.722	3.094	0.361	11.362
PC	14	1.841	0.933	2.535	0.056	9.974
PICP1	14	1.459	0.713	2.219	0.000	8.141
CGP	14	1.869	0.488	4.297	0.000	16.577
PICP2	12	2.127	1.411	2.606	0.105	10.052
RAIN	14	2.543	1.526	2.324	0.447	7.124
			ON (mg/l)			
A1	13	0.611	0.298	0.728	0.158	2.869
A2	11	0.847	0.235	1.615	0.127	5.598
PC	13	0.812	0.401	1.090	0.022	4.112
PICP1	13	0.376	0.230	0.512	0.000	1.818
CGP	13	0.695	0.228	1.309	0.036	4.885
PICP2	12	0.619	0.341	0.719	0.027	2.724
RAIN	13	0.724	0.379	0.811	0.055	2.497

Table A8. (continued)

Variable	N	Mean	Median	Std Dev	Minimum	Maximum
			------------------------------- **OPO4 (g)** -------------------------------			
A1	19	0.060	0.051	0.048	0.002	0.154
A2	15	0.038	0.020	0.067	0.001	0.274
PC	19	0.072	0.044	0.080	0.001	0.312
PICP1	19	0.051	0.022	0.075	0.000	0.319
CGP	19	0.061	0.020	0.087	0.000	0.280
PICP2	17	0.063	0.030	0.072	0.002	0.263
RAIN	19	0.132	0.043	0.188	0.000	0.664
			------------------------------- **TP (g)** -------------------------------			
A1	16	0.123	0.116	0.079	0.021	0.317
A2	14	0.123	0.059	0.188	0.012	0.711
PC	16	0.224	0.178	0.312	0.005	1.295
PICP1	16	0.147	0.050	0.264	0.000	1.084
CGP	16	0.243	0.115	0.402	0.000	1.662
PICP2	14	0.221	0.130	0.321	0.006	1.278
RAIN	16	0.250	0.160	0.335	0.033	1.160
			------------------------------- **TSS (g)** -------------------------------			
A1	19	27.379	13.171	36.526	0.936	156.994
A2	14	31.890	8.233	61.968	1.005	237.444
PC	19	26.065	7.141	41.692	0.000	156.205
PICP1	19	17.221	6.125	24.350	0.000	84.429
CGP	19	16.016	4.182	29.847	0.000	127.444
PICP2	17	28.967	9.471	44.416	0.489	161.075
RAIN	19	17.331	18.772	10.639	2.266	41.006

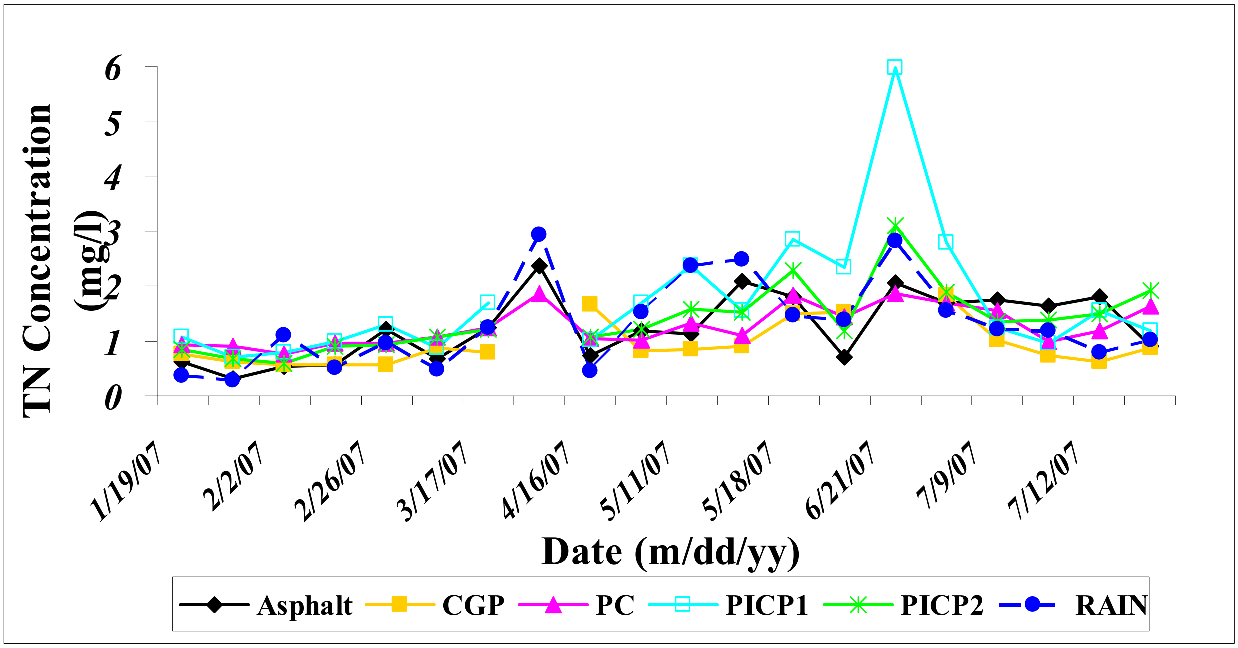


Figure A2. TN concentrations.

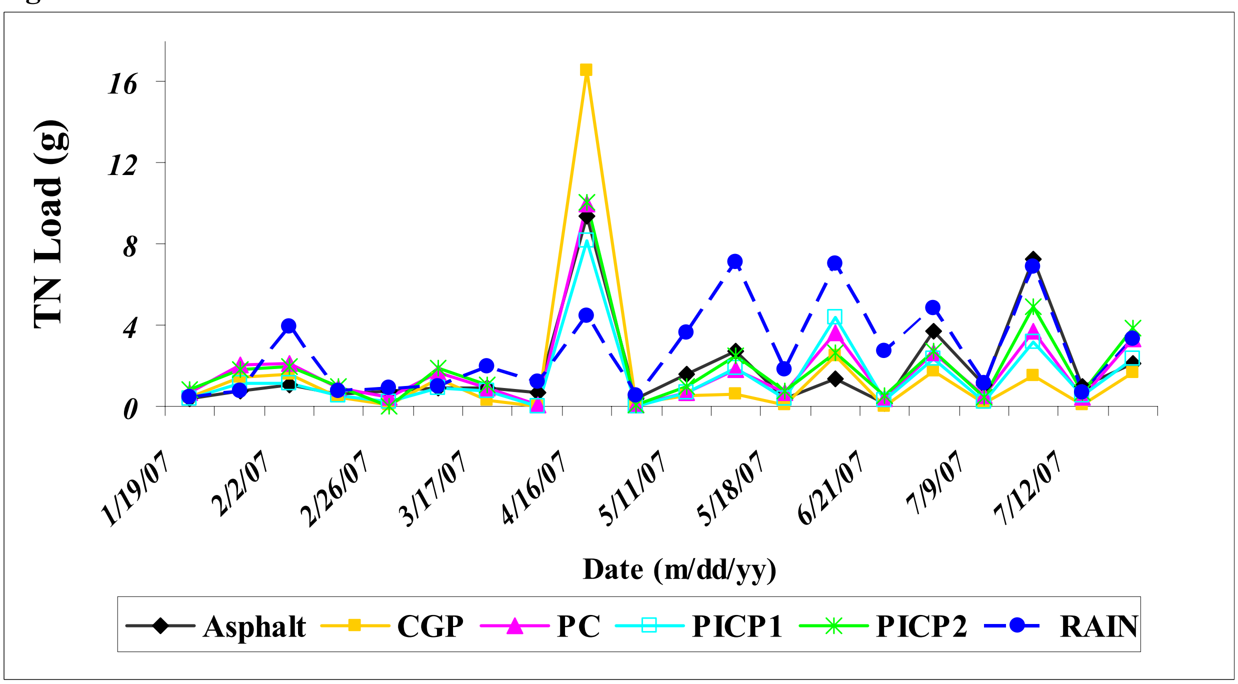


Figure A3. TN loads.

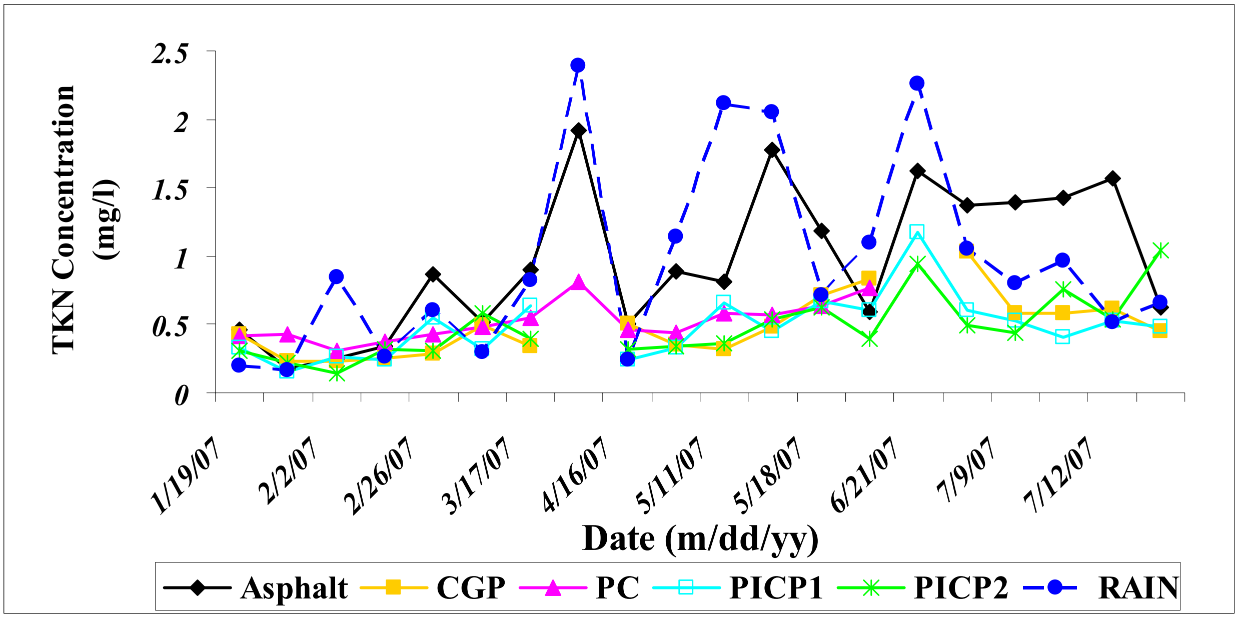


Figure A4. TKN concentrations.

