AGU100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE
10.1029/2019WR024769

Key Points:
- Urban streams had more discharge across all flows, more cumulative discharge at higher flows, and reduced seasonality
- Stream nutrient export increased, shifted to higher flows, and relative importance of dissolved organic N decreased with imperviousness
- Particulate N ranged from 19 to 42% of total N export, and was highest in the stream draining stormwater ponds due to pond algal production

Supporting Information:
- Supporting Information S1

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Citation:
Gold, A. C., Thompson, S. P., & Piehler, M. F. (2019). The effects of urbanization and retention-based stormwater management on coastal plain stream nutrient export. *Water Resources Research*, *55*, 7027–7046. https://doi.org/10.1029/2019WR024769

Received 14 JAN 2019
Accepted 15 JUL 2019
Accepted article online 25 JUL 2019
Published online 21 AUG 2019

The Effects of Urbanization and Retention-Based Stormwater Management on Coastal Plain Stream Nutrient Export

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Abstract Stormwater nutrient pollution can be more effectively managed if there is a predictable link between urbanization and pollutant export. The goal of this study was to determine the effects of increased watershed impervious surface cover (ISC) and retention-based stormwater management on stream discharge and nutrient export from coastal plain streams in the southeastern United States. To quantify coastal plain stream nutrient export, measurements of stream discharge and concentrations of dissolved nutrients, particulate nitrogen, and algal biomass (as chlorophyll *a*) were collected during baseflow and stormflow for four years from five streams on Marine Corps Base Camp Lejeune near Jacksonville, North Carolina. The study streams had watersheds that spanned a range of ISC (1–38%) and included an urban watershed drained extensively by stormwater ponds. Urban streams had higher rates of annual discharge than less impacted streams due to elevated discharge at all rates of flow, more cumulative discharge at high flows, and dampened seasonal patterns. Streams with higher watershed ISC had higher rates of annual export of all measured nutrients due to increased stream discharge and concentrations of inorganic and particulate nitrogen. The relative importance of dissolved organic nitrogen decreased with watershed ISC, but it was still the dominant form of nitrogen export in every study stream except the stream that was dominated by particulate nitrogen export from stormwater pond algal production. Based on these findings, this study suggests that stormwater management emphasizing stormwater harvesting and evapotranspiration, increased wetland area, and decreased anthropogenic nutrient sources could reduce nutrient export from urban coastal plain streams.

1. Introduction

Urbanization changes watershed hydrology and increases stream nutrient export (O'Driscoll et al., 2010; Walsh et al., 2005), but understanding the specific effects of urbanization can allow for more effective municipal water management. The typical effects of urbanization are increased rates of stormflow and decreased rates of baseflow (Paul & Meyer, 2001; Walsh et al., 2005), but this change in hydrology (especially at low flows) is also influenced by changes in evapotranspiration, contributions from leaky wastewater infrastructure, and physical properties of watersheds or drainage networks (Bhaskar, Beesley, et al., 2016; Meierdiercks et al., 2017; Price, 2011; Walsh et al., 2005). Various relationships between concentration and discharge can suggest mechanisms of nutrient delivery to a stream and sources of nutrients within a watershed (Duncan et al., 2017; Musolff et al., 2015), which can be important for management given that urbanization alters watershed biogeochemical processes, increases nutrient sources, and degrades nutrient sinks (Hobbie et al., 2017; Kaushal et al., 2011; Newcomer Johnson et al., 2014; Reisinger et al., 2016). Understanding changes in hydrology, sources of nutrients, and pathways of nutrient delivery with urbanization can help determine what type of stormwater management strategy might be most effective (Jefferson et al., 2017).

Coastal plain streams in the southeastern United States have unique hydrology and biogeochemistry that suggests that they may have a different response to urbanization than streams from other regions. The effects of urbanization on watershed hydrology and stream nutrient dynamics can vary by region and depend on physiographic attributes (Hopkins et al., 2015; Utz et al., 2011). For example, a study comparing the Mid-Atlantic coastal plain and Piedmont found that urbanization affected stream water quality similarly between the two regions, but hydrologic metrics associated with high flows were more affected by urbanization in the coastal plain than the Piedmont (Utz et al., 2011). Many coastal plain streams in the southeastern United States are characterized as "blackwater" streams due to high concentration of dissolved organic matter derived from forested wetlands (Meyer, 1990) and watersheds with low slopes and sandy soils (Markewich et al., 1990). Dissolved organic nitrogen (DON) is the dominant form of dissolved nitrogen in these blackwater coastal plain streams while concentrations of dissolved inorganic nitrogen (DIN) and algal biomass are low (Meyer, 1990; Tufford et al., 2003 ; Wahl et al., 1997). Previous studies in this area have found that even small increases in DIN can cause algal blooms (Mallin et al., 2004), and urbanization increases the concentrations of DIN (Tufford et al., 2003; Wahl et al., 1997), the volume of streamflow (Wahl et al., 1997), and the flashiness of streamflow (Jayakaran et al., 2014). Further, coastal plain streams may have a disproportionate impact on nutrient-sensitive coastal waters due to their close proximity that limits processing within the stream network compared to upland streams. Coastal environments are ecologically, economically, culturally, and recreationally important (Costanza et al., 1997), but nutrient enrichment from land-based nutrient export has degraded water quality and ecosystem function in many estuaries (Bricker et al., 2008; Deegan et al., 2012) and freshwater tidal creeks (Sanger et al., 2013).

Previous studies have reported some effects of urbanization on southeastern U.S. coastal plain streams, but there are still gaps in understanding that must be addressed to inform management (O'Driscoll et al., 2010). The relative amount of particulate nitrogen (PN) has not been measured in either less impacted or urban coastal plain streams, nutrient export for all nitrogen species during storm events has not been quantified due to methodological challenges (Mallin et al., 2009; Tufford et al., 2003; Wahl et al., 1997), and there are few records of long-term measurements of streamflow and nutrient export across a range of watershed ISC. The effects of stormwater control measures on watershed hydrology and nutrient export compared to unmitigated urban development is an especially critical gap in understanding given the mandated use of stormwater control measures for new development in this region. Determining the effects of coastal plain watershed urbanization on stream nutrient export and discharge is critical for informing stormwater management policy for coastal areas and improving coastal water quality through effective mitigation.

To address these gaps in understanding, this study measured four years of streamflow and nutrient export (dissolved and particulate nitrogen, orthophosphate, and algal biomass) from five streams with watersheds spanning a range of imperviousness in the coastal plain of North Carolina. One of the three urban watersheds was drained by stormwater ponds, which allowed for comparisons in discharge and nutrient export between types of stormwater management strategies. The primary goal of this study was to determine the impacts of increased watershed ISC and retention-based stormwater management on stream discharge and nutrient export from coastal plain streams in the southeastern United States. Specifically, this study analyzed the magnitude and timing of stream discharge and nutrient export and the relationships between nutrient concentrations and discharge.

