Effects of Stormwater Pipe Size and Rainfall on Sediment and Nutrients Delivered to a Coastal Bayou

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ABSTRACT: Pollutants discharged from stormwater pipes can cause water quality and ecosystem problems in coastal bayous. A study was conducted to characterize sediment and nutrients discharged by small and large (< 20 cm and >20 cm in internal diameters, respectively) pipes under different rainfall intensities (< 2.54 cm and > 2.54 cm, respectively). Results showed that large pipes had greater discharge than small pipes. Pollutants concentrations did not vary by pipe size. Large pipes had greater loads of TSS (138.2 vs. 24.0 mg/s), NO_3^- (5.54 vs. 2.74 mg/s), and NH_4^+ (0.39 vs. 0.19 mg/s) than small pipes. Neither discharge nor constituents varied by rainfall events. Pipe size may be a useful metric for estimating loads to a system. Nutrient reduction efforts should be directed to reducing the dissolved nutrient pools, while stormwater management efforts should be directed to reducing pipe freshwater discharge volumes that drive constituent loads. *Water Environ. Res.*, **87,** 796 (2015).

KEYWORDS: stormwater; drainage pipes; pipe size; rain intensity; TSS, nutrients.

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Introduction

Point source loads are typically defined as end of pipe loads and non-point source loads are characterized as diffuse overland runoff and groundwater inputs. Intermediary of point and non-point sources are stormwater drainage pipe loads, which, though defined as a point source (Novotny, 2003), differ from permitted wastewater point sources in their episodic nature and influence by surrounding landscape. Drainage pipe pollutant concentrations have been characterized and reported in some other areas (e.g., Toran and Grandstaff, 2007). However, this is poorly studied in watersheds along the Northern Gulf of Mexico coast. These storm pipe loads may be significant pollutant sources owing to their elevated chemical concentrations and connectivity to waterways through pipes that bypass natural pollutant buffers such as vegetation, soils, and riparian zones (Walsh et al., 2005; Edwards and Withers, 2008).

Studies of pollutant loading at the drainage pipe scale are needed because best management practices (BMPs) recommended for managing stormwater are typically implemented at a similar small scale. These BMPs include decentralized practices such as pervious parking lots, vegetated swales, and infiltration basins, all of which are important aspects of low impact development (US EPA, 2000). In sum, the BMPs seek to restore a more natural hydrologic connectivity from land to groundwater to surface water, thereby reducing stormwater runoff and pollutant loads. However, little is currently known about contributions of drainage pipes (i.e., number and size of pipes) to increased hydrologic connectivity (Hatt et al., 2004), thus making it difficult to quantitatively assess drainage pipe pollutant loads and to prioritize the placement of BMPs to reduce these loads.

In this study, we conducted a study to quantify stormwater discharge volumes, concentrations of suspended sediment, particulate carbon, and nutrient species from drainage pipes that discharge into a Mississippi coastal bayou, Bayou Chicot. We examined the effects of pipe size and rainfall intensity on storm pipe discharges, and constituent concentrations and loads. To our knowledge, there have been few previous studies that have examined the effects of pipe size on the magnitude of storm pipe loads. Determining such a scaling relationship will aid in assessment of the relative importance of storm pipe loading. Such relationships could also allow stormwater management entities challenged with reducing pollutant loads to prioritize areas for stormwater retrofits or planning for implementation of low impact development BMPs.

Materials and Methods

Study Area. The lower Bayou Chicot watershed (Figure 1) is located in the city of Pascagoula, Jackson County, Mississippi, which in 2010 had a population of 22 392 people. The lower watershed that encompasses the bayou has an area of 231

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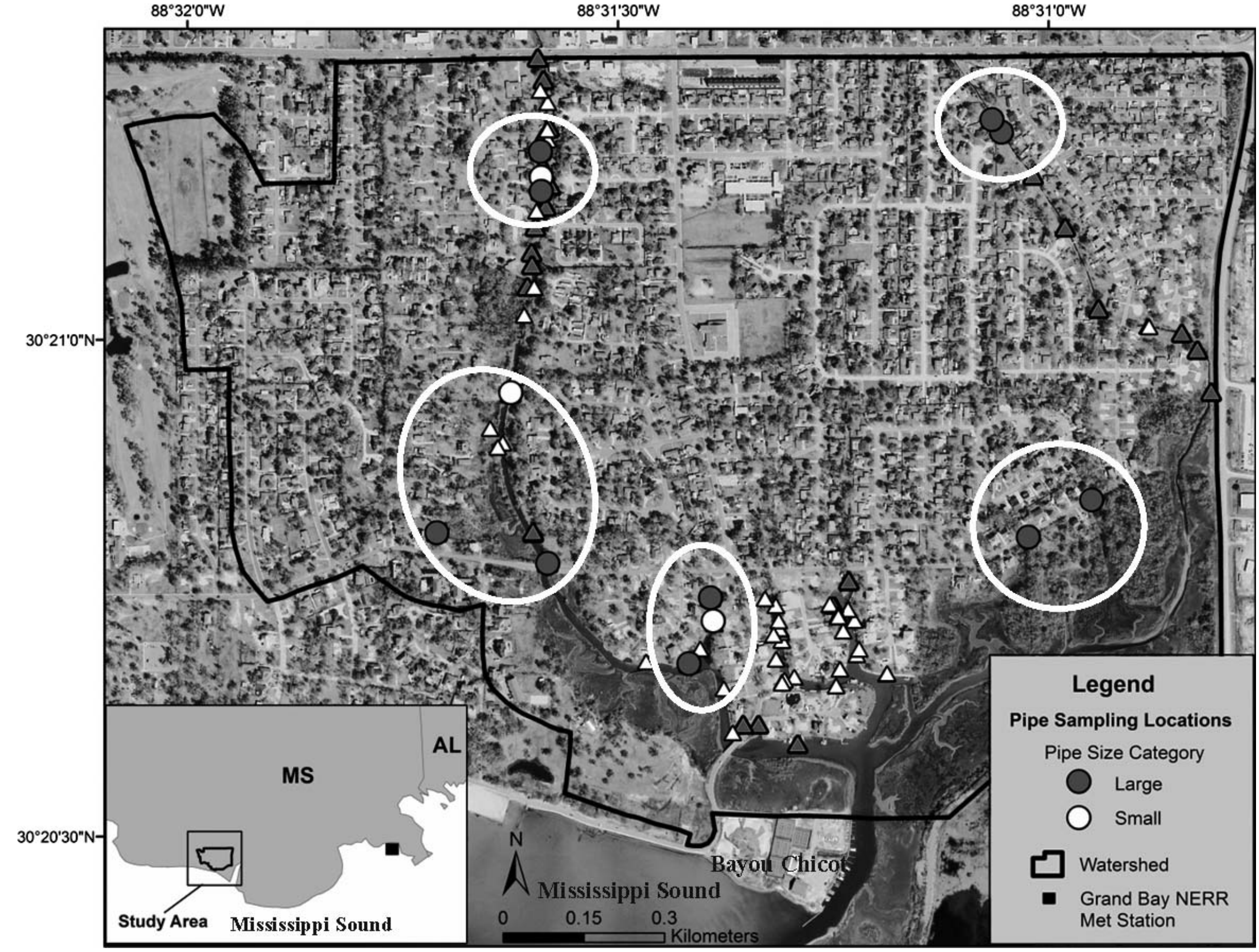