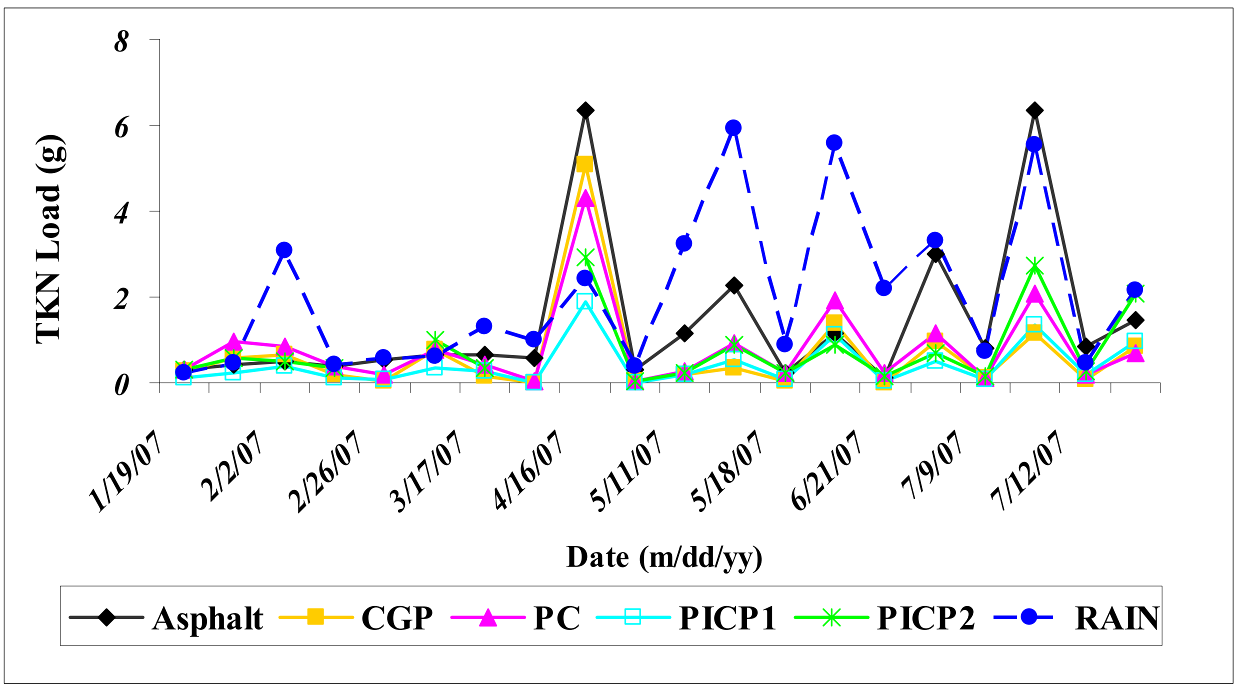


Figure A5. TKN loads.

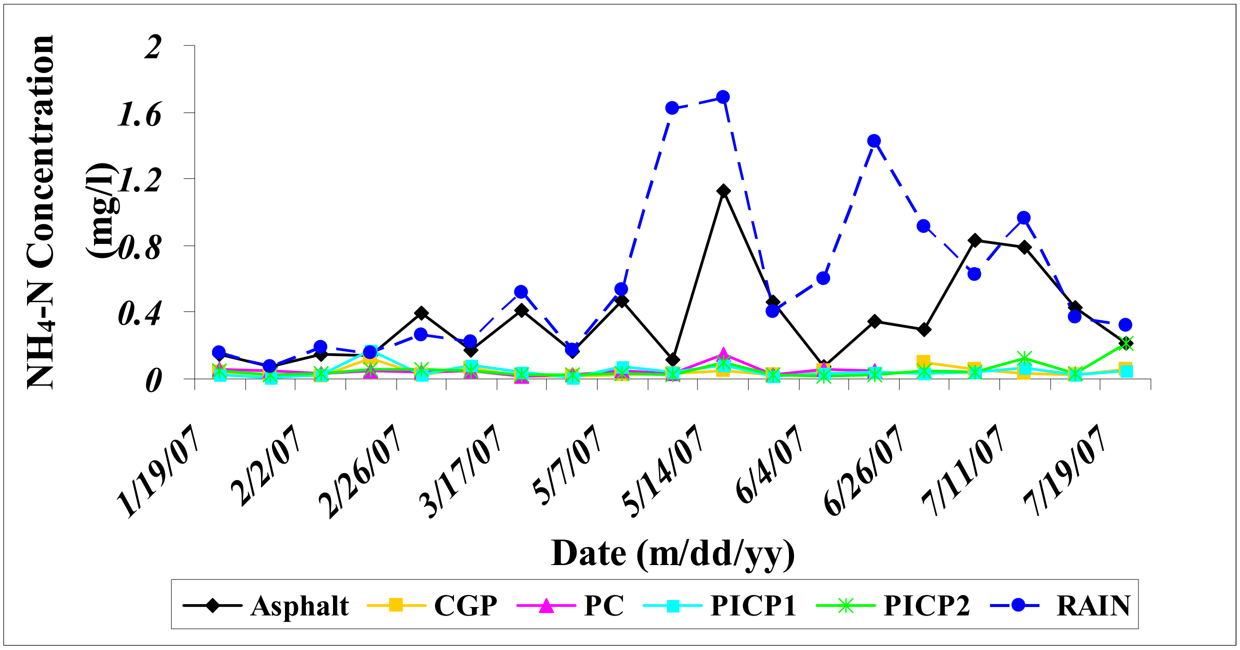


Figure A6. NH_4-N concentrations.

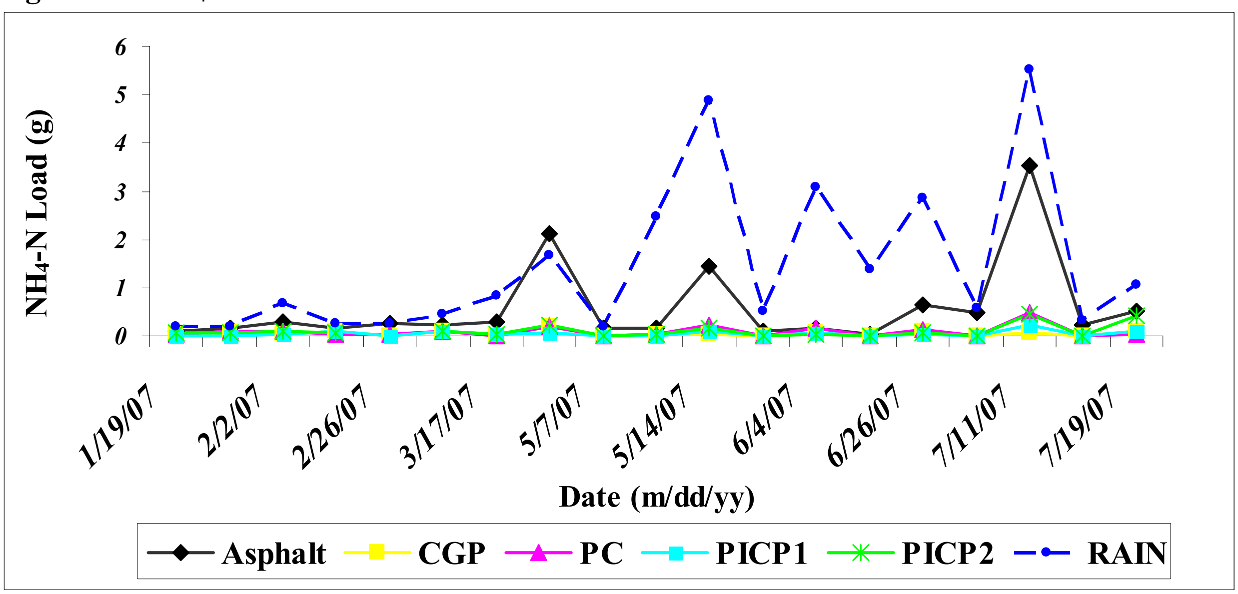


Figure A7. NH_4-N loads.

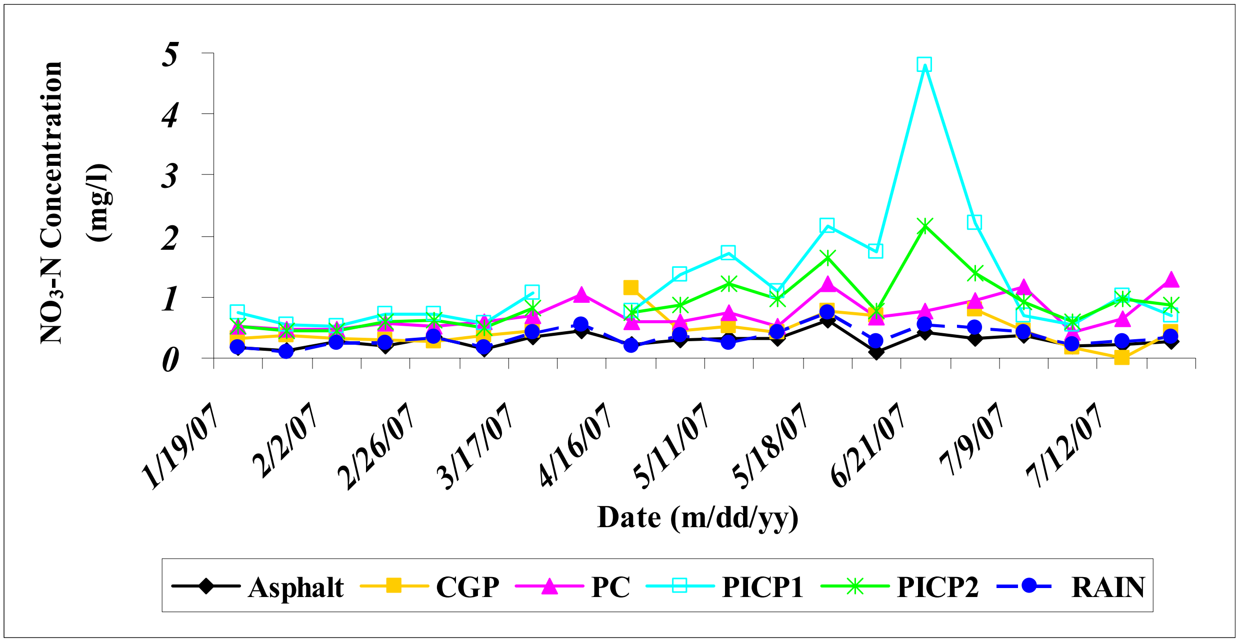


Figure A8. $NO_{2,3}$-N concentrations.

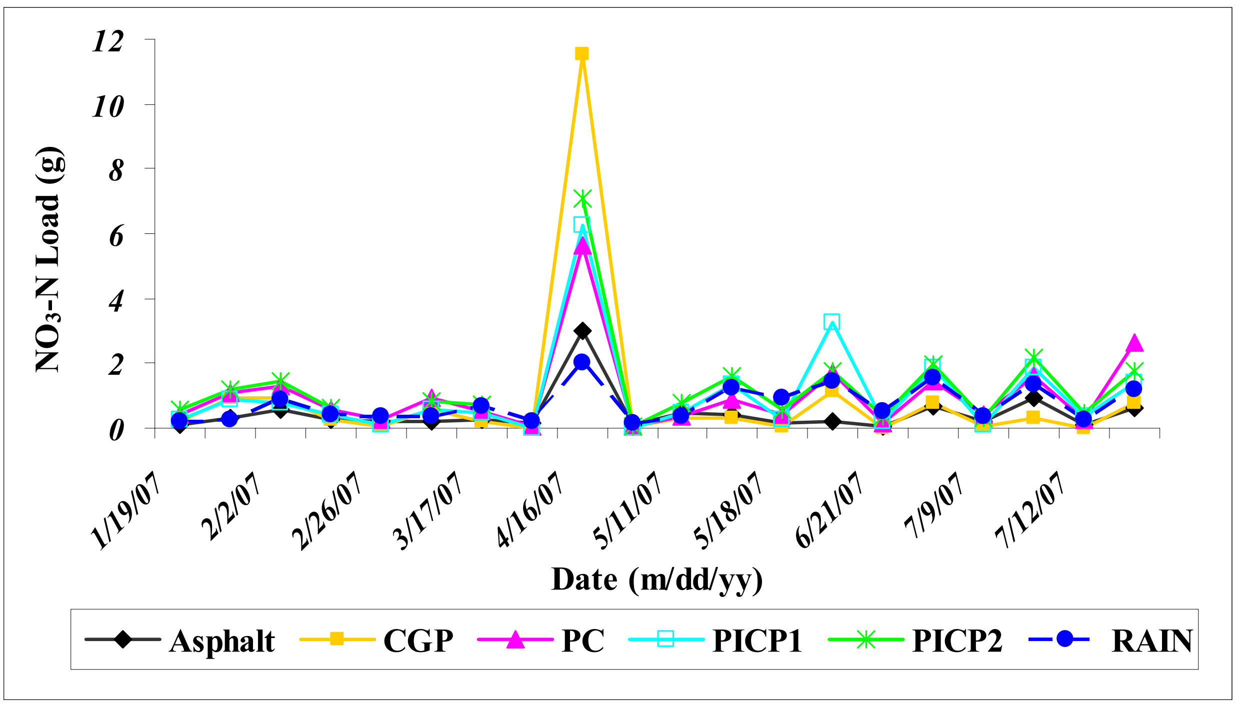


Figure A9. $NO_{2,3}$-N loads.