2. Materials and Methods

2.1. Study Sites

Five streams with watersheds spanning a wide range of imperviousness (1–38%) on U.S. Marine Corps Base Camp Lejeune (MCBCL) in Jacksonville, NC were selected for study (Figure 1 and Table 1). Watersheds were delineated in ArcGIS 10.4 using 1-m resolution elevation data provided by the Environmental Services division of MCBCL, and watershed impervious area was manually delineated using high-resolution orthoimagery collected by the MCBCL in 2013. The MCBCL is the largest Marine Corps base in the world and surrounds most of the New River Estuary. The study area lies in the outer coastal plain, an area comprised mostly of sandy soils that range from excessively drained to very poorly drained (Soil Survey Staff, 2015) and was historically vegetated with longleaf pine savannah with bottomland hardwood species fringing the streams (Messina & Conner, 1997; Outcalt & Sheffield, 1996). Natural streams in this area are blackwater, low-gradient streams. The MCBCL provided an excellent location to study the impacts of urbanization on coastal plain stream nutrient export due to the range of impervious cover of watersheds within its boundaries and the fact that all study watersheds were owned by the same entity, thus constraining differences in management that could impact hydrology (e.g., groundwater withdrawal, stormwater control measure selection, and maintenance). As a labeling convention, the percent watershed ISC is used to identify streams and watersheds (e.g., 1% ISC stream, 1% ISC watershed).

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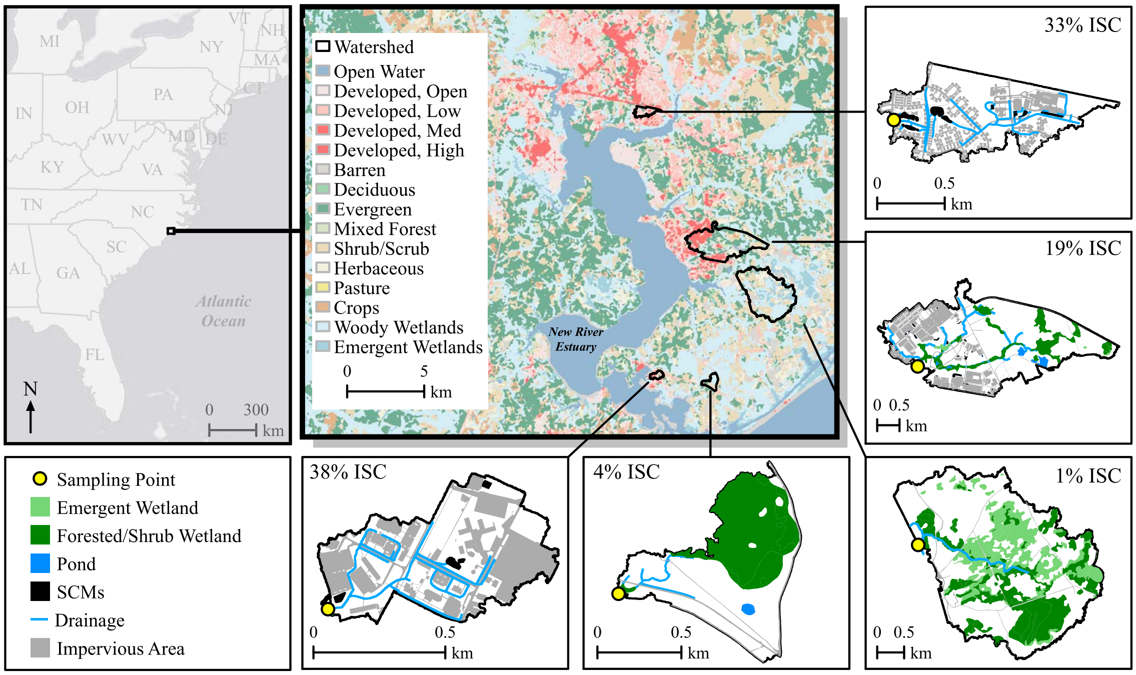

Figure 1. Overview map of study watersheds and stream sampling locations. Land cover data from the 2011 NLCD data set and the USFWS.

The study watersheds ranged in size and imperviousness but were all located along the eastern shore of the New River Estuary (Figure 1 and Table 1). The two watersheds with the lowest levels of imperviousness (1% and 4% ISC) exemplified the two most common natural land cover types in this area. The 1% ISC watershed contains large areas of emergent wetlands, forested wetlands, and shrub/scrub land cover, while the 4% ISC watershed contains mostly forested wetlands and shrub/scrub land cover (Table S1; Gold et al., 2017a). The 19% ISC watershed contains high-density, commercial land cover and large amounts of forest and forested wetland cover (Table 1). The stormwater management in this watershed drains approximately half of the impervious area in the watershed using retention ponds and infiltration basins, and most of the stormwater is routed to stormwater control measures or the stream by a complex network of ditches along the road network (Table 1). The 33% ISC watershed contains mostly residential urban area, and 97% of the watershed area is drained by curb and gutter drainage to stormwater retention ponds (Gold et al., 2017a; Table 1). The most impervious watershed in this study (38% ISC) contains commercial development that is drained through a series of ditches along the roadways, and a parking lot drains to a stormwater retention pond near the sampling site (Table 1). The most impervious watershed was undergoing construction during data collection, resulting in increased watershed ISC from 24% to 38% between 2009 and 2013. The watershed was denoted as 38% ISC in this study because this amount of ISC was maintained for most of the study period. Watershed ISC was the main focus of this study because this metric was negatively

Table 1
Study Watershed Statistics

ISC (name)	ISC (%)	Area (ha)	Unmitigated impervious area (%)	Total wetland area[a] (%)	Percent well-drained[b] (%)
1% (French)	0.96	835.05	0.96	42.19	35.07
4 % (Traps)	3.93	61.48	3.92	44.37	23.17
19% (Cogdel)	19.24	725.41	9.49	12.37	70.03
33% (Tarawa)	33.27	70.16	0.98	0.44	82.87
38% (Courthouse Bay, CHB)	38.16	31.77	26.13	0.11	100.00

[a]Total wetland area (%) does not include area of stormwater retention ponds. [b]Hydrologic soil types A and B for areas not under impervious surfaces.

correlated with wetland cover (R^2 = 0.95) and positively correlated with percent well-drained soils (hydrologic class A or B; R^2 = 0.94; Table 1). Together, these sample sites capture variation in watershed ISC as well as differences in stormwater management at the higher limit of imperviousness.

2.2. Discharge, Export, and Concentration Measurements

Streams from the five study watersheds were gauged for discharge for a period of four years (June 2011 to June 2015) using Teledyne Isco automatic water samplers outfitted with flow sensors (acoustic Doppler velocity and pressure transducer level). Velocity and level measurements were recorded every 30 min, and stream cross sections allowed for the conversion of level and velocity measurements to stream discharge. Twice-monthly water grab samples were collected, filtered through Whatman GF/F filters (25-mm diameter, 0.7-μm nominal pore size), and analyzed for nitrate-N (NO_x^-; detection limit = 0.05 μM), ammonium (NH_4^+; detection limit = 0.24 μM), DON (detection limit = 0.75 μM), and orthophosphate (PO_4^{3-}; detection limit = 0.02 μM) with a Lachat QuickChem 8000 nutrient autoanalyzer. Filters were then analyzed for chlorophyll *a* (Chl *a*) as a proxy for algal biomass. Analysis for Chl *a* was conducted with a Turner Designs Trilogy fluorometer after sonicating and extracting frozen filters for 24 hr in a 90% acetone solution (Welschmeyer, 1994). Results for Chl *a* will be referred to interchangeably as algal biomass. PN concentrations were measured during the final two years of the study (June 2013 to June 2015). PN was measured by filtering water samples with the filters specified above and analyzing filters for nitrogen content with a Costech Elemental Combustion System with Elemental Analysis software. Water samples were also collected at greater frequency during storm events for one storm a month with the Isco automatic water samplers using a velocity-based trigger and flow-paced sampling scheme set to span the entire storm hydrograph. Export was calculated for each 30-min interval to match the frequency of discharge measurements. Baseflow and stormflow volumes were calculated by delineating discharge volume into baseflow or stormflow during manually identified storm events using a digital filter (Nathan & McMahon, 1990). During baseflow, export was estimated for each water quality variable by multiplying the most recent measured baseflow nutrient concentration by discharge (period-weighted approach—discussed by Aulenbach et al., 2016). During storm events, concentration was interpolated between storm samples encompassing the hydrograph (regression-model approach—discussed by Aulenbach et al., 2016). Export during unsampled storm events was estimated by multiplying measured discharge by concentration calculated from discharge-concentration relationships for rising and falling limbs of sampled storms. All values of export and discharge were normalized by watershed area for comparisons between study streams. Data analysis was conducted in Microsoft Excel and R (R Core Team, 2019).