Figure 1—An aerial image of the urbanized study area watershed (delineated by the thick black line) and the locations of sampled (circles) and unsampled (triangles) storm pipes where gray symbols represent pipes > 20 cm internal diameter and white symbols represent pipes < 20 cm. The five sampling sections are shown within the white ovals. Inset (bottom left) is the study area relative to the northern Gulf of Mexico coastline of southeast Mississippi and southwest Alabama. The location of the Grand Bay NERR meteorological station (black square) is shown in the inset.

hectares. There were 1432 buildings within this watershed boundary, as counted from an aerial photograph (Figure 1), resulting in a building density of 6.2 buildings/hectare. Buildings immediately surrounding the Bayou Chicot were primarily residential.

Study Design and Data Collection. A census of the pipes along the banks of Bayou Chicot was conducted by small outboard motorboats in 2010. A total of 83 pipes were identified, and for each pipe the internal diameter was measured. These pipes were draining primarily from residential lawns and streets in the watershed, carrying the runoff underground and discharging it into the bayou. To stratify the pipes by size for sampling, pipes were categorized as small (< 20 cm in internal diameter) or large (>20 cm in internal diameter). Of the 83 pipes, only 13 pipes (3 small and 10 large) were readily accessible for rain event sampling.

Our sampling frame included all the 13 pipes that we could access following rainfall events from June 2010 to July 2011. Given the reduced number of pipes we could potentially sample, it was still not possible to manually sample all 13 pipes during each rainfall event because they were widely distributed across the study area (Figure 1). Thus, to obtain a spatially representative sample across the study area, we divided the area into five sampling sections. Three of the five sections contained two large and one small pipe, whereas the remaining two sections contained only two large pipes.

Once determined from Doppler radar that a rainfall event was likely to occur, we randomly selected one of the 5 sampling sections and sampled pipes from that section for the duration of the stormwater discharge event. Rainfall totals per event were determined from rainfall measurements recorded at 15-minute intervals at the Crooked Bayou meteorological station (Figure 1) maintained by the Grand Bay National Estuarine Research Reserve (about 10 km east of Bayou Chicot, NERRS, 2012).

During a sampling event, discharge measurements and water sample collections were made at the largest pipes first followed by smaller pipes (if present). For the first hour, stormwater was sampled every 6 to 7 minutes at each pipe. After the first hour, discharge monitoring continued every 6 to 7 minutes at each pipe, however, nutrient and suspended sediment sampling frequency was reduced to 20-minute intervals. This sampling process was continued until discharge ceased at all the pipes.