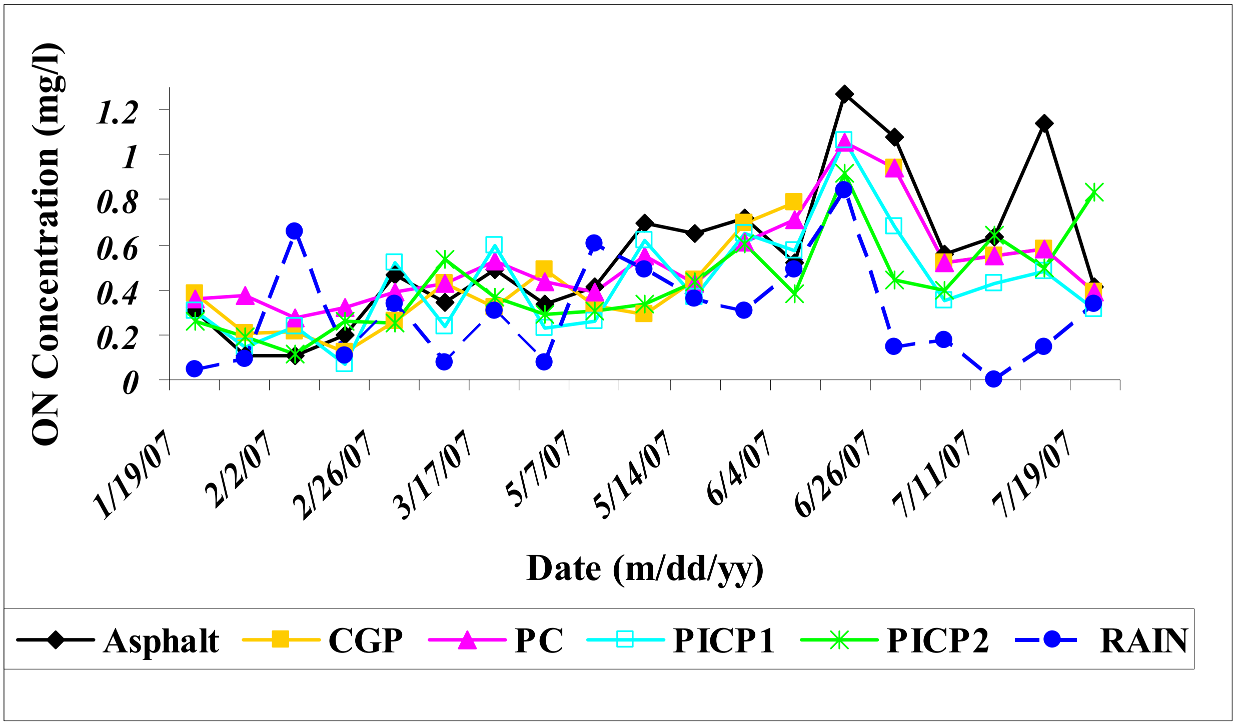


Figure A10. ON concentrations.

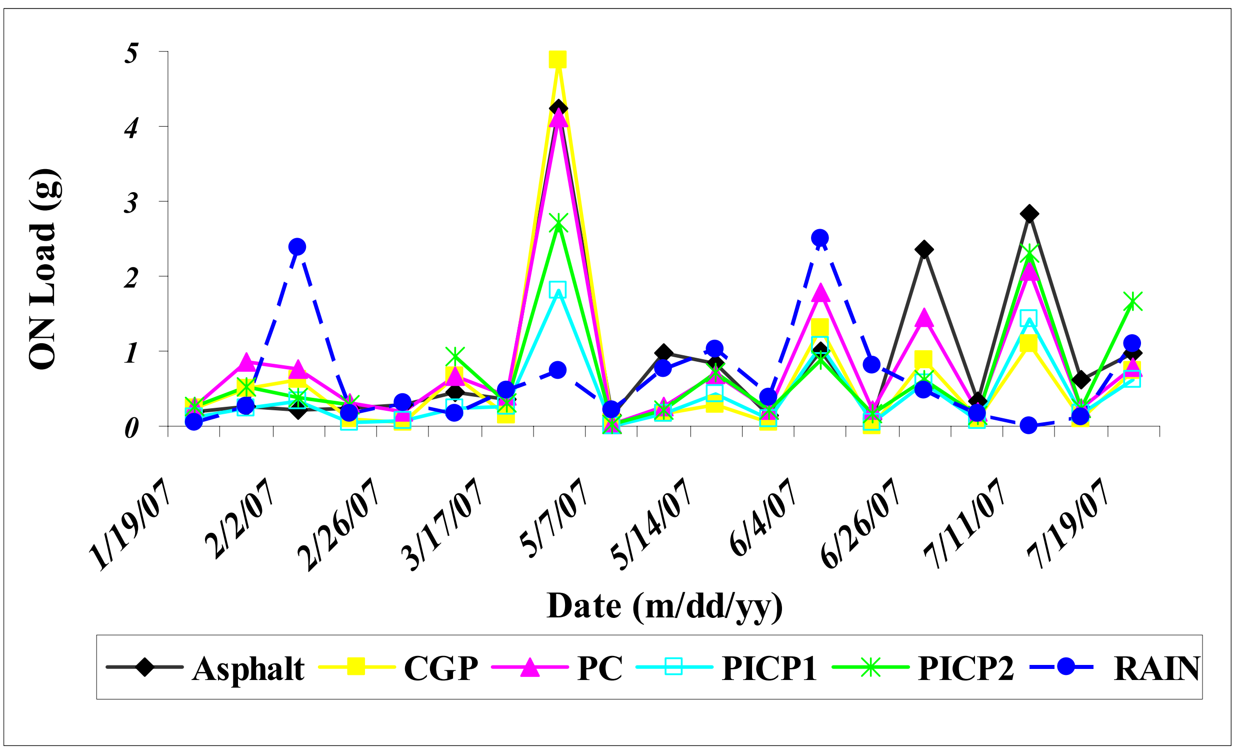


Figure A11. ON loads.

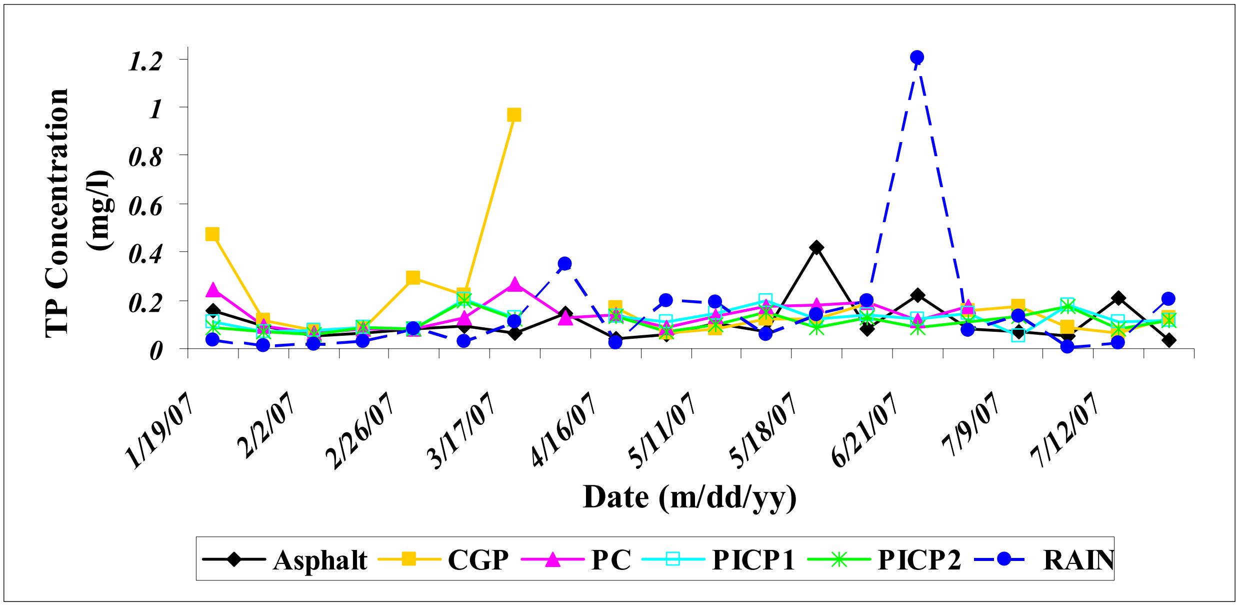


Figure A12. TP concentrations.

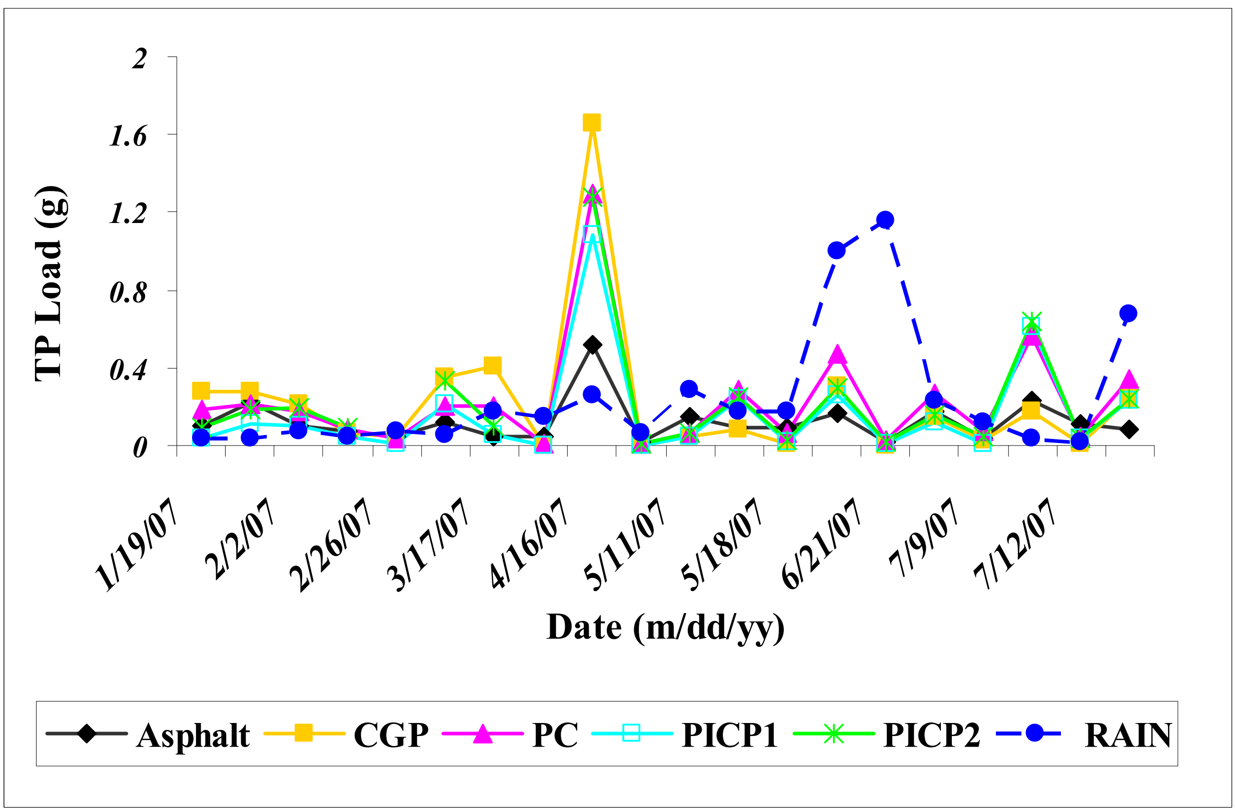


Figure A13. TP loads.