2.3. Streamflow and Hydrologic Metrics

Daily discharge values were calculated by summing measurements of discharge collected every 30 min for each day, and daily discharge values were used for all analyses. Average annual streamflow was calculated for each stream by taking the mean of annual discharge for each year of the sampling period ($n = 4$). Dates of missing streamflow data due to equipment failures were not estimated, but annual values of discharge and export were adjusted for missing days (48 missing days total, mostly 17 August 2011 to 20 September 2011 due to equipment removal prior to tropical storm). Daily discharge values sorted from low to high were used to calculate percentiles for each value of discharge as well as cumulative discharge for each stream following established methods (Duan et al., 2012; Pennino et al., 2016; Shields et al., 2008). Gini coefficients, which can be used as a measure of temporal inequality in discharge or nutrient export (Jawitz & Mitchell, 2011), were calculated from this sorted list of discharge values using the “ineq” R package. The Richards-Baker flashiness index was calculated for each month for each stream, although two months were removed due to missing data (August and September 2011; Baker et al., 2004). Baseflow index (BFI) values were calculated, and average annual BFI values were calculated. Paired *t* tests were performed on log-transformed annual streamflow and BFI values to test for significant differences between streams ($\alpha = 0.05$). Discharge values for each study stream were parsed into seasons (winter = December, January, February; spring = March, April, May; summer = June, July, August; fall = September, October, November), and differences between seasons were determined through nonparametric Kruskal-Wallis and Dunn's tests ($\alpha = 0.05$) because data could not be normalized with transformations.

2.4. Nutrient Export and Concentrations

Average annual export for each water quality constituent was calculated in the same way as average annual discharge, and paired *t* tests were performed on log-transformed annual values to test for significant differences between streams ($\alpha = 0.05$). The ratios of dissolved nitrogen species from water samples were plotted on a ternary plot using the ggtern R package (Hamilton & Ferry, 2018). Differences in concentrations of various water quality constituents between study streams were analyzed using one-way ANOVAs and Tukey HSD post hoc tests on log-transformed concentration measurements. To analyze the timing of export, the ranked discharge values from each stream were used to calculate cumulative export and cumulative percent export for each water quality constituent using the same methodology discussed previously for cumulative discharge.

2.5. Relationships Between Concentration, Discharge, and Export

Metrics that describe the influences of discharge and concentration on nutrient export were calculated for each study stream and water quality constituent. The metric CV_C/CV_Q, which compares the coefficient of variation of concentration measurements to the coefficient of variation of discharge measurements (Thompson et al., 2011), was calculated for manually sampled concentration and discharge measurements (n range = 211–249). The linear slope of the log-log relationship between measured concentration and discharge (b from the equation $C = aQ^b$, where C = concentration and Q = discharge) was calculated for each study stream and measured water quality constituent. Due to the inclusion of concentration and discharge measurements below detection limits, a value of 0.01 was added to all values of discharge and orthophosphate and a value of 0.1 was added to all values of nitrate, ammonium, and DON. The combination of the CV_C/CV_Q metric and C-Q slope can suggest nutrient sources and means of delivery from the watershed to the stream. For example, a water quality variable that has a low CV_C/CV_Q value (<0.5) and low b value ($-0.2 < b < 0.2$) would be considered chemostatic (i.e., variability in discharge control export). The b value can better inform the source of water quality variables that are chemodynamic ($CV_C/CV_Q > 0.5$, variability in concentration control export), with positive b values indicating a flushing of material during storm events and negative b values indicating dilution of material due to increased discharge (Godsey et al., 2009).

To compare the export of nitrogen species across flows, values of discharge were binned every 10 percentiles, and the export of each species of nitrogen was summed within each bin. The ratio of export of each nitrogen species in each bin was then calculated.

3. Results

3.1. Streamflow and Hydrologic Metrics

Average annual stream discharge increased with watershed ISC, and this increase in overall discharge volume with watershed ISC was driven by increases in streamflow across all flows and more cumulative discharge at high flows (Figure 2). The 38% ISC stream had much higher flow than all of the other study watersheds, and had nearly twice the amount of discharge as precipitation (~1.3 m/year of precipitation; Figure 2). In general, streamflow flashiness and the relative importance of high flows to overall discharge volume increased with watershed ISC and BFI decreased with watershed ISC (Figure 2 and Table S2). However, the hydrologic metrics of the 4% ISC stream were similar to those of the streams with the most developed watersheds despite large differences in discharge volume. The timing of the "flashy" behavior of the 4% ISC stream differed from that of the more developed streams, with higher values of flashiness occurring during months with less discharge and low BFI values rather than more discharge and low BFI values (Figure S2).

Stream discharge was highest during winter for every study stream, but there were differences in the seasonal patterns between the study streams for the other seasons (Figure S1). The two least developed streams had significantly lower summer flows compared to all other seasons, which aligns with peak growing season and increased evapotranspiration. The 4% ISC stream had no flow during periods of the summer for the first two years of the study. The three more developed streams either exhibited a muted seasonal pattern or a different seasonal pattern than that of the less developed streams (Figure S1 and Table S3). Streamflow in these three streams was continuous throughout the year.

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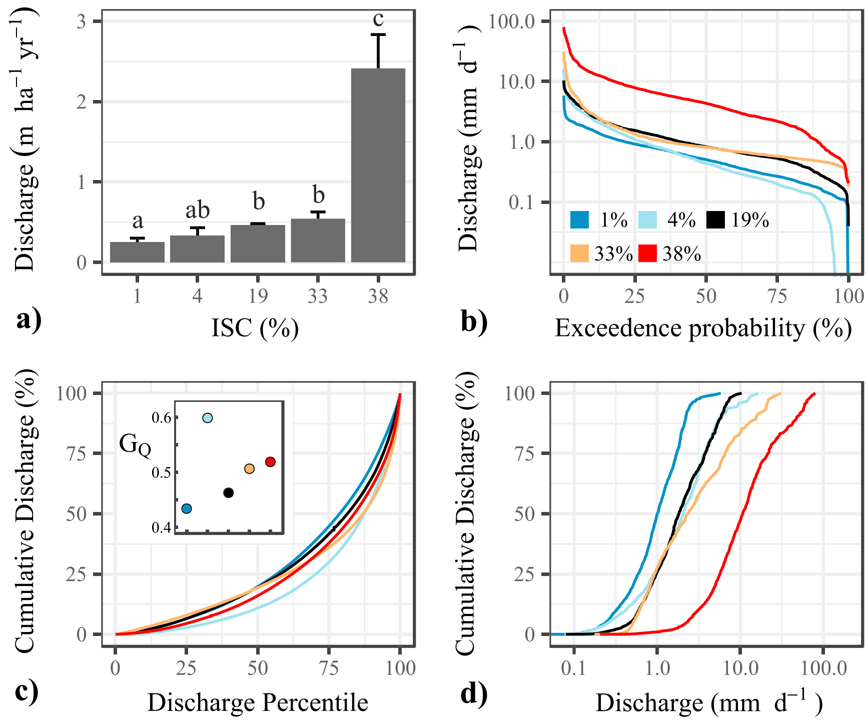

Figure 2. (a) The mean annual volume of streamflow, (b) flow duration curves, (c) Lorenz curves of discharge with Gini coefficients (inset), and (d) cumulative flow distribution curves for each study stream. Letters indicate significant differences based on paired *t* tests ($p < 0.05$). Error bars indicate standard error.