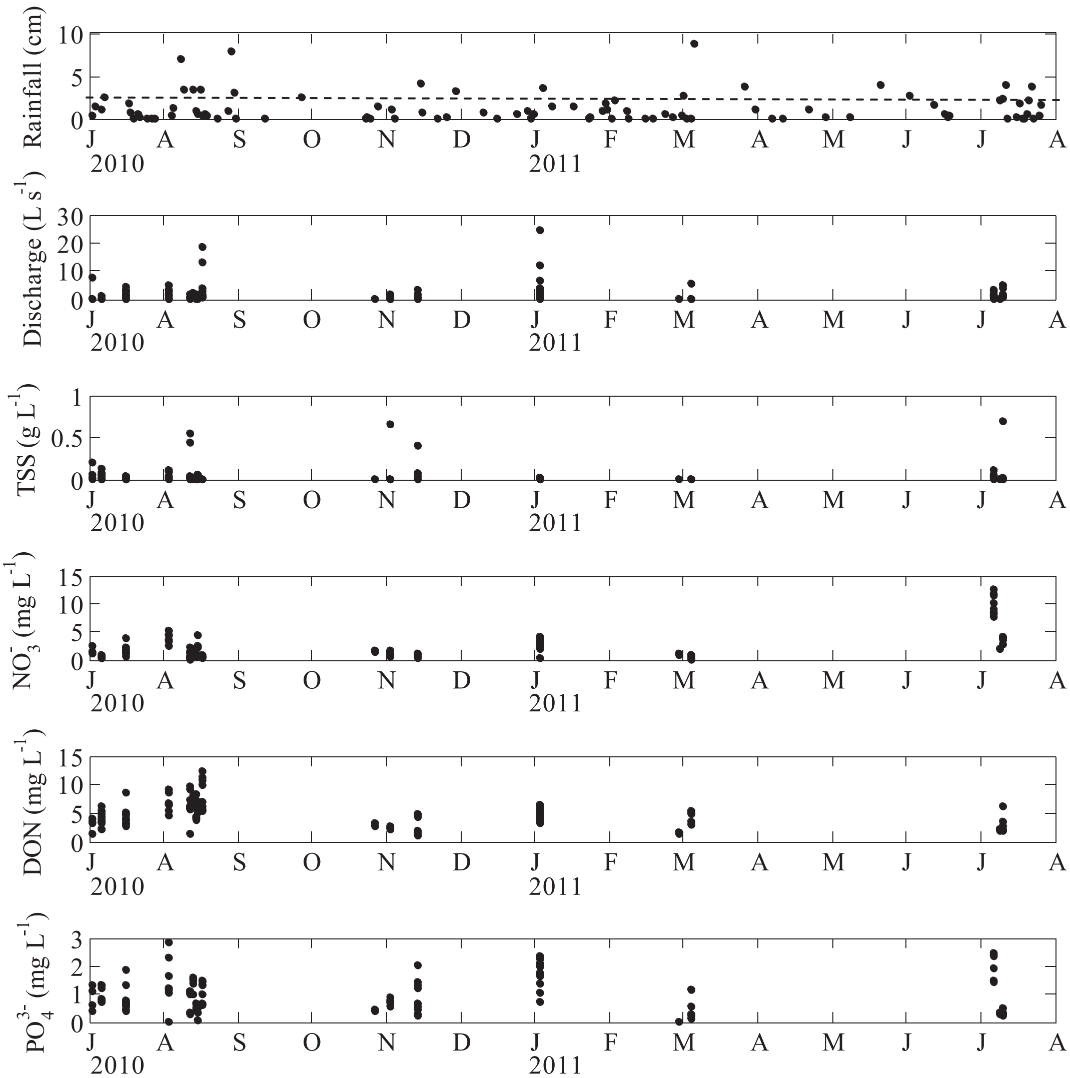

Figure 2—Daily cumulative rainfall and pipe measures of stormwater discharge, total suspended sediment (TSS), nitrate (NO_3^-), dissolved organic nitrogen (DON), and phosphate (PO_4^{3-}). The dashed line in the rainfall subplot represents 2.54 cm rainfall, which was used in this study to group observations by 'small $<$ 2.54 cm' and 'large $>$ 2.54 cm' rainfall events. Pipe discharge and concentration plots display the range of values observed across all pipes during sampled stormwater events (n = 19).

Pipe discharge (L/s) was measured by either recording the time required to fill an 18.9 L bucket or by using a current meter (Model 203R mechanical discharge meter, General Oceanics, Miami, FL). For the latter method, the flooded cross-sectional area of the pipe (cm^2) was calculated from measurements of pipe diameter and instantaneous water height within the pipe, and multiplied by the corresponding velocity measurements (cm/s) from the current meter. Water samples were collected either from the bucket used to measure discharge (triple-rinsed with sample water prior to sample collection) or by plunging a sample bottle (after a triple rinse) into the pipe discharge.

On the same day they were collected, water samples were brought back to the lab and filtered through ashes (450 °C for 90 minutes) pre-weighed glass fiber filters (Whatman GF/F nominal pore size = 0.7 μm). Samples for total suspended solids (TSS), particulate carbon (PC), and particulate nitrogen (PN) were collected on filter pads. Filtrate was collected in acid-washed bottles for determination of nitrate+nitrite (hereafter referred to as NO_3^-), ammonium (NH_4^+), dissolved organic nitrogen (DON), and phosphate (PO_4^{3-}). Samples were stored at –70 °C until they could be analyzed.

Analyses of pipe stormwater concentration were conducted following standard methods (APHA, 2005). Briefly, TSS (Method 2540 D) filters were dried at 105 °C and TSS was determined gravimetrically as the difference between the dried filter weight and the initial filter weight. PC and PN were assayed on a Carlo-Erba CN analyzer. NO_3^- (Method 4500-NO_3^- E), NH_4^+ (Method 4500-NH_3 F), PO_4^{3-} (Method 4500-P E), and total dissolved nitrogen (TDN) were determined colorimetrically on a Skalar SAN^{++} nutrient autoanalyzer. TDN samples were oxidized to NO_3^- prior to sample analysis by addition of persulfate followed by high temperature oxidation in an autoclave. DON was calculated as the difference of TDN – DIN, where dissolved inorganic nitrogen was $DIN = NO_3^- + NH_4^+$. Total nitrogen (TN) was calculated as the sum TDN + PN.

Table 1—Two-way ANOVA results for log transformed pipe discharge, constituent concentrations, and loads across two groups of pipe size (small < 20 cm internal diameter: large > 20 cm internal diameter) and two groups of daily cumulative rainfall (small < 2.54 cm rainfall; large > 2.54 cm rainfall). * denote significant result ($\alpha = 0.05$).