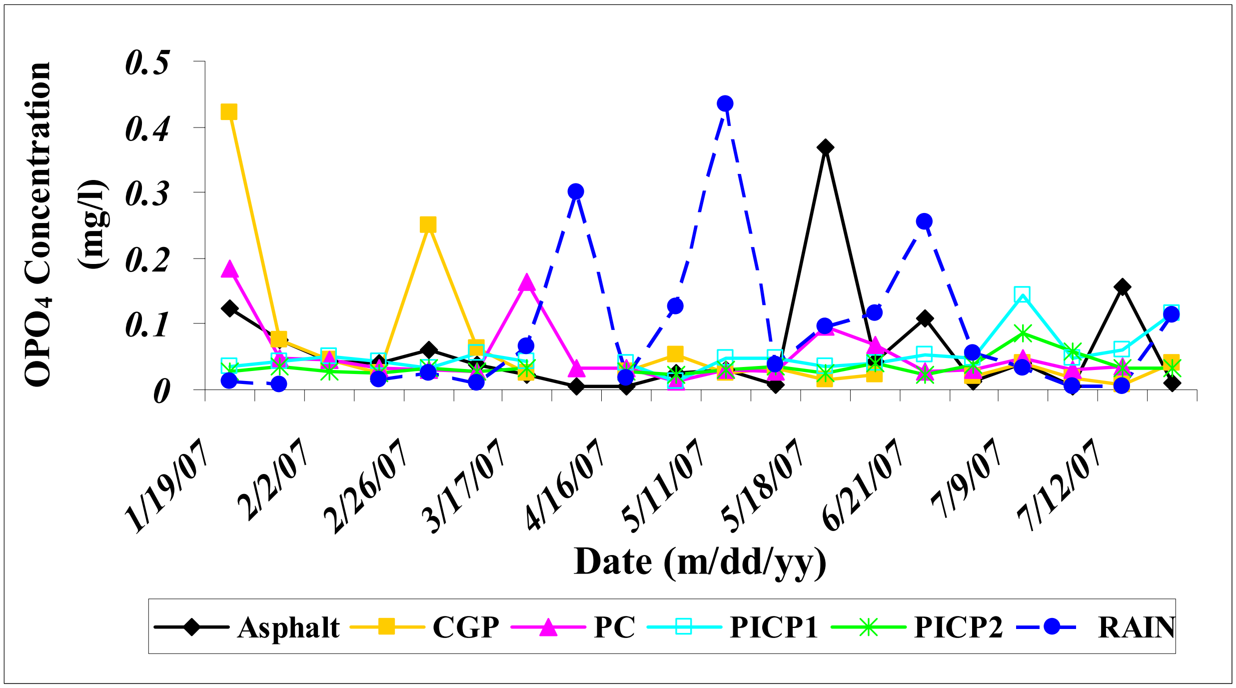


Figure A14. OPO_4 concentrations.

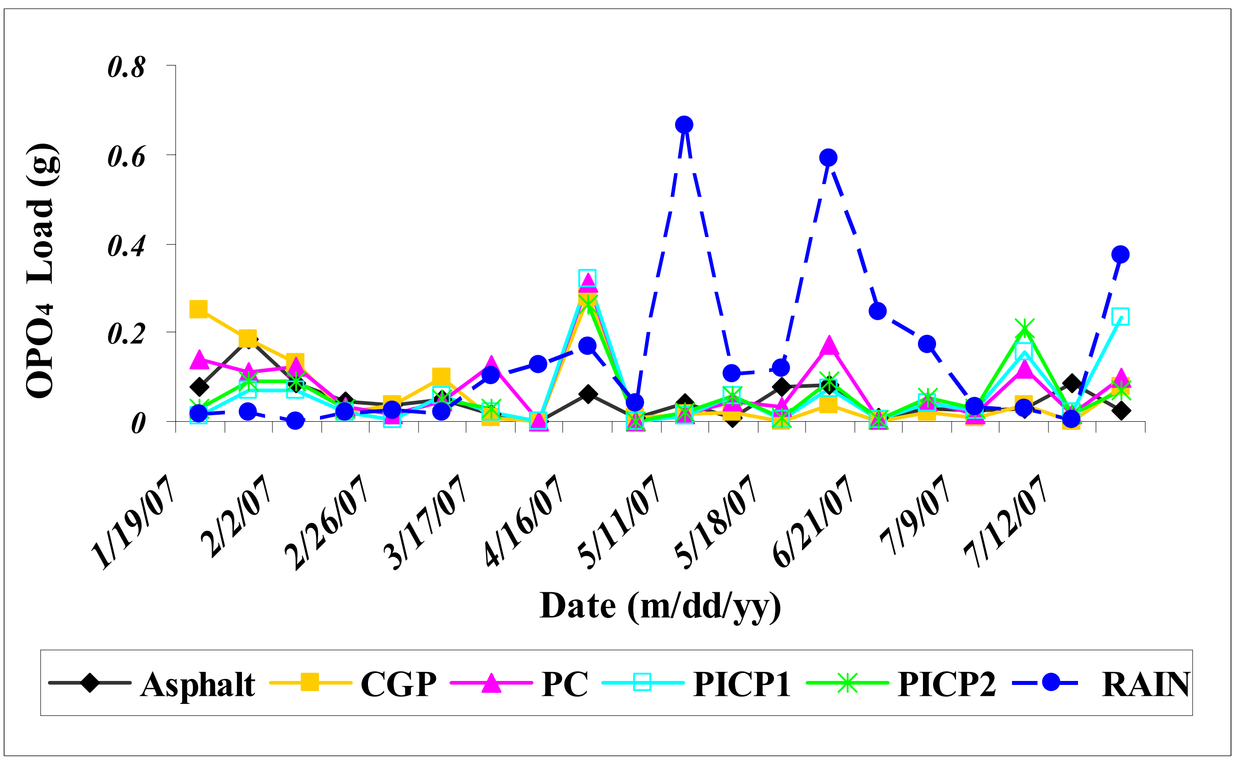


Figure A15. OPO_4 loads.

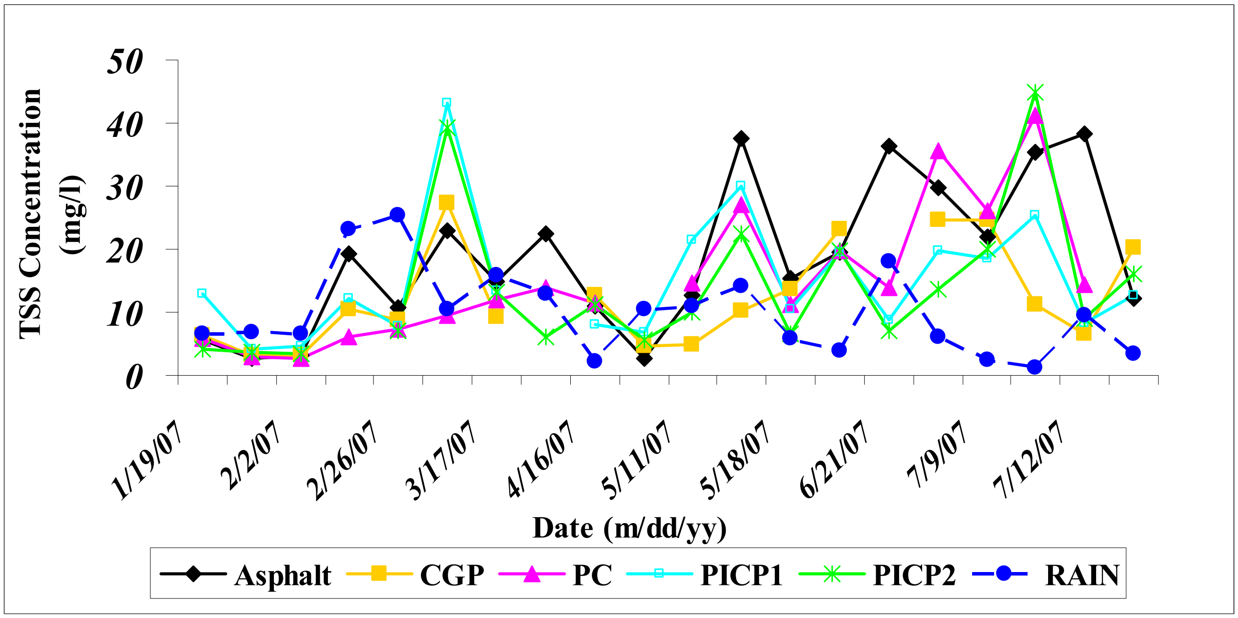


Figure A16. TSS concentrations.

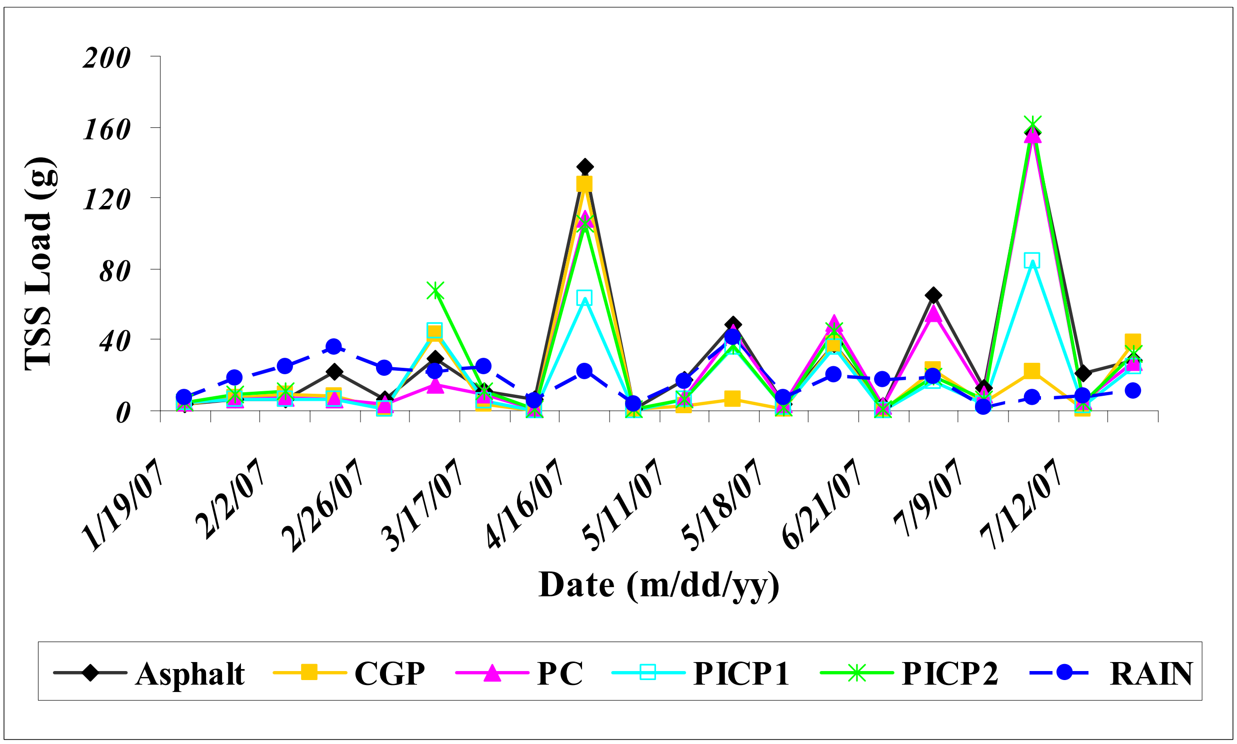


Figure A17. TSS loads.