3.2. Nutrient Export and Concentrations

Average annual nutrient export increased with watershed ISC for all measured variables, but as with discharge, export from the 38% ISC stream was much higher than all other streams (Figure 3 and Table S4). DON export was similar between all streams except for the most urban stream which had much higher rates of export (Figure 3). Differences between the three more developed streams and the two less developed streams were largest for nitrate and algal biomass export (Chl *a*), while the two most developed streams had higher rates of export than all other watersheds for ammonium, orthophosphate, and PN (Figure 3). There were no discernable differences in seasonal patterns of nutrient export between watersheds (Figure S1), and nutrient export from each watershed followed similar seasonal patterns as discharge (Figure S1). Generally, nutrient export was highest in the winter during higher flows and was lowest in the summer or spring during lower flows (Figure S1).

All water quality variables had more exports during higher flows with increasing watershed ISC (Figure S4). This pattern was similar to discharge, with watersheds (except the most developed stream) grouping together at lower flows and diverging at high flows.

Concentrations generally increased with watershed imperviousness for all measured variables except DON and orthophosphate (Table 2). The 19% ISC stream had concentrations that were similar to the two least developed streams except for higher concentrations of nitrate and significantly lower concentrations of DON (Table 2). The 33% ISC stream had significantly higher concentrations of all measured variables except DON (second lowest concentrations) and ammonium (second highest concentrations; Table 2). The most urban stream had much higher concentrations of ammonium than all other streams as well the highest or second highest concentrations of all other variables (Table 2). Different seasonal trends in concentrations between watersheds were only apparent for nitrate. Compared to other seasons, the two least developed streams had significantly higher summer concentrations of nitrate that coincided with higher seasonal temperatures and significantly less discharge (Figure S1), while lower nitrate concentrations coincided with the coldest seasonal temperatures and the highest discharge (Figure S1). In contrast, the three streams with more impervious

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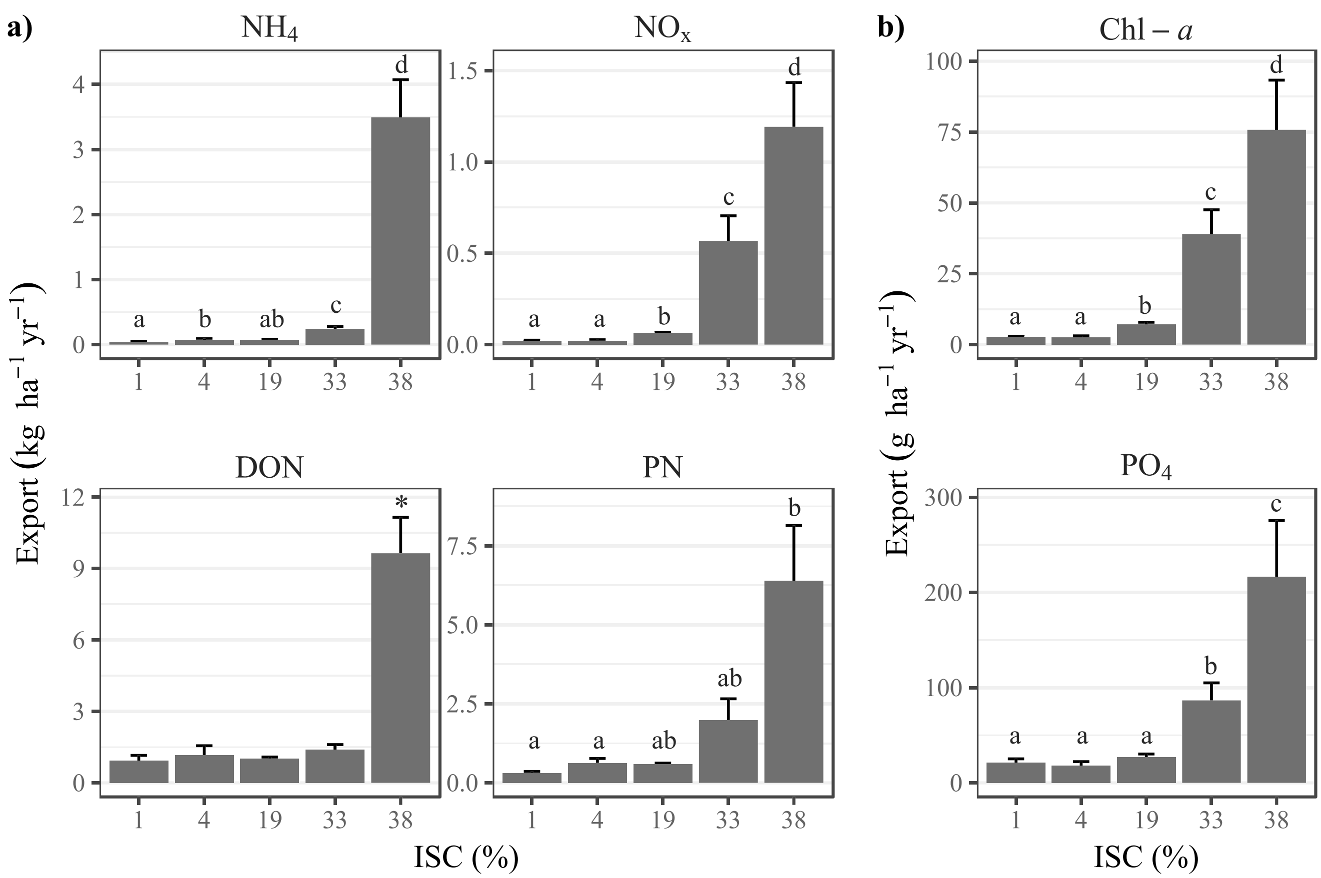

Figure 3. (a) Mean annual export of measured variables over the entire study period (June 2011 to June 2015) in kg/ha and (b) g/ha. Note different y axes for each plot. Particulate nitrogen (PN) was only measured for the last two years of the study period (June 2013 to June 2015). Letters (or asterisk when only one group is different) indicate significant differences based on paired t tests ($p < 0.05$). Error bars indicate standard error.

watersheds had the highest concentrations of nitrate during the winter and followed the same pattern as discharge (Figure S1).