	Pipe Size			Rainfall			Pipe × Rainfall		
	df	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
Discharge	1	5.94	**0.02***	1	1.02	0.32	1	0.30	0.58
TSS	1	0.38	0.54	1	0.01	0.93	1	1.82	0.19
PC	1	0.07	0.79	1	0.92	0.35	1	0.80	0.38
PN	1	0.03	0.85	1	0.34	0.57	1	0.21	0.65
NO_3^-	1	0.92	0.34	1	0.01	0.91	1	0.93	0.34
NH_4^+	1	0.95	0.34	1	0.02	0.89	1	0.00	0.99
DON	1	1.43	0.24	1	2.37	0.14	1	0.94	0.34
PO_4^{3-}	1	0.22	0.64	1	1.14	0.30	1	2.67	0.11
TSS load	1	4.09	**0.05***	1	0.55	0.47	1	0.18	0.68
PC load	1	3.66	0.07	1	2.38	0.14	1	0.01	0.91
PN load	1	2.53	0.13	1	1.47	0.24	1	0.00	0.99
NO_3^- load	1	5.41	**0.03***	1	0.70	0.41	1	0.74	0.40
NH_4^+ load	1	5.76	**0.02***	1	0.77	0.39	1	0.19	0.67
DON load	1	3.07	0.09	1	2.06	0.16	1	0.40	0.53
PO_4^{3-} load	1	2.40	0.13	1	1.45	0.24	1	1.26	0.27

Data Analyses. Means and standard errors (SE) were calculated by pipe and by event from the time-series monitoring data collected. Data were grouped by factors of pipe size (i.e., small and large as defined above) and daily cumulative rainfall: large (> 2.54 cm) and small (< 2.54 cm) rainfall events. Two-way ANOVAs were conducted on log-transformed mean event discharges, nutrient concentrations, and loads to investigate the effects of pipe size and rainfall. If significant differences ($\alpha = 0.05$) were determined in the ANOVAs, post-hoc multiple comparison procedures were performed using Tukey's honestly significant difference criterion. Linear regressions were performed on pairs of constituent concentrations to test for covariation among various nutrient forms. Regressions, ANOVAs, and post-hoc multiple comparisons were performed in Matlab (Mathworks, Natick, MA).

Results

Rainfall Events and Storm Pipes. The study occurred during a period of severe drought across the southern U.S. During the study period there were 86 days with rainfall and a total rainfall accumulation of 115 cm at the Grand Bay NERR meteorological station (Figure 2). The average duration of rainfall events during these 86 days was 2.4 hours (SE = 0.27). Per our grouping into small rainfall events (< 2.54 cm daily accumulation) and large

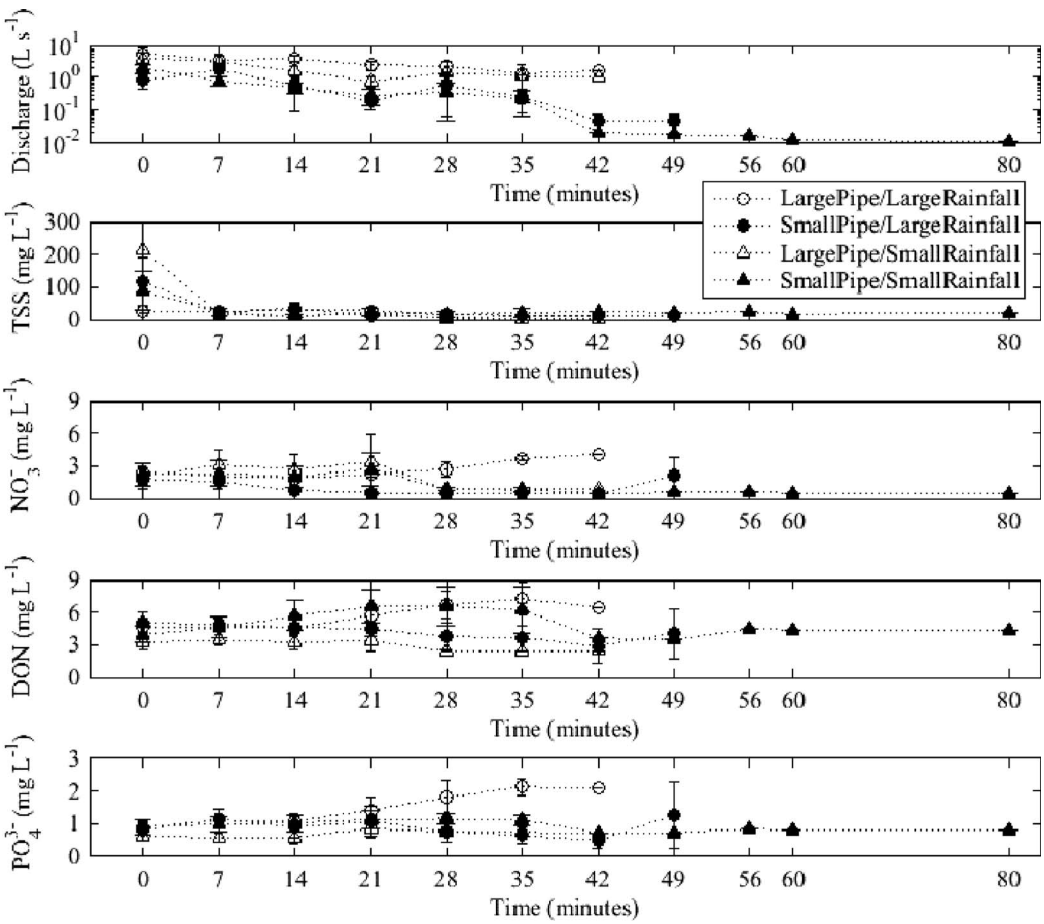

Figure 3—Mean sampling time history of discharge, total suspended sediment (TSS), nitrate (NO_3^-), dissolved organic nitrogen (DON), and phosphate (PO_4^{3-}) for combinations of large pipes/large rainfall, small pipes/large rainfall, large pipes/small rainfall, and small pipes/small rainfall.