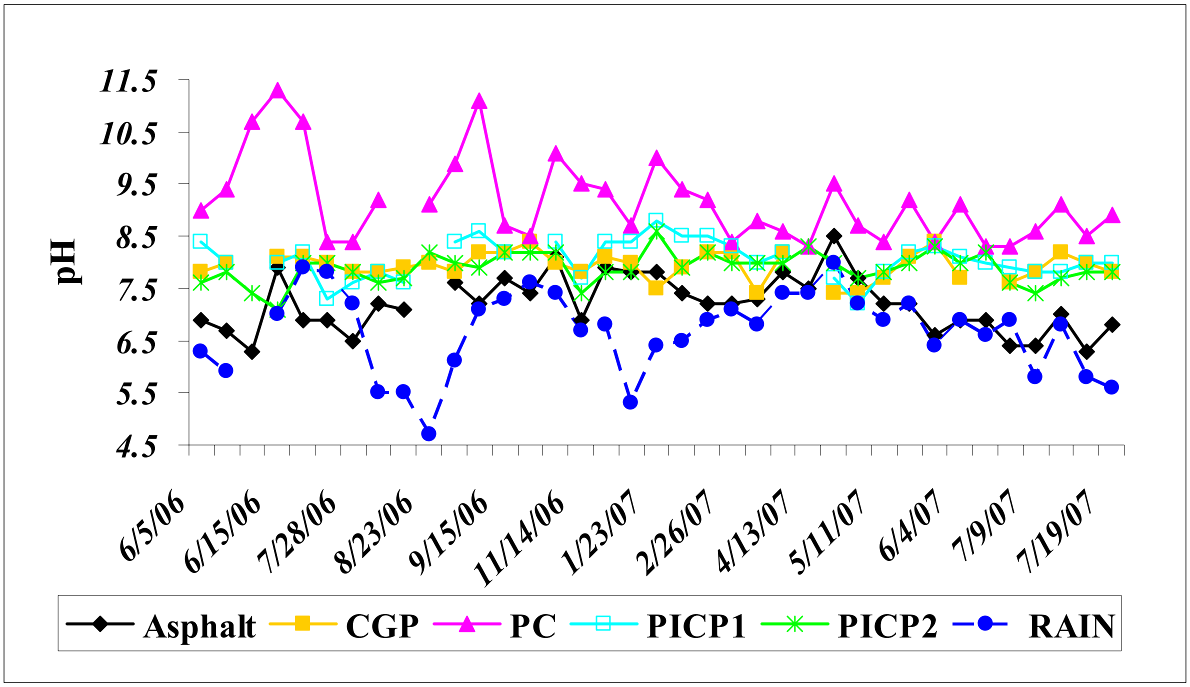
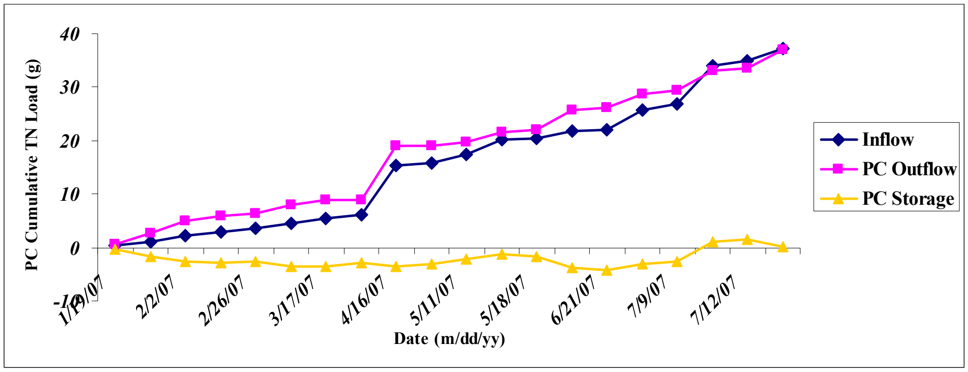
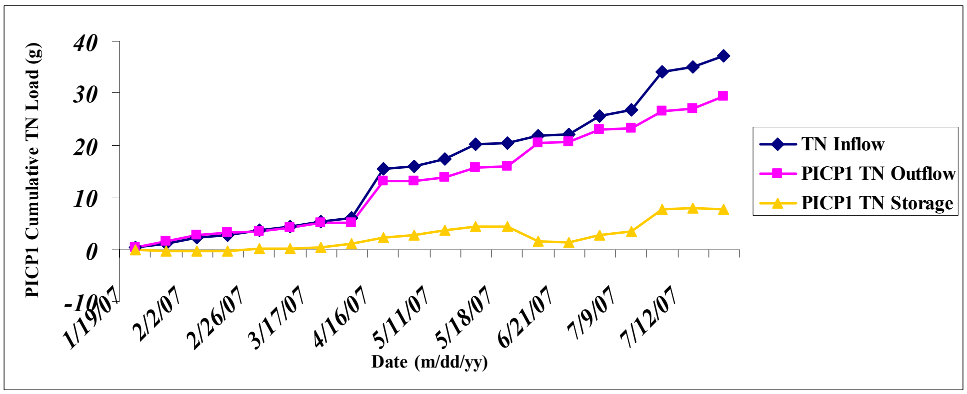


Figure A18. pH measurements.

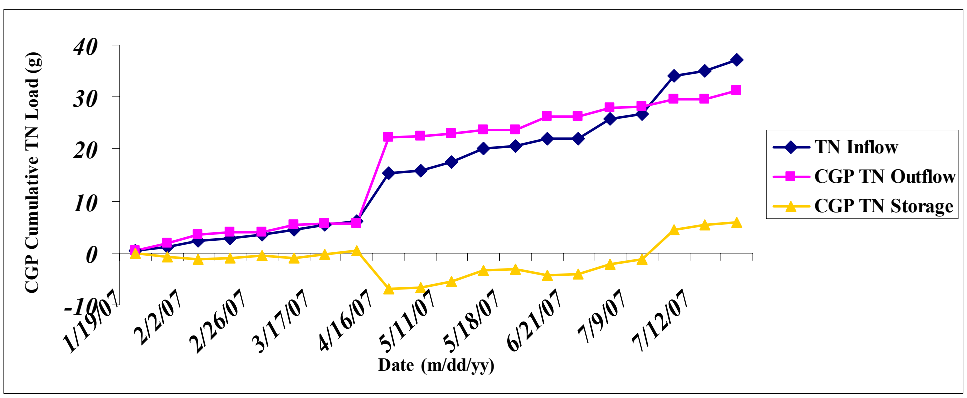
Cumulative Nutrient Mass Balances



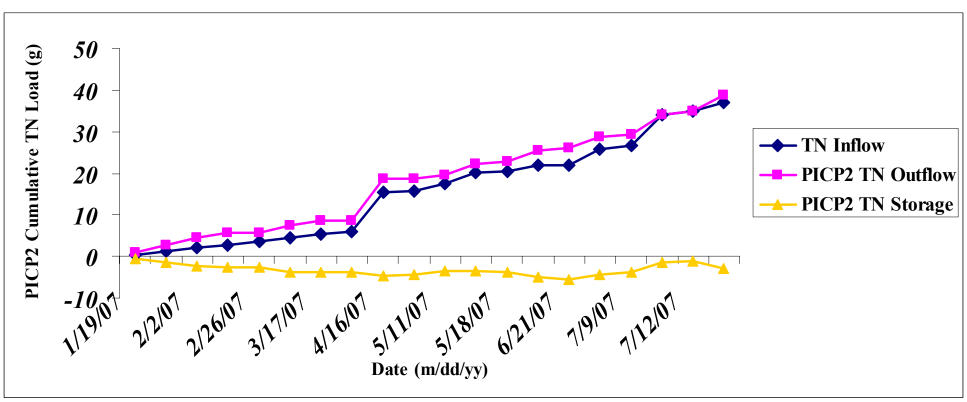
(a)



(b)

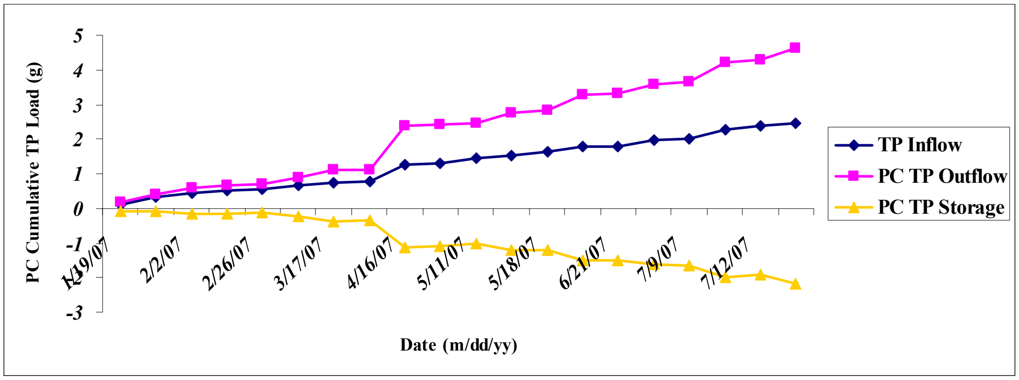


(c)

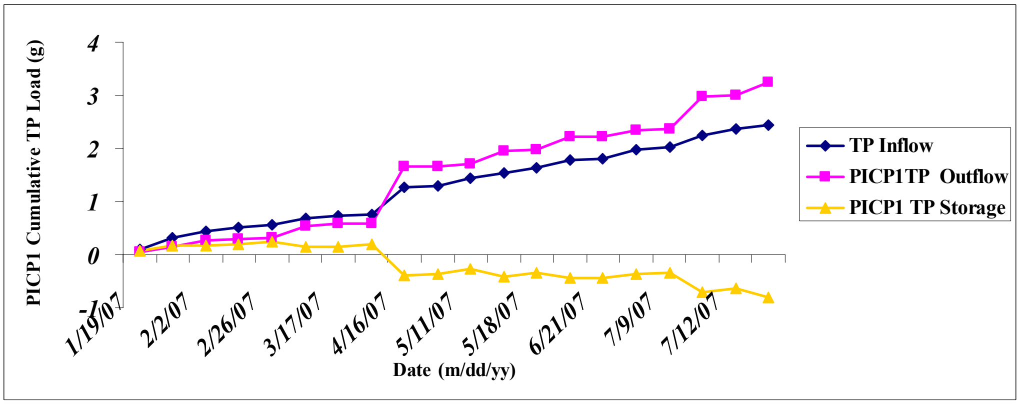


(d)