There were clear differences in the dominant forms of nitrogen export between study streams (Figures 4a and 4b). Overall, DON was the dominant form of nitrogen exported from all study streams except the 33% ISC stream with stormwater ponds, where particulate nitrogen was the dominant form of nitrogen exported (Figure 4b). PN export was generally the second largest species of nitrogen exported followed by either ammonium or nitrate. The relative importance of DON to total nitrogen export decreased with watershed ISC, while the relative importance of PN and DIN export increased (Figure 4b). The increase in the relative importance of DIN export was driven by different nitrogen species in the most urban study streams—the 33%

Table 2
Summary of Nutrient Concentrations From Study Streams (Mean ± SE)

ISC (%)	NO_x (μM)	NH_4 (μM)	DON (μM)	PN (μg/L)*	PO_4 (μM)	Chl *a* (μg/L)
1	0.75 ± 0.05^a	1.26 ± 0.04^a	26.38 ± 0.81^{ab}	137.68 ± 11.98^a	0.29 ± 0.01^a	1.39 ± 0.11^a
4	0.68 ± 0.08^a	1.59 ± 0.09^a	24.61 ± 0.76^b	156.35 ± 13.62^a	0.21 ± 0.01^b	0.97 ± 0.11^b
19	1.34 ± 0.11^b	1.2 ± 0.08^b	14.6 ± 0.34^c	167.88 ± 23.15^a	0.26 ± 0.01^a	1.55 ± 0.17^a
33	5.93 ± 0.26^c	3.96 ± 0.35^c	19.51 ± 0.51^d	313.86 ± 23.22^b	0.64 ± 0.03^c	11.27 ± 0.96^c
38	4.25 ± 0.29^d	12.69 ± 1.45^d	27.88 ± 0.73^a	229.14 ± 14.84^b	0.31 ± 0.02^a	4.79 ± 0.35^d

Note. Letters indicate significant differences between means based on one-way ANOVAs and Tukey HSD post hoc tests of log-transformed data.
*Data from only final two years of study.

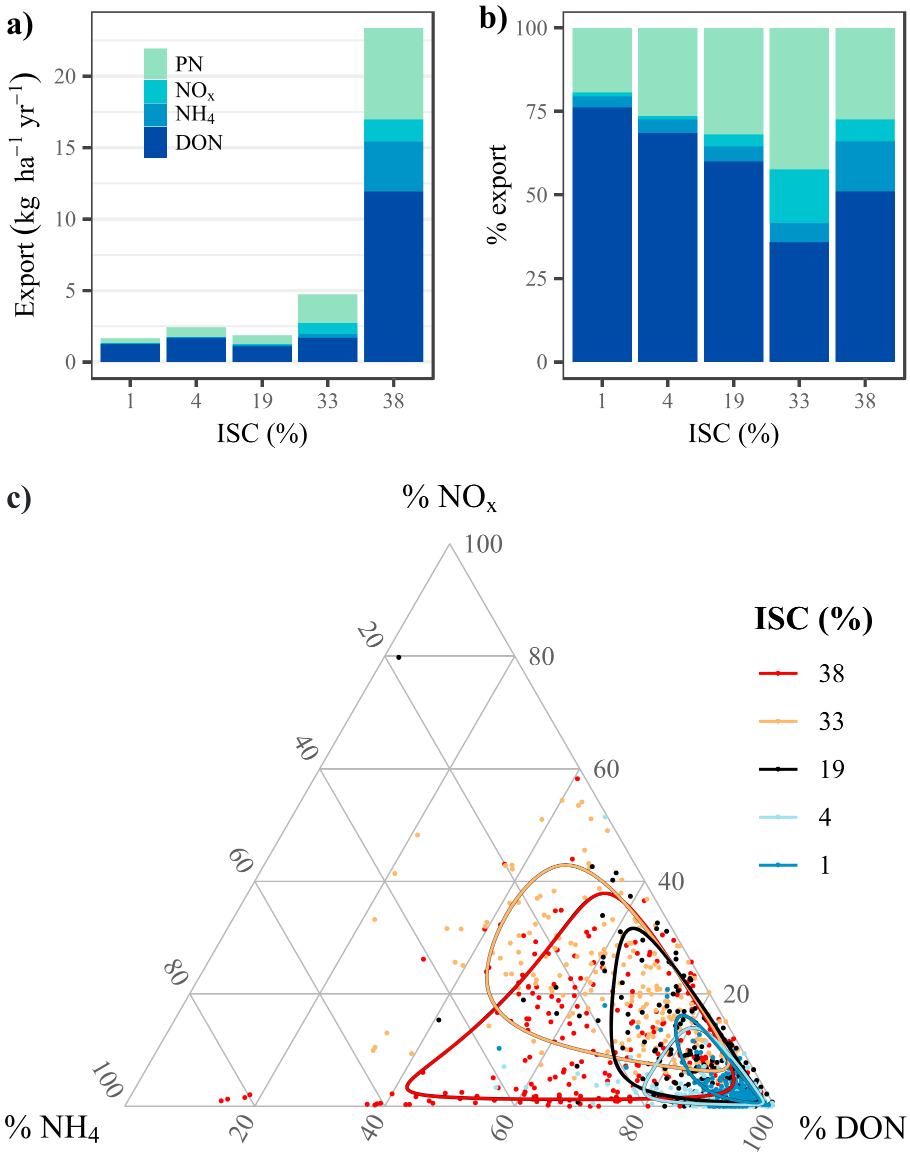

Figure 4. (a) Mean annual total nitrogen export, (b) the relative export of nitrogen species for each study stream between June 2013 to June 2015 when PN was measured, and (c) a ternary plot showing the percent of each dissolved nitrogen species within water samples collected over the entire study period with outlines of 66% confidence intervals to illustrate groupings. ISC = impervious surface cover of watershed.

ISC stream had more nitrate export than ammonium and the most urban stream had more ammonium export than nitrate (Figure 4b). The decreased relative importance of DON in the more urban watersheds also corresponded with increased Chl *a* concentrations and particulate N concentrations (Figure S3).

The differences in the dominant forms of nitrogen between study streams can also be visualized by comparing the percent contribution of each dissolved nitrogen species to total dissolved nitrogen in collected water samples (Figure 4c). The two less developed streams cluster at high percentages of DON and low DIN percentages. The stream with the 19% ISC watershed also encompasses high % DON and low % DIN water samples, but it also extends farther out along the % NO_x and % NH_4 axes. Finally, the two most urban streams move away from high % DON (very few water samples near 100% DON) and extend out along the % NO_x and % NH_4 axes farther than the other study streams. Similar to Figure 4b showing the relative important of different nitrogen species to export, the 33% ISC has higher values of % NO_x and the most urban stream has higher values of % NH_4.

3.3. Relationships Between Concentration, Discharge, and Export

Plotting *b*, or the linear slope of the log-log relationship between concentration and discharge, versus CV_C/CV_Q can classify the export regime of a stream and point to possible sources within the watershed (Musolff et al., 2015). For ammonium, the 4% ISC stream was the only stream that was chemostatic, the 1% ISC stream and the 33% ISC stream were slightly chemodynamic with *b* values of approximately zero, and the 19% ISC stream and the 38% ISC stream were more chemodynamic with negative *b* values indicating the dilution of ammonium with increased discharge (Figure 5). Nitrate export from the two most developed streams was chemodynamic with small *b* values, the 19% ISC stream was chemodynamic with a positive *b* value, and the two least developed streams exhibited large, negative *b* values (Figure 5). DON export was chemostatic for all streams except the least developed stream, which was weakly chemodynamic and had a positive *b* value (Figure 5). All study streams had small *b* values for PN export, but the 4, 33, and 38% ISC streams were weakly chemodynamic and the 1 and 19% ISC streams were strongly chemodynamic (Figure 5). This grouping of streams aligns with differences in watershed size, which can influence CV_C/CV_Q values (Diamond & Cohen, 2018). Differences in Chl *a* CV_C/CV_Q values between streams were similar to that observed for PN, but the main difference in *b* values was that the 33% ISC stream with stormwater ponds had a large and positive *b* value while the other study streams had small *b* values (Figure 5). All study streams had orthophosphate CV_C/CV_Q values indicating chemostatic or weak chemodynamic behavior, and the *b* value generally increased with watershed ISC (Figure 5).