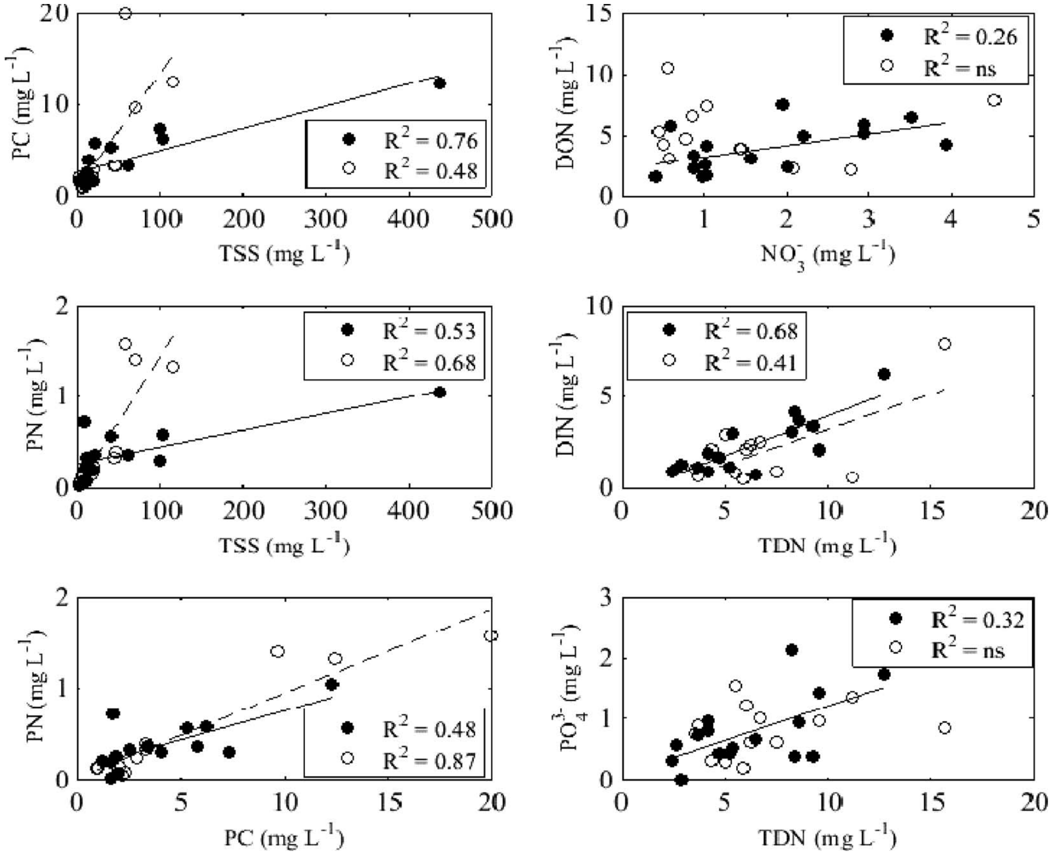

Figure 4—Large (black circles) and small (open circles) pipe relationships among event mean concentrations of particulate carbon (PC), nitrogen (PN), and total suspended sediment (TSS) (left column of plots) and among dissolved organic nitrogen (DON), dissolved inorganic nitrogen (DIN), and phosphate (PO_4^{3-}) (right column of plots). Regression results (solid lines for large pipes and dashed lines for small pipes) and R^2 are shown for significant ($\alpha = 0.05$) relationships between concentrations.

rainfall events (>2.54 cm), 70 of the rainfall events had cumulative daily totals < 2.54 cm and were classified as small and the remaining 16 were classified as large. Mean (SE) daily cumulative rainfall for small events was 0.64 (0.08) cm, while for large events was 4.28 (0.48) cm. In total, 22% (19 of 86) of the events were sampled to characterize stormwater discharges through pipes. Of the sampled rainfall events, 11 samplings were categorized as occurring during small (< 2.54 cm rainfall accumulation) events and 8 were large (> 2.54 cm accumulation). Mean cumulative rainfall during sampled small events was 1.38(0.21) cm, while mean rainfall during sampled large events was 5.16(1.08) cm.

Eighty-three storm pipes were counted in the study area with pipes ranging in size from 2.50 to 182.90 cm in internal diameter. Grouping by pipe size resulted in 51 small pipes (internal diameter range = 2.50 to 20 cm) and 32 large pipes (internal diameter range = 20 to 182.90 cm). However, as mentioned above, only 13 of the 83 pipes could be routinely sampled (Figure 1). Further, due to the random selection among the five sampling sections of the study watershed on a per event basis, at most, two large and one small pipe were sampled per event. A final consideration affecting our sample size was that for some events, not all pipes in a section produced discharge. Thus, of the 19 rainfall events sampled, we were able to collect stormwater time duration histories of discharge and constituent concentrations for 31 pipes. Of these 31 pipes, 14 were classified as small and 17 as large.

Storm Pipe Discharge and TSS, PC, and PN Concentrations and Loads. Larger pipes had significantly greater (Table 1) mean discharge [2.64(0.74) L/s] than small pipes [0.85(0.25) L/s]. However, mean pipe discharges were not significantly different among small and large rainfall events (Table 1). Following rainfall events, discharge decreased rapidly varying over orders of magnitude (Figure 3).

Observed effluent concentrations of TSS (1.5 to 694 mg/L), PC (0.5 to 56.3 mg/L), and PN (0.01 to 5.3 mg/L) ranged over two orders of magnitude across sampled rainfall events (Figure 2). However, mean concentrations did not vary significantly by pipe size or rainfall amount for any of the constituents (Table 1). The grand means (SE) of TSS, PC, and PN event means were 51.5(15.6), 4.67(0.91), and 0.44(0.09) mg/L, respectively. TSS, PC, and PN concentrations exhibited 'first flush' type dynamics with large initial runoff concentration decreasing with increasing discharge (Figure 3, PC and PN not shown).