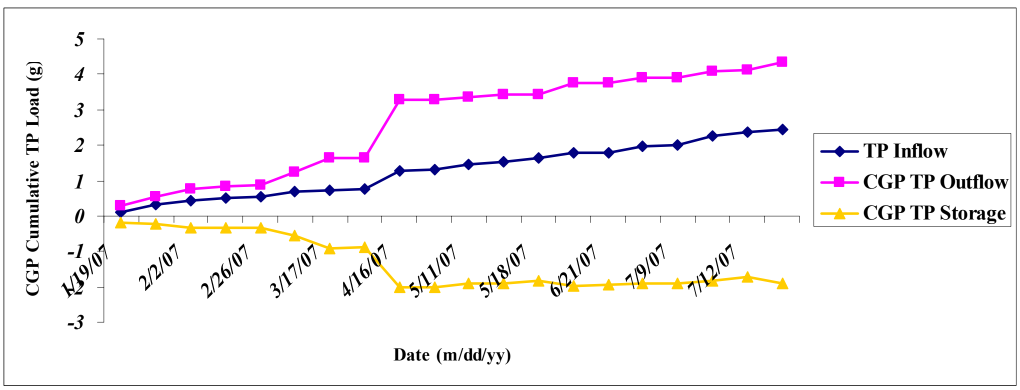
Figure A19. TN cumulative mass balance for **(a)** PC cell **(b)** PICP1 cell **(c)** CGP cell **(d)** PICP2 cell



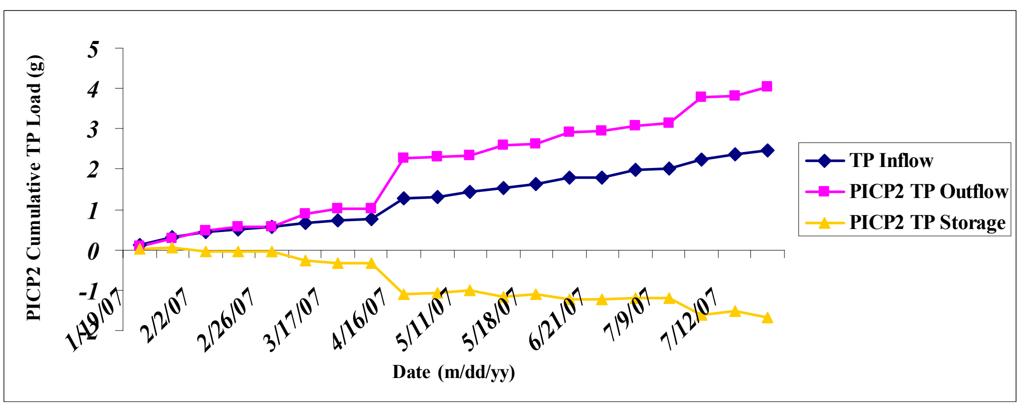
(a)



(b)



(c)



(d)

Figure A20. TP cumulative mass balance for **(a)** PC cell **(b)** PICP1 cell **(c)** CGP cell **(d)** PICP2 cell

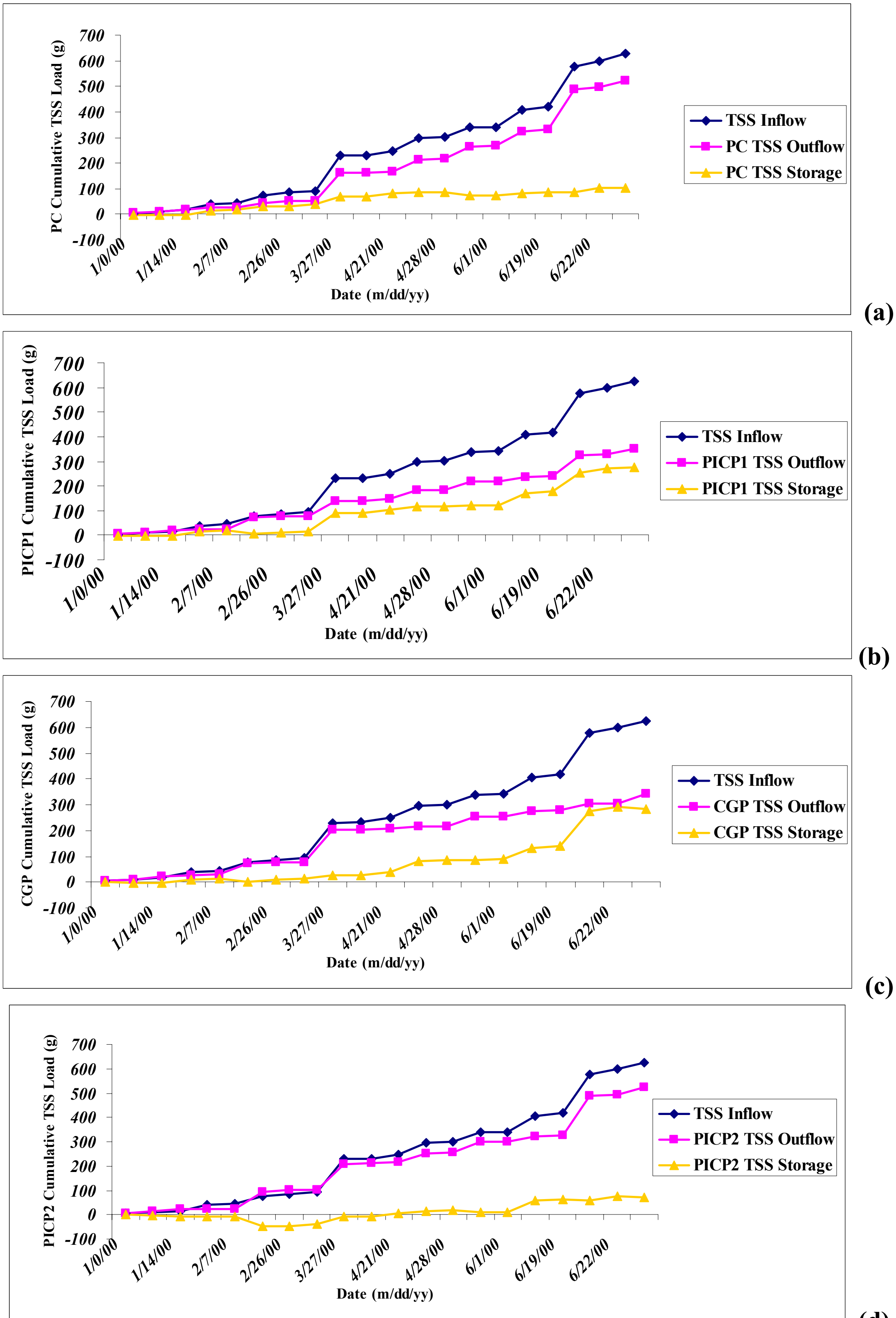


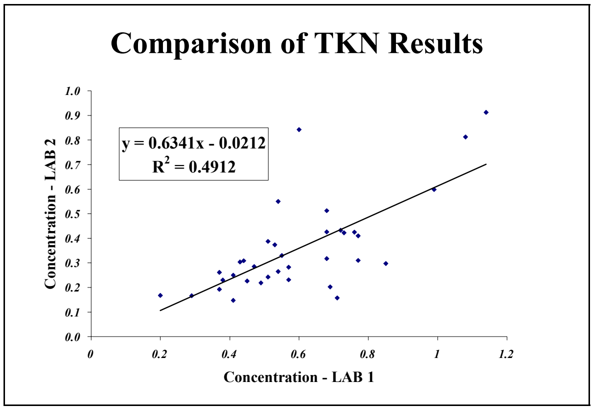
Figure A21. TSS cumulative mass balance for **(a)** PC cell **(b)** PICP1 cell **(c)** CGP cell **(d)** PICP2 cell

PRELIMINARY LABORATORY RESULTS

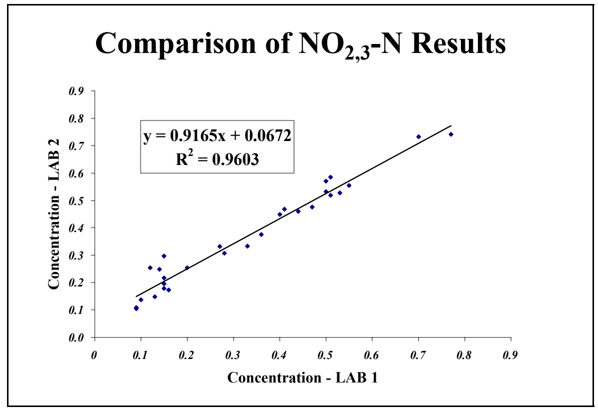
From June 2006 through December 2006, water quality analyses were completed on composite pavement and rainfall samples for 20 storm events. At this time, it was noticed that the TP concentrations being reported from the laboratory were higher than values typically reported in stormwater literature. Average TP concentrations of asphalt runoff were around 0.42 mg/l (N=20). Average rainfall TP concentrations were 0.56 mg/l (N=30), higher than those of asphalt. Table 5-50 shows reported asphalt and rainfall TP concentrations from previous studies. Blank samples submitted to the initial laboratory in another study suggested that the minimum TP detection limit was roughly 0.2 mg/l (Dan Line, 2007).

In response, for 5 successive storm events, samples from all locations were duplicated at the original laboratory (LAB 1) and an EPA certified water quality laboratory (LAB 2). Parameters analyzed by LAB 2 were limited to total Kjeldahl nitrogen (TKN), nitrate-nitrite as nitrogen ($NO_{2,3}$-N), ammonium as nitrogen (NH_4-N), total phosphorus (TP), orthophosphate (OPO_4), and total suspended solids (TSS). Results from the five duplicated storms were compared both graphically and statistically by parameter. Data for each parameter are shown in Appendices D and E.

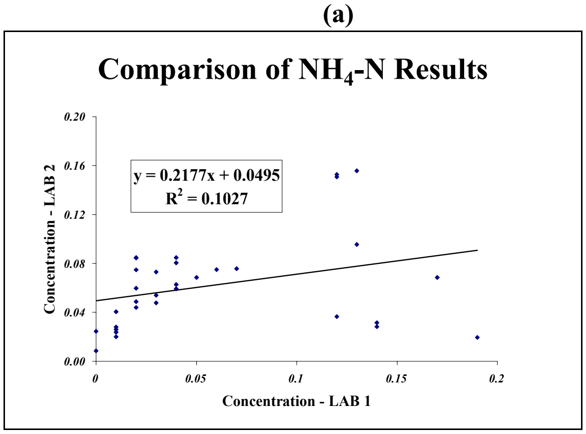
Concentrations were plotted for LAB 1 results versus LAB 2 results, and a trendline was generated to estimate the relationship between laboratory results. A linear trendline with a slope value of 1.0, intercept of zero, and an R^2 value of 1.0 would indicate identical laboratory results between labs. Figure A22 shows the regression for each duplicated parameter. With the possible exception of $NO_{2,3}$-N, it was apparent that the two labs yielded different results for each parameter. This was particularly true for the concentrations of NH_4-N, TP, PO_4, and TSS.