There were small differences between cumulative nutrient export and cumulative discharge that can be seen by comparing the relationship between the two indices, and this comparison can highlight important periods of export in water quality variables that are chemodynamic (Figure S5). Only patterns that differ from the *C*-*Q* slopes presented above are shown. For nitrate, the least developed stream had more cumulative export than discharge at lower flows compared to all other watersheds despite a wide range of *b* values among streams (Figure S5). Every stream except for the least developed stream had relatively more ammonium export than discharge at lower flows (Figure S5). Higher flows were important periods of PN export for all study streams despite differences in *b* and CV_C/CV_Q values (Figure S5).

The speciation of nitrogen export across flows differed based on watershed ISC (Figures 6 and S6). Relative to total nitrogen export, the relative amount of DON increased and PN decreased from low to high flows in both less developed streams (Figures 6b and S6). Also, the importance of ammonium decreased from low to high flows in the 4% ISC stream. The timing of export for all nitrogen species was similar for the two less developed streams except for nitrate in the 1% ISC stream and ammonium in the 4% ISC stream (Figures 6 and S6). The three more urban streams had notable increases in the importance of PN export from low to high flows (Figures 6b and S6). There was also a slight decrease in the importance of DON and DIN export from low to high flows, although the speciation of inorganic species varied among the more urban streams (Figures 6b and S6). The more extreme differences in speciation of nitrogen export across flows in the three more urban streams led to larger differences in the timing of cumulative nitrogen export among nitrogen species (Figure 6c). PN was exported at higher flows than all other nitrogen species in the three more urban streams, followed by nitrate in the 19 and 38% ISC streams and DON in the 33% ISC stream (Figure 6c).

4. Discussion

4.1. Watershed Hydrology and ISC

This study found that streams with more developed watersheds had higher rates of discharge across all flows, more cumulative discharge at higher flows, and dampened seasonal patterns of discharge when compared to streams with less developed watersheds (Figures 2 and S1 and Table S3). These findings agree with studies in other physiographic regions that observed increased high flows during storms but differ slightly from previous studies that found urbanization typically decreases discharge at low flows (Hardison et al., 2009; O'Driscoll et al., 2010; Walsh et al., 2005). Also, the shift toward more discharge at higher flows with watershed ISC appears to be less intense than in other areas, likely because of increased low flows. R-B flashiness values generally increased with watershed ISC which was also reported in past studies, but the 4% ISC stream was flashy at low and intermittent flows during the summer (Figure S2 and Table S2). The

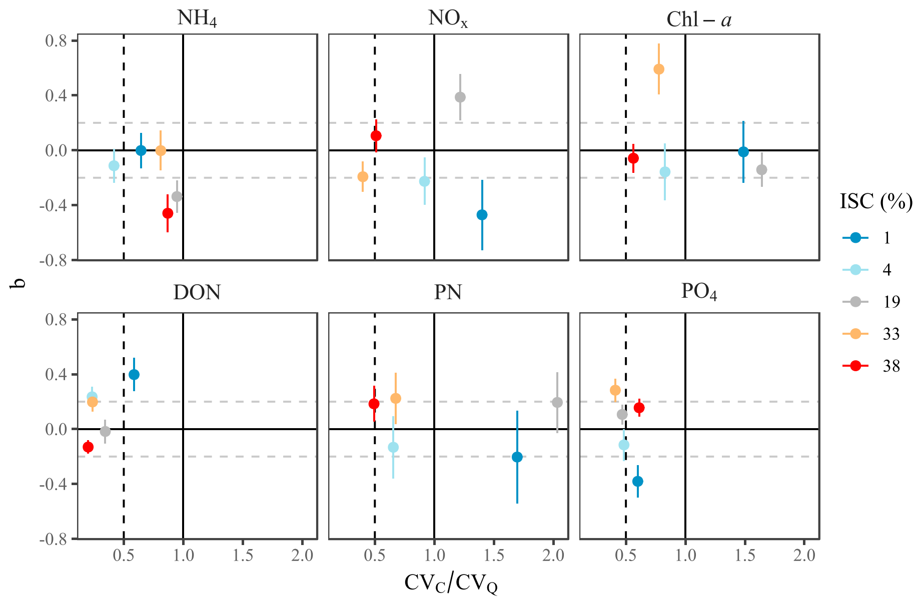

Figure 5. CV_C/CV_Q (proxy of export regime) and b (linear slope of log-log C and Q relationship) for each stream. Values of CV_C/CV_Q that are less than 0.5 indicate chemostasis, and values of b between 0.2 and −0.2 (between horizontal grey lines) indicate weak flushing or dilution patterns.

flashy behavior at low flows in the 4% ISC stream due to storm events during intermittent summer flow highlights the fact that seasonal differences in discharge were dampened in the more impervious watersheds (Figure S1 and Table S3).

The most likely mechanisms for the increased rates of discharge across all flows and dampening of seasonal trends with increasing ISC are increased stormwater runoff, reduced evapotranspiration, increased input from wastewater infrastructure, and increased surface water storage in the form of stormwater ponds. Elevated stormflow and decreased infiltration due to impervious surfaces is an extremely well documented occurrence (Walsh et al., 2005) that was evident in this study. Increased discharge at low flows may be due to decreased evapotranspiration from forested and wetland area in the urban watersheds. Approximately 70% of precipitation in southeastern coastal plain wetlands is evapotranspired (Sun et al., 2002) and decreased evapotranspiration can lead to increased discharge (Mclaughlin et al., 2013). Increased discharge due to decreased evapotranspiration has been observed previously in urbanizing watersheds with well-drained soils (Barron et al., 2013) and in southeastern coastal plain watersheds that experience large losses of forested land for silviculture (Mclaughlin et al., 2013; Sun et al., 2010). Increased flow from decreased evapotranspiration in urban areas hypothesized here may be regionally specific, though, as a study of streams in the inner Coastal plain found that increasing watershed ISC led to deeper water tables and decreased baseflow (Hardison et al., 2009). Water inputs from leaky water and wastewater infrastructure can also lead to increases in discharge (Bhaskar, Beesley, et al., 2016; Price, 2011), and this likely explains the consistently high flow in the most urban stream which was undergoing additional development during the study period. The extensive use of stormwater ponds, which are not designed to reduce stormwater volume but rather to reduce peak flows and extend the hydrograph (Hancock et al., 2010), may have contributed to reduced seasonality in discharge by supplementing low flows after storm events (two- to five-day drawdown period). Decreased seasonality in baseflow has been observed in low-impact development watersheds that have extensive stormwater infiltration (Bhaskar, Hogan, et al., 2016), and while we observed a similar decrease in seasonality, flow from stormwater ponds to the stream could consist of either infiltration or flow to the stream due to drawdown of the temporary pond storage volume. Increased discharge and reductions in seasonality of flow have been noted in southeastern coastal plain streams previously (Jayakaran et al., 2014; Wahl et al., 1997), so this phenomenon is likely caused by decreased evapotranspiration and supplemented by stormwater ponds or wastewater infrastructure leaks.