Covariation among TSS, PC, and PN was observed (Figure 4), but the relationships were different in large and small pipes. TSS from small pipes tended to have a greater proportion of PC and PN than did TSS from large pipes. PC and PN exhibited similar relationships to each other for both small and large pipes. Thus, we hypothesized that the different relationships between PC/PN

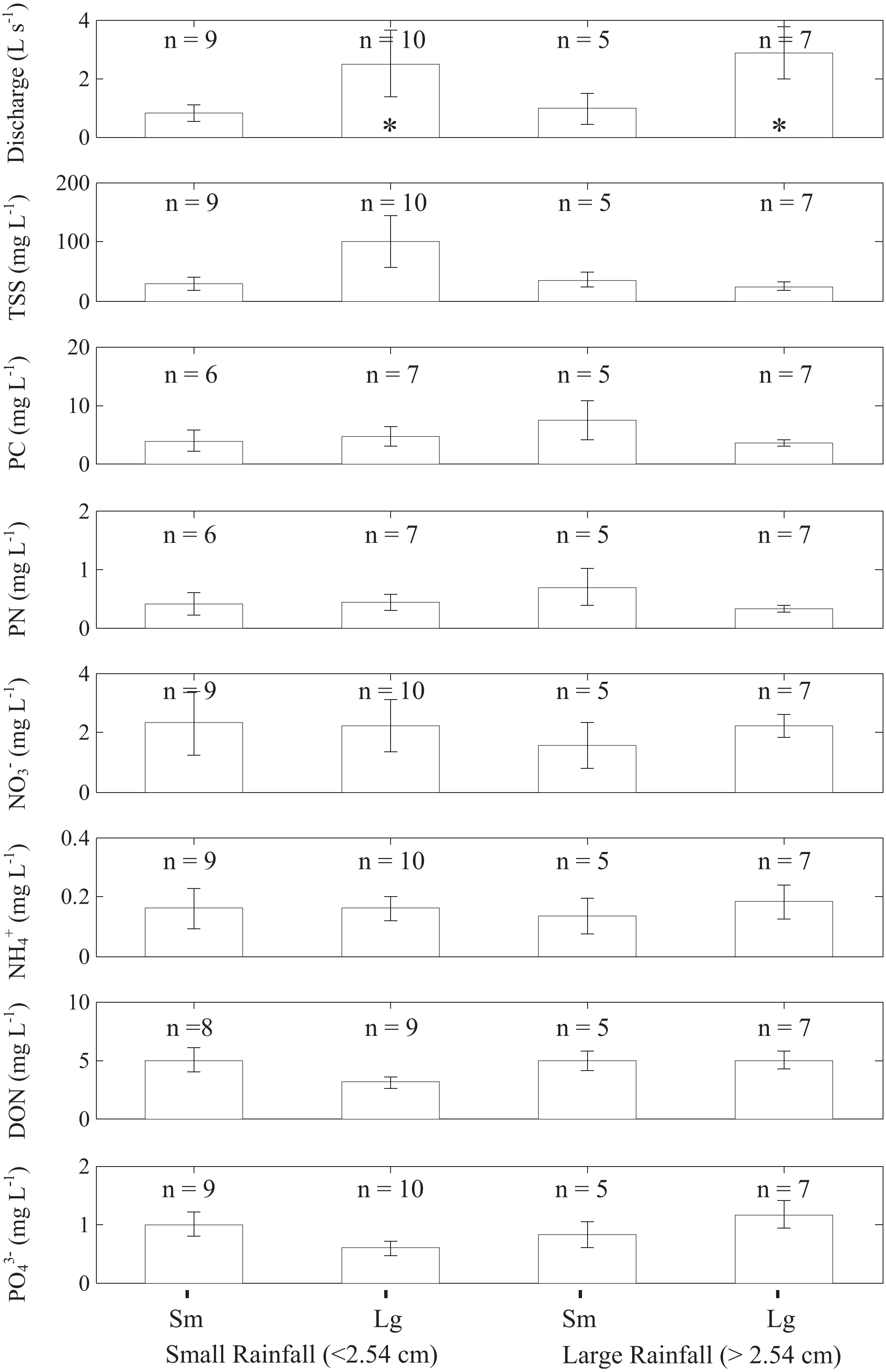

Figure 5—Discharge and constituent concentrations by small rainfall/small pipe, small rainfall/large pipe, large rainfall/small pipe, and large rainfall/large pipe. Small pipes (< 20 cm internal diameter) designated as Sm and large pipes (< 20 cm internal diameter) as Lg.

Table 2—Mean event discharge (L s^{-1}), constituent concentration (mg s^{-1}) and loads (mg s^{-1}) for small and large pipes (small $<$ 20 cm internal diameter: large $>$ 20 cm internal diameter). Sample size (n) and standard errors (SE) of the mean are shown. * denotes statistical difference in loads by small and large pipes (ANOVA on log-transformed loads, $\alpha = 0.05$).

	Small Pipes		Large Pipes		
	n	mean (SE)	n	mean (SE)	*p*
Discharge	14	0.85 (0.25)	17	2.64 (0.74)	**0.02***
TSS	14	31.1 (8.73)	17	68.3 (27.2)	0.34
PC	11	5.46 (1.82)	14	4.06 (0.83)	0.86
PN	11	0.53 (0.18)	14	0.38 (0.07)	0.89
NO_3^-	14	2.04 (0.72)	17	2.20 (0.53)	0.45
NH_4^+	14	0.15 (0.05)	17	0.17 (0.03)	0.30
DON	13	4.96 (0.70)	16	3.91 (0.47)	0.22
PO_4^{3-}	14	0.93 (0.16)	17	0.83 (0.14)	0.44
TSS load	14	24.0 (11.0)	17	138.2 (53.0)	**0.03***
PC load	11	6.16 (4.80)	14	9.51 (2.53)	0.06
PN load	11	0.52 (0.38)	14	0.87 (0.23)	0.11
NO_3^- load	14	2.74 (1.29)	17	5.54 (1.59)	**0.03***
NH_4^+ load	14	0.19 (0.09)	17	0.39 (0.10)	**0.02***
DON load	13	4.74 (1.86)	16	12.7 (4.56)	0.10
PO_4^{3-} load	14	0.79 (0.28)	17	2.69 (1.00)	0.18

and TSS in small and large pipes is due to a larger inorganic fraction of TSS in the large pipes.