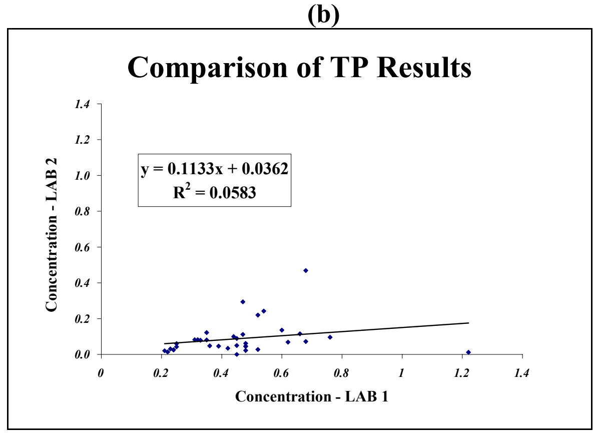
(a)



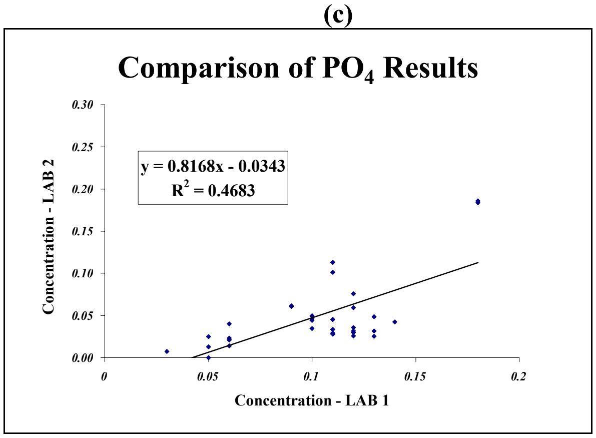
(b)



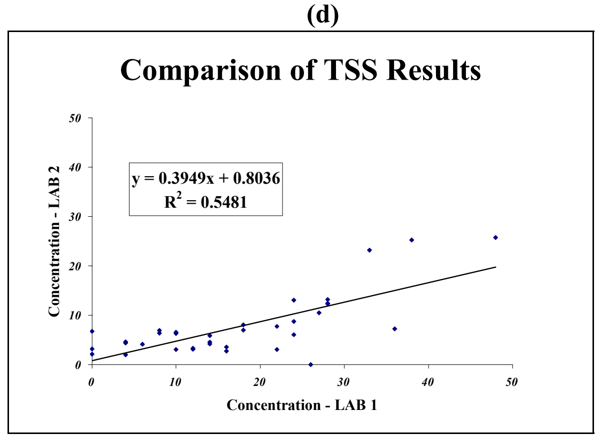
(c)



(d)



(e)



(f)

Figure A22. Linear regression of laboratory data (LAB 1 and LAB 2).

Tables A9 and A10 compare pollutant concentration results of this study to previous findings from studies examining pollutant concentrations of rainfall and asphalt parking lot runoff throughout the southeast. CAAE lab results were closely related to previous findings, and no major differences for any particular parameter were observed.

Table A9. Observed pollutant concentrations of rainfall in the Southeastern U.S.

Study	Location	Mean Rainfall Concentrations (mg/l)					
		NO_3N	NH_4N	TKN	TN	TP	TSS
Rushton (2001)	Tampa, FL	0.27	0.13	0.37	0.49	0.02	-
Moran (2003)	Goldsboro/ Kinston, NC	0.12	0.16	0.38	0.5	0.05	-
Line (1998)	North Carolina	0.31	0.42	0.64	0.95	-	-
Bean	Cary, NC	0.39	0.64	1.26	1.62	0.26	-
CAAE Lab	Kinston, NC	0.35	0.59	0.96	1.30	0.16	9.8
LAB1*	Kinston, NC	0.22	0.36	0.89	1.11	0.56	19.72

* Several results from LAB 1 are not accurate, particularly TP data

Table A10. Observed pollutant concentrations from asphalt parking lot runoff.

Study	Location	Mean Asphalt Concentrations (mg/l)					
		NO_3N	NH_4N	TKN	TN	TP	TSS
Rushton (2001)	Tampa, FL	0.28	0.13	0.42	0.55	0.11	12.4
Bean *et al.* (2007b)	Goldsboro, NC	0.30	0.31	1.03	1.33	0.13	43.8
Passeport and Hunt (2007)	North Carolina	0.36	0.32	1.24	1.63	0.21	-
CAAE Lab	Kinston, NC	0.29	0.34	0.95	1.24	0.14	19.4
LAB1*	Kinston, NC	0.28	0.24	1.00	1.28	0.42	33.8

* Several results from LAB 1 are not accurate, particularly TP data

Data from the CAAE laboratory were assumed to be more accurate, and, therefore, comprises the majority of the water quality study. Due to similarities between the two labs, $NO_{2,3}$-N data from LAB 1 is discussed in detail. Because of the possibility that LAB 1 results for certain parameters may have been accurate relative to other samples analyzed at LAB 1, additional data from LAB 1 are included, but are generally assumed to be erroneous.

<u>LAB 1 Data</u>

Results from LAB 1 seem to indicate a possible flushing of nutrients over time, particularly for $NO_{2,3}$-N and TSS. Concentrations of these parameters were high soon after lot construction, but appeared to stabilize at lower concentrations with aging of the lot. It is likely that soils and the aggregate base course of the permeable sections were disturbed during construction, and that an initial wash out period occurred.

LAB1 Total Suspended Solids

Compared to the CAAE lab, concentrations of TSS were much higher from LAB 1 (Figures A23 and A24). A linear relationship between data sets with a moderate R^2-value (R^2=0.5481) indicates that LAB 1 TSS results for various pavements may be relative to one another.

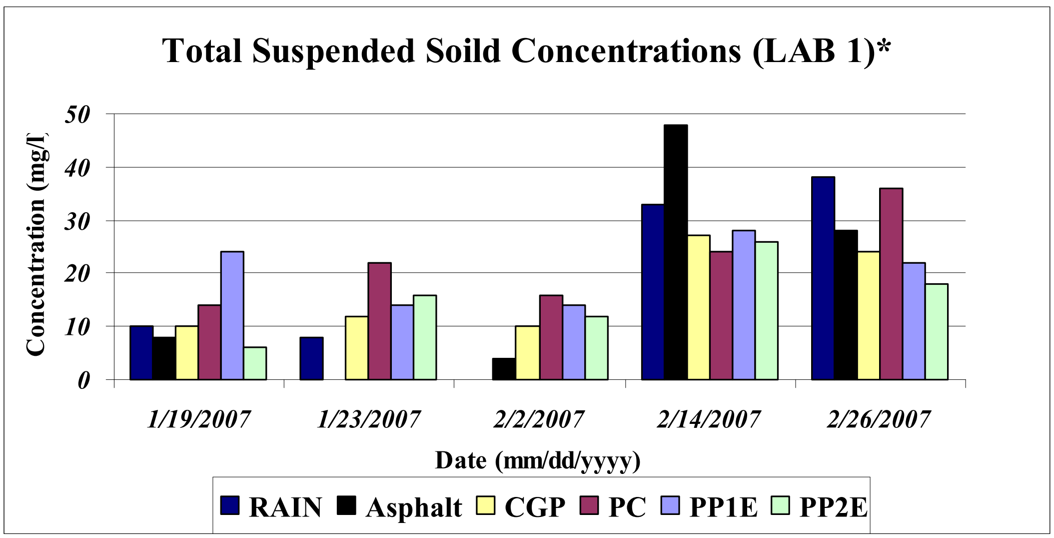


Figure A23. TSS concentrations from LAB 1 (duplicated samples).

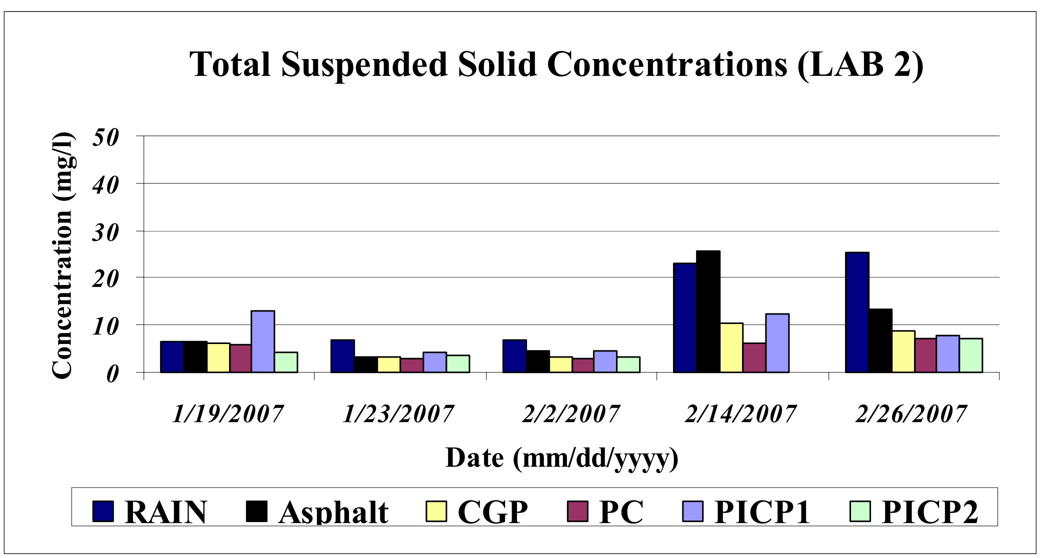


Figure A24. TSS concentrations from CAAE Lab (duplicated samples).

Figure A25 shows TSS concentrations measured from LAB 1 over the course of the study. Seasonal variation is seen. High TSS spikes are observed early in the monitoring process, but seem to stabilize toward the end of the monitoring period.

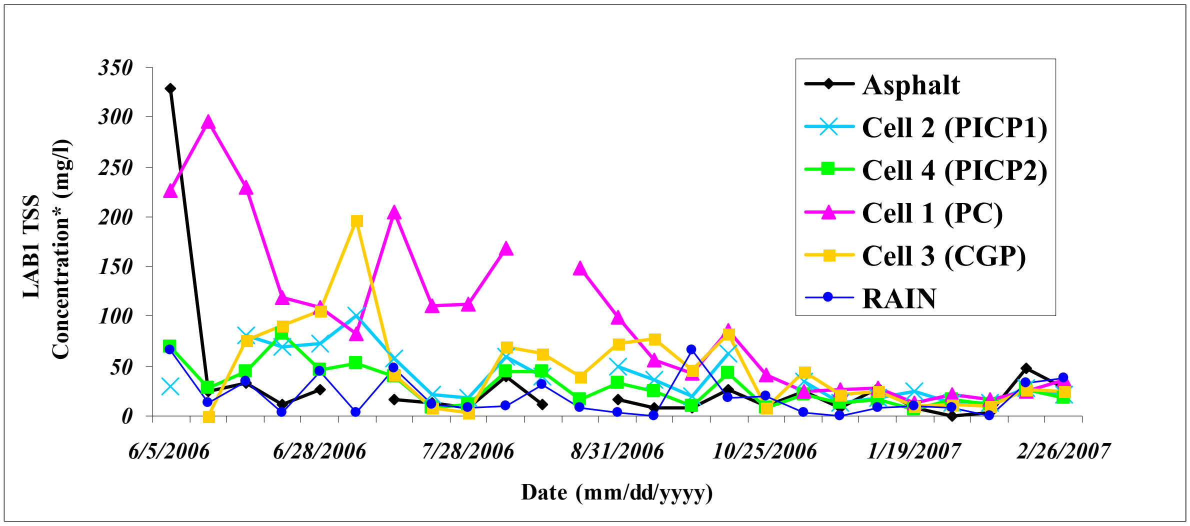


Figure A25. TSS concentrations from LAB 1 for October 2006 to February 2007.