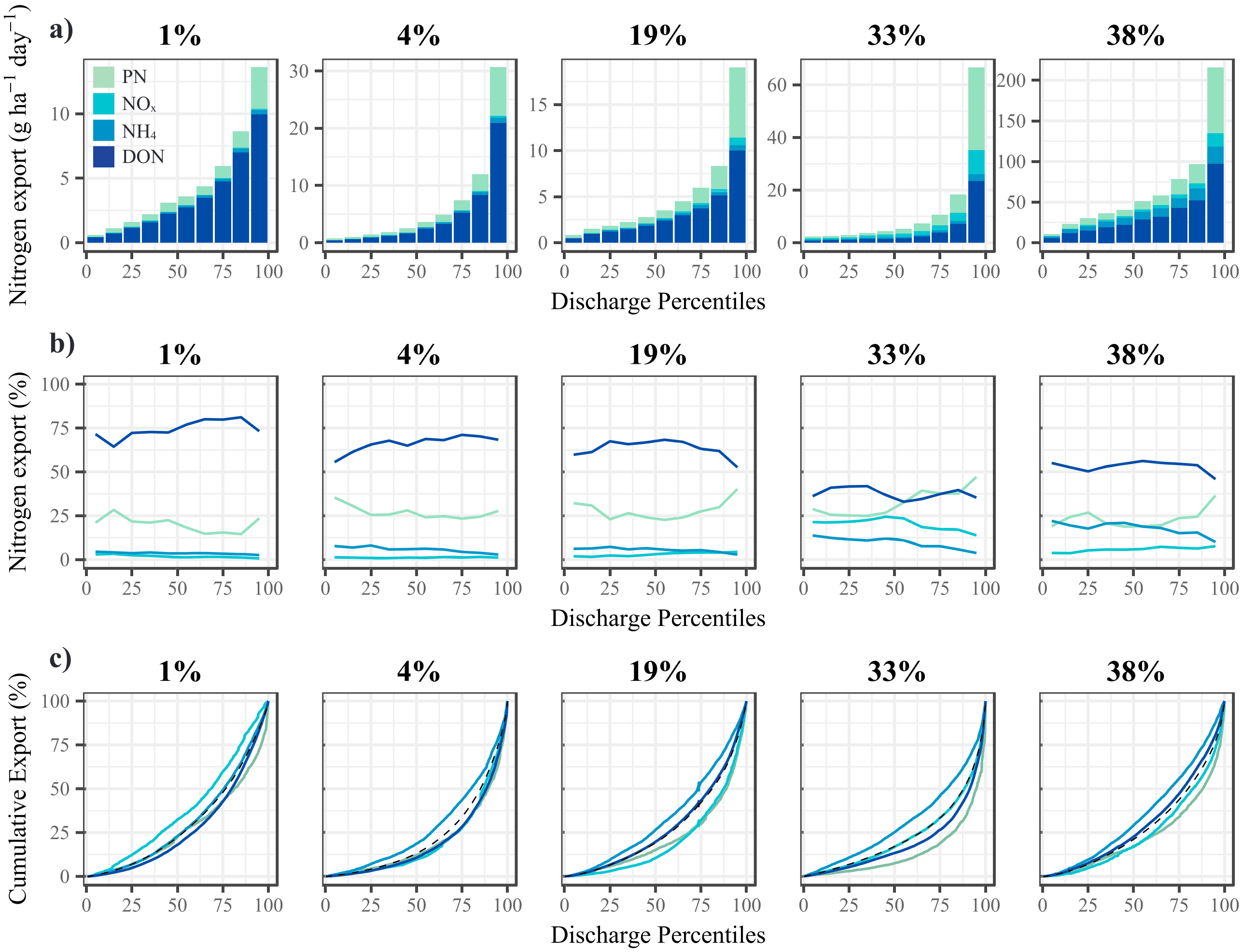

Figure 6. (a) Total nitrogen export separated into nitrogen species over the full range of flows, (b) the percent of each nitrogen species exported within each bin of discharge percentiles (bins = 10), and (c) cumulative export for each nitrogen species across the full range of flows. Data are from the final two years of monitoring (June 2013 to June 2015).

4.2. Stream Nutrient Export and ISC

Stream nutrient export increased with watershed ISC, and this increase was caused by elevated discharge, inorganic nitrogen export, and PN export. More nutrients were exported at higher flows in the more urban streams as seen in past studies (Duan et al., 2012; O'Driscoll et al., 2010; Paul & Meyer, 2001; Walsh et al., 2005), but nitrate and PN export notably shifted to higher flows relative to other nitrogen species with increasing watershed ISC (Figure 6). The two streams with the least developed watersheds exhibited typical blackwater stream biogeochemistry—low N, high proportions of DON, and low concentrations of algal biomass and PN. The three more urban streams maintained the same amount of DON export (or greater in the case of the 38% ISC stream), but were differentiated from the less developed streams by increased concentrations and export of DIN, PN, and algal biomass.

The quantity of DON exported from the study streams was similar to export from streams and rivers throughout the continental United States (Lewis, 2002) and western Australia (Petrone, 2010), although concentrations were lower than those from forested watersheds in a review of DON concentrations (Pellerin et al., 2006). PN export is often not reported due to methodological constraints, but PN export from the two least developed streams was similar to minimally disturbed streams in the SE United States and Maryland coastal plain (Correll et al., 1999; Lewis, 2002), and PN export from the more urban streams was much higher than streams of similar imperviousness in western Australia (Petrone, 2010). The export of nitrate from the study streams was lower than previously reported values in streams with watersheds of similar impervious cover (Lewis, 2002; Pennino et al., 2016; Petrone, 2010; Shields et al., 2008), most likely because this study was conducted in a coastal area where the reference blackwater streams are characteristically low in nitrate (Mallin et al., 2004; Wahl et al., 1997). Ammonium export from the stream with the least impervious watershed in this study was much lower than that measured in a relatively undisturbed stream in the inner coastal plain of South Carolina (Lewis, 2002), but ammonium export for all of the study streams was similar to that measured in urbanized streams in the coastal plain of western Australia (Petrone, 2010). The magnitude of annual orthophosphate export in this study was also similar to previous studies (Duan et al., 2012; Pennino et al., 2016; Petrone, 2010), but concentrations of orthophosphate were not clearly related with watershed imperviousness as was found in a previous study on coastal plain streams (Mallin et al., 2009).

4.3. Nitrogen Speciation and ISC

The three more developed streams exported more nutrients and had a smaller relative amount of DON than the less developed streams, and this pattern was driven by increased concentrations of PN and DIN (Figure 4). The relative amount of dissolved nitrogen export as DON for all streams was similar to results from previous studies in coastal plain blackwater streams (Tufford et al., 2003; Wahl et al., 1997) but much higher than reported values from upland areas (Groffman et al., 2004; Pellerin et al., 2006; Shields et al., 2008) and inner coastal plain streams (Lewis, 2002; Yarbro et al., 1984). Despite the higher relative amount of DON in the study, the decreased relative importance of DON shown here has been documented in many different geographic areas, including in nearby coastal South Carolina (Pellerin et al., 2006; Tufford et al., 2003). This phenomenon appears to occur regardless of reference stream chemistry, and is likely controlled by land use, wastewater discharges, and the abundance of wetlands in the watershed (Pellerin et al., 2006).