Mean constituent loads per event were calculated as the product of event mean discharge (i.e., the average of the monitored discrete discharges) and mean concentration (i.e., the average of the monitored discrete concentrations). Thus, because of the differences in discharge among small and large pipes (Table 1), the constituent loads of TSS, PC, and PN varied by pipe size (Figure 5). TSS loads were nearly 6-fold greater from large pipes than small pipes with average loads being 138.2 (53.0) mg/s and 24.0 (11.0) mg/s, respectively. The differences between large and small pipe loads for PC and PN were smaller and not statistically significant, likely due to the smaller sample sizes (Table 2).

Storm Pipe Dissolved N and P Concentrations and Loads. NO_3^-, NH_4^+, DON, and PO_4^{3-} exhibited order of magnitude concentration ranges across events, 0.2 to 12.7, 0.02 to 0.9, 1.3 to 12.5. 0.01 to 2.9 mg/L, respectively (Figure 2, NH_4^+ not shown). Dissolved nutrient concentrations were not significantly related to pipe size or rainfall (Table 2). Grand means (SE) of concentrations (mg/L) were calculated for $NO_3^- = 2.13$ (0.42), $NH_4^+ = 0.16$ (0.03), DON = 4.38 (0.41), and $PO_4^{3-} = 0.87$ (0.10); total nitrogen TN = 7.11 (0.60) mg/L consisted mainly of NO_3^- (29%) and DON (62%). Interestingly, during pipe sampling events, dissolved nutrient concentrations did not exhibit 'first flush' concentration patterns (Figure 3, NH_4^+ not shown). Similar to TN, TDN variation was primarily explained by DON (Figure 4) and to lesser extent by DIN. PO_4^{3-} and TDN were also observed to covary in large pipes. Relationships among dissolved nutrients were similar for both large and small pipes.

Because of the greater discharge from large pipes, some dissolved nutrient loads were also larger for large pipes (Figure 5). NO_3^- and NH_4^+ loads were approximately twice as large in large pipes as in small (Table 2), NO_3^-: 5.54 (1.59) versus 2.74 (1.29) mg/s and NH_4^+: 0.39 (0.10) versus 0.19 (0.09) mg/s. Large pipe average DON loads of 12.7 (4.56) and PO_4^{3-} loads of 2.69 (1.00) mg/s were also double the loads from small pipes, but were not statistically different owing to the large standard errors.

Discussion

Storm pipe concentrations of all constituents were highly variable (Figure 2) with some of the within event variability attributable to first flush type responses that were observed for discharge and TSS (Figure 3). In contrast to a first flush response, dissolved nutrient concentrations remained fairly level across different pipe discharges (Figure 3) suggesting that relatively homogenous sources of nutrients were being mobilized during rainfall events. These nutrient results are consistent with those observed from stormwater runoff from pipes draining a residential area of Philadelphia, Pennsylvania, USA (Toran and Grandstaff, 2007).

In comparison to the national TSS mean value of 150 mg/L for stormwater runoff from residential areas (US EPA, 1983), mean TSS observed in this study, 51.5(15.6) mg/L was smaller. In contrast, the mean TN of 7.11(0.60) mg/L and mean PO_4^{3-} of 0.87(0.10) observed in this study were much larger than the EPA (1983) national urban runoff mean TN and TP of 2.0 mg/L and 0.36 mg/L, respectively. The study mean TN and PO_4^{3-} concentrations also greatly exceeded those observed in nearby urbanized streams in southwest Alabama, where median TN and TP concentrations ranged from 0.5-0.8 and 0.01-0.05 mg/L, respectively (Lehrter, 2008). Background concentrations of TN and TP in streams of the southern U.S. coastal plain range from 0.2-0.9 and 0.02-0.04 mg/L, respectively (Smith et al., 2003). The sources of the N and P in the study area are not known. However, there is a possibility that sources to this study area may be similar to those described for other systems where sources have been identified as lawn fertilizers, atmospheric deposition, automobile exhaust, detergents, and septic and sewer leaks (US EPA, 1983).

The homogeneity of nitrogen composition and concentration during different rainfall (Table 1) and discharge (Figure 3) events has also been suggested to result from the highly turbulent and oxidized situation in urban storm pipes that may establish equilibrium between N species (Taylor et al. 2005). A similar mechanism may explain the relatively constant relationships observed in this study between DON, DIN (mainly NO_3^-), and TDN (Figure 4) and the relatively constant proportion of TN as NO_3^- (29%) and DON (62%). Similarly, in the large pipes, PO_4^{3-} and TDN covaried (Figure 4), which may indicate the dissolved N and P pools are possibly derived from similar sources.

Likewise, the source material for TSS, PC, and PN was the same based on the covariation observed among these constituents (Figure 4). However, different from the dissolved constituents, the slopes of the relationships of PC and PN with TSS varied by pipe size such that PC and PN were a greater fraction of TSS in small pipes than in large pipes. We speculate that this difference was due to greater mobilization and conveyance of inorganic sediments (e.g. sand) in the large pipes. The similarity in the slopes of the relationships between PC and PN in the small and large pipes (Figure 4) seems to negate the possibility of substantially different particulate organic sources as a reason for the differing relationships with TSS.