LAB 1 Nitrate-Nitrite

Values and trends for $NO_{2,3}$-N data between LAB 1 and the CAAE lab were found to be similar. Patterns for the five duplicated events from both labs are depicted in Figures A26 and A27.

Over the entire study sampling period, all pavements had a significantly higher $NO_{2,3}$-N concentrations than asphalt and rain samples ($p<0.01$). No differences between rain and asphalt were observed. The PICP1 cell concentrations were greater than the PC and CGP cell, and PICP2 cell concentrations were greater than the PC cell ($p<0.01$). Overall concentrations for the CGP cell were higher than the PC cell; however, results were not significant. $NO_{2,3}$-N concentrations for all locations were positively correlated to rainfall $NO_{2,3}$-N concentrations ($p<0.10$), with asphalt demonstrating the strongest correlation for all pavements ($r=0.75$, $p<0.01$).

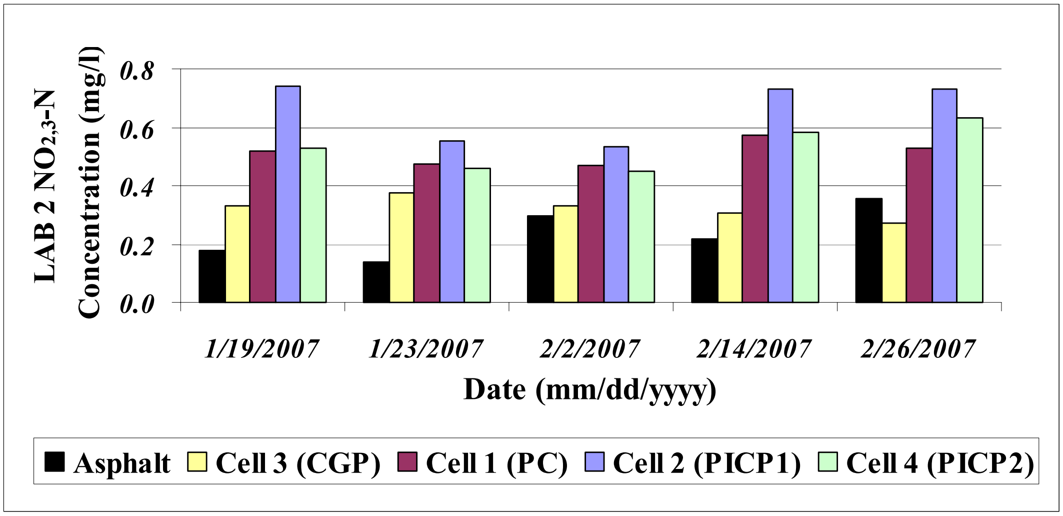


Figure A26. $NO_{2,3}$-N concentrations from LAB 1 (duplicated samples).

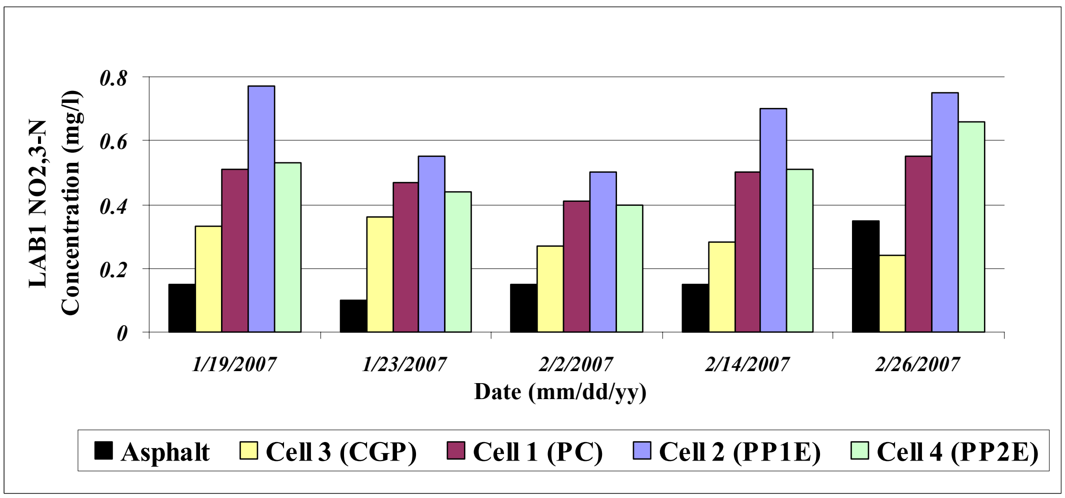


Figure A27. $NO_{2,3}$-N concentrations from LAB 2 (duplicated samples).

Rainfall depth was a significant predictor of $NO_{2,3}$-N concentration for all locations ($p<0.10$). Negative correlations to rainfall depth were observed for all samples, but were significant only for asphalt, rain, and the PICP1 and PICP2 cells ($p<0.10$). Negative rainfall depth correlations to the PC ($p<0.1089$) and CGP ($p<0.1557$) cells were just outside the significance of $\alpha=0.10$. Also, PICP1, CGP, and PICP2 cells $NO_{2,3}$-N concentrations were negatively correlated to the age of the parking lot ($p<0.01$). For these sections, $NO_{2,3}$-N concentrations were highest during the summer months, which was also the earliest period of the study. Table A11 lists the significant predictor variables for each location. Seasonal effects can be seen in Figure A28.

Table A11. MLR analysis of $NO_{2,3}$-N concentration predictor variables.

Pavement	Significant Predictor Variables	R^2-value
Asphalt	Rainfall Depth, Age	0.5454
PC cell	Rainfall Depth, Dry Period	0.2989
PICP1 cell	Age, Rainfall Depth, Dry Period	0.8154
CGP cell	Age, Rainfall Depth	0.6801
PICP2 cell	Age, Rainfall Depth, Dry Period	0.8626
RAIN	Rainfall Depth	0.6498

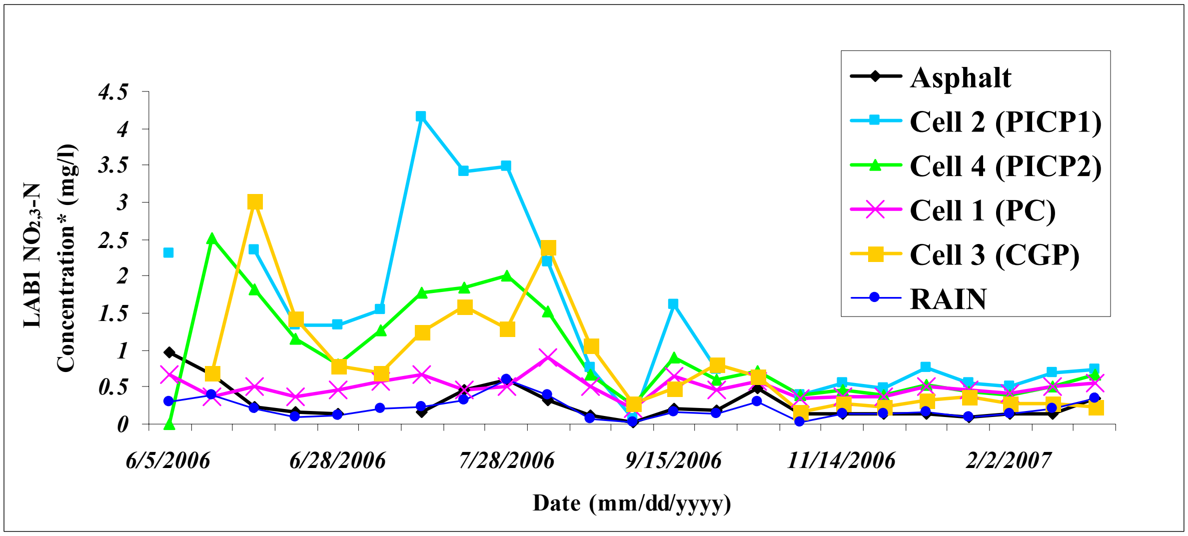


Figure A28. $NO_{2,3}$-N concentrations from LAB 1 for June 2006 to February 2007.

Over the entire study period, asphalt had significantly lower $NO_{2,3}$-N loadings than the PC cell ($p<0.05$), the PICP1 cell ($p<0.01$) and the PICP2 cell ($p<0.01$). Only the PICP1 and PICP2 cells had greater loadings than rain ($p<0.01$). Among the permeable sections, the CGP cell had lower loadings than the PICP1 and PICP2 cells. The PC cell had a lower loading than the PICP2 cell. Loadings were positively correlated to rainfall depth for all pavements ($p<0.05$). $NO_{2,3}$-N loadings from 6/2006 to 2/2007 are shown in Figure A29.

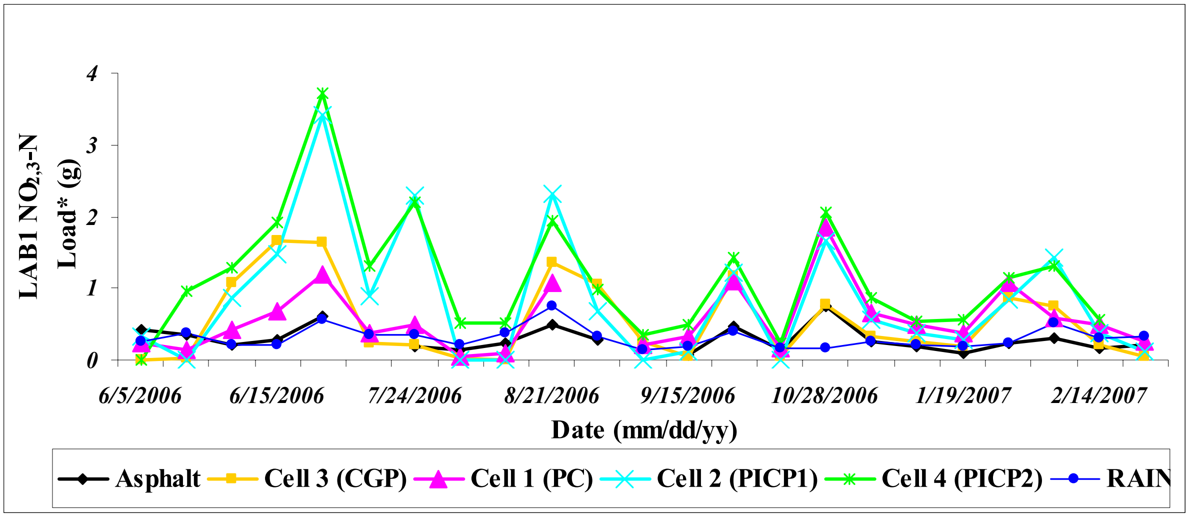


Figure A29. $NO_{2,3}$-N loadings from LAB 1 for June 2006 to February 2007.

Some seasonal variation in $NO_{2,3}$-N loadings may exist, but the relationship is not as evident as the seasonal variation in the $NO_{2,3}$-N concentration data. Analysis run on storms occurring from June 2006 through September 2006 found that PICP2 cell $NO_{2,3}$-N loadings were greater than those from the the PC and CGP cells ($p<0.01$). No difference between PC and CGP $NO_{2,3}$-N loadings was observed. Analysis run on data from October 2006 through February 2007 found that CGP cell $NO_{2,3}$-N loadings were lower than both the PC cell ($p<0.05$) and the PICP2 cell ($p<0.01$). No differences between the PC, PICP1, and PICP2 cells $NO_{2,3}$-N loadings were observed.