Although constituent concentrations did not vary across small and large pipes (Figure 5), pipe discharge and several of the constituent loads (Figure 6) did significantly vary with pipe size

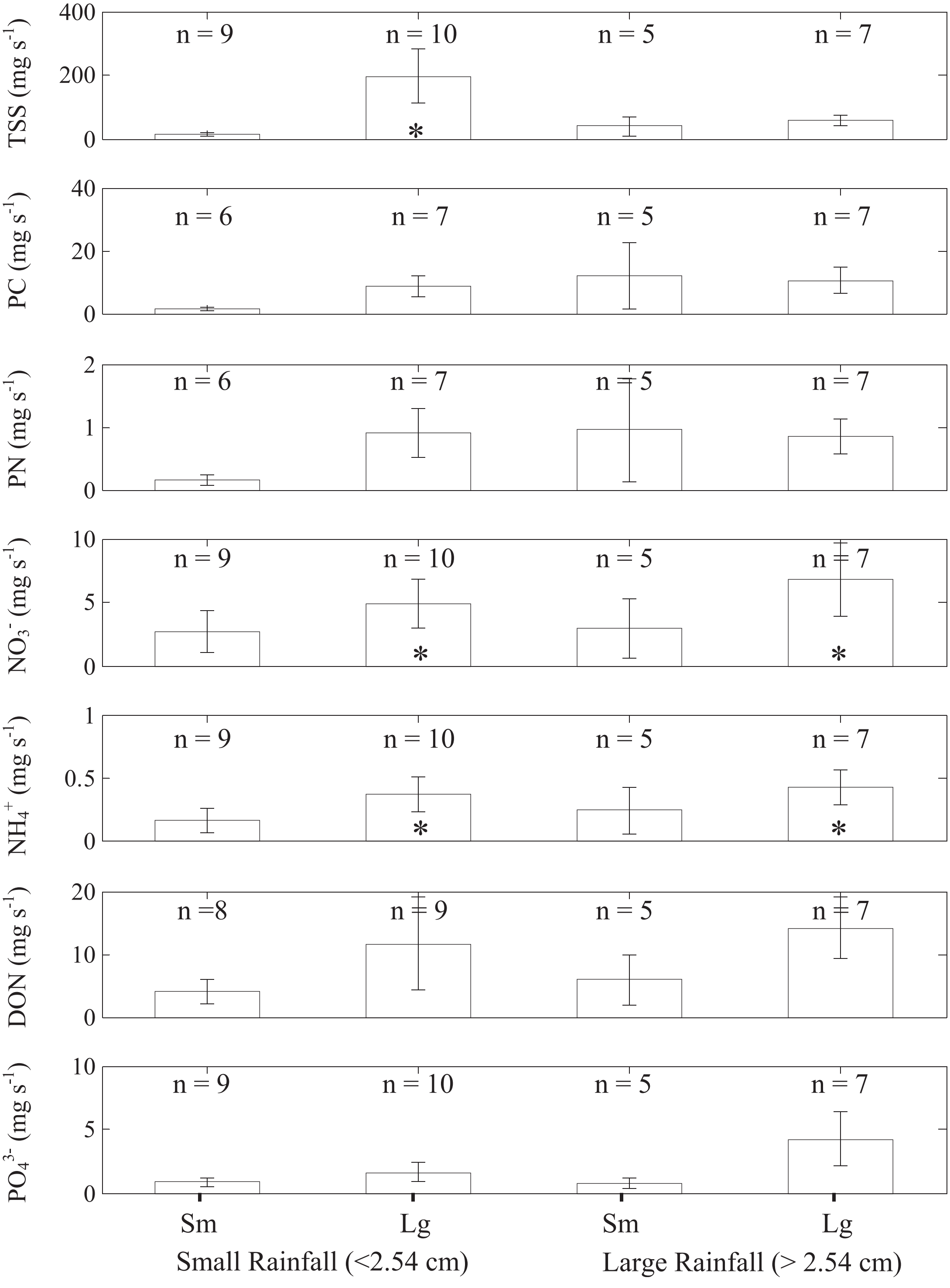

Figure 6—Constituent loading rates by small rainfall/small pipe, small rainfall/large pipe, large rainfall/small pipe, and large rainfall/large pipe. Small pipes (< 20 cm internal diameter) designated as Sm and large pipes (< 20 cm internal diameter) as Lg.

(Table 1). The constituent loads, which are the products of the discharge and concentration, varied due to the differences in discharge between small and large pipes (Table 2). These results indicated that pipe size is a measure of hydrologic connectivity as large pipes convey greater discharges and loads and thereby have greater hydraulic transfer efficiency from the watershed to the receiving water body. This interpretation is consistent with observations from a stormwater study that showed increased drainage connectivity between impervious surface areas and pipes resulted in greater pollutant loads (Hatt et al., 2004). The increased hydrologic connectivity associated with pipe drainage may also result in overall greater nutrient concentrations because the pipes bypass soils and riparian areas where denitrification and uptake by bacteria and plants attenuate nutrient transport (Groffman et al., 2002).

The intensity of rainfall events did not significantly impact pipe discharges (Table 1), constituent concentrations (Figure 5) or loads (Figure 6). However, there were some notable differences in mean loads of TSS, DON, and PO_4^{3-} for small and large rainfall events (Figure 6). TSS loads were greater from large pipes during the small rainfall events, while DON and PO_4^{3-} were greater from large pipes during large rainfall events. The DON and PO_4^{3-} loads fit the expectation that larger rainfall results in greater loads from large pipes. Greater TSS loads during small rainfalls, however, is counter-intuitive.

The management implications of our results are that nutrient reduction efforts need to be directed towards reducing the dissolved nutrient pools, especially for nitrogen, which in this study TDN was 91% of TN. This information may become more useful for coastal managers as annual amount of rainwater and frequency of runoff from a specific site can be estimated by the recent released US EPA's National Stormwater Calculator (US EPA, 2014). Pipe number and pipe size may be useful for assessing which pipes may be the largest contributors of stormwater loads, which could suggest target areas for reduction efforts. In addition, best management practices (BMPs) for low impact development should be implemented to reduce pipe freshwater discharge volumes that are the main drivers of loads. Future work examining the effects of pipe size and rainfall intensity on pollutants loads would greatly benefit from sampling more pipes and events, especially in wet years.

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