PN constituted a sizable portion of the total nitrogen pool in all study streams (Figure 4b), but algal biomass was likely the driver of PN export for only the 33% ISC stream with stormwater ponds. Blackwater streams typically have low concentrations of algal biomass and particulate organic matter (Meyer, 1990; Yarbro et al., 1984), so the proportion of total nitrogen exported as particulates (19–26%) in the two least developed streams is somewhat unexpected. Although, this relative amount of particulate nitrogen is still low, and previous studies in natural coastal plain streams have shown that particulate phosphorus is the dominant form of phosphorus export (Tufford et al., 2003; Yarbro et al., 1984). Algal growth in blackwater streams can be stimulated with even small amendments of DIN or labile DON due to their typically low concentrations of DIN and slower flow velocities (Mallin et al., 2004), so increased DIN and Chl *a* concentrations suggest that algal biomass likely contributes to the PN pool in the more urban streams (Figure S3). However, differences in the timing of PN and algal biomass export for all study streams except the 33% ISC stream indicate that algal biomass was a major driver of increased PN export for only the 33% ISC stream.

Another consideration for PN is that PN was exported at higher flows than other types of nitrogen in the urban streams (Figure 6), and this may increase downstream impacts more than just an increase in the magnitude of PN export. Due to the close proximity of the study streams to coastal waters, this change in timing of PN export relative to other nitrogen species will likely lead to more intense pulses of PN to coastal waters during storm events. PN and other particulate material that is exported to coastal waters can immediately contribute to increased biological oxygen demand which can negatively impact aquatic ecosystems (Mallin et al., 2009). This consideration is especially relevant for the stream with the 33% ISC watershed and stormwater ponds where nitrogen export was dominated by PN and large amounts of algal biomass export during high flows.

4.4. Changing Nutrient Sources With Urbanization

This study found that relationships between concentration and discharge changed with watershed ISC, indicating that nutrient sources shifted from natural to urban sources that varied by watershed. To highlight differences in nutrient sources with watershed ISC, the two least developed streams (1 and 4% ISC) will be described as “minimally impacted,” the two streams with higher ISC and minimal retention-based stormwater management (19 and 38% ISC) will be grouped as “urban,” and the 33%

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ISC stream extensively drained by stormwater ponds will be referred to as "urban with retention-based stormwater management."

4.4.1. Minimally Impacted Watersheds

Major nutrient sources in the two least developed streams were attributed to DON from extensive wetland area; PN from leaf material or other organic, nonalgal sources; and inorganic nitrogen and phosphorus from groundwater or biogeochemical processes within the stream channel. DON export was chemostatic for both minimally impacted streams, and positive *C*-*Q* slopes (*b* values), higher concentrations of DON than the more urban streams, and extensive wetland area indicate that wetlands and forested area were the main source of DON. The timing of export aligns with past studies showing that wetlands and forested areas are the main sources of DON in minimally impacted coastal plain watersheds, and these sources are typically transported to streams during storm events when wetlands are flushed or inundated (Flint & McDowell, 2015; Lehrter, 2006; Pellerin et al., 2004). Negative *C*-*Q* slopes for PN that were not significantly different from zero, lower concentrations of algal biomass than the urban streams, and differences in the timing of PN and algal biomass export mean that algal biomass was not the main source of PN. However, algal biomass could constitute a portion of the particulate N pool in the two least impervious streams that is exported at lower flows when streamflow velocities are low (Figure S5). The main source of PN in these two streams were likely leaf material (Newcomer et al., 2012), and a past study in coastal plain streams found that particulate material in a minimally disturbed stream was organic (Jayakaran et al., 2014). Nitrate export was low and chemodynamic with negative *C*-*Q* slopes, and concentrations were highest during summer when flow decreased or ceased. This pattern is indicative of a natural source of nitrate transported via groundwater or nitrified in the streambed or riparian zone during baseflow (Duncan et al., 2015). Ammonium export was lower than all other nitrogen species exported from the less developed streams, and chemostatic or weakly chemodynamic ammonium export with flat *C*-*Q* slopes suggests that the source is likely mineralization of organic matter during baseflows and ammonium from wetland processing during storm events. A chemostatic or weakly chemodynamic dilution pattern for orthophosphate hints at a consistent source at low flows, possibly in-stream processing such as mineralization and desorption from sediments (Hensley et al., 2017; Mallin et al., 2004).

4.4.2. Urban Watersheds

The relationships between concentration and discharge for the 19% ISC stream suggested that DON was supplied by wetlands within the stream network and groundwater, nitrate from anthropogenic sources mobilized during stormflow (i.e., fertilizers, atmospheric deposition), and PN, ammonium, and orthophosphate from stream channel degradation and altered nutrient removal processes. DON export from 19% ISC stream was chemostatic with a flat *C*-*Q* slope that was different than those of the two less developed streams. This stream had the lowest DON concentrations of all study watersheds despite a moderate amount of wetland area (12.37% watershed area), so it is possible that increased discharge across all flows due to urbanization diluted DON concentrations relative to the less developed streams. PN export from the 19% ISC stream had a positive *C*-*Q* slope that was opposite that of the less developed streams, and storm events were more important times of export relative to other nitrogen species. Algal biomass export was significantly higher in the 19% ISC stream than the less developed streams, likely due to increased nutrient availability (Mallin et al., 2004; Smucker et al., 2013) and light availability (Reisinger et al., 2019; Tank et al., 2018), but differences in the timing of PN and algal biomass means that a PN source other than algal biomass was exported at higher flows. PN in urban streams can originate from leaf material, sediment, grass clippings, and periphyton (Newcomer et al., 2012), and a study in a similar study area found that exported particulate material was largely mineral (as opposed to organic) and due to stream channel erosion (Jayakaran et al., 2014). Nitrate export from the 19% ISC stream was chemodynamic with a large, positive *C*-*Q* slope indicating a flushing of nitrate from the watershed during storm events. Potential sources of nitrate in more urbanized watersheds can include leaky wastewater infrastructure, lawn fertilizers, and atmospheric deposition of nitrate onto impervious surfaces (Kaushal et al., 2011). The 19% ISC stream had chemodynamic ammonium export with a negative *C*-*Q* slope suggesting that there were sources mobilized during baseflow and diluted during storms, although ammonium export from the 19% ISC stream was not higher than the two least developed streams. This shift in timing of ammonium export to lower flows may be driven by processes occurring during baseflow such as elevated net nitrogen mineralization within the floodplain and throughout the watershed (Reisinger et al., 2016), elevated rates of remineralization due to increased algal biomass (McMillan et al., 2010; O'Brien et al., 2012), or decreased rates of ammonium

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uptake due various effects of development (Meyer et al., 2005). Finally, orthophosphate *C*-*Q* slopes were positive rather than negative like the less developed streams, and this enrichment pattern aligns with previous studies that show that hydrologic change from urbanization can increase orthophosphate export via erosion within the watershed or stream (Withers & Jarvie, 2008).

The major sources of nutrients in the 38% ISC watershed were similar to those of the 19% ISC stream, but leaky sanitary sewers were likely the dominant source of ammonium and DON. A chemostatic, dilution pattern for DON in the 38% ISC stream was attributed to this persistent sanitary sewer leak that provided a consistent source of flow and nutrients. Leaky sanitary sewers can occur in urban areas and convey large amounts of water (Bhaskar, Beesley, et al., 2016) and fecal bacteria, nitrate, and organic matter to streams (Cahoon et al., 2016; Hosen et al., 2014; Iverson et al., 2018; Kaushal et al., 2011; Pennino et al., 2016). The clearest indicators of leaky sanitary sewers in the most urban stream (besides abnormally high discharge volume) were ammonium concentrations that were nearly 4 times higher than the next highest stream and DON concentrations that were significantly higher than the other urban streams and similar to concentrations in the two less impacted streams despite having no wetland area in the watershed. A strong dilution pattern for ammonium export was also likely the result of this leak. Nitrate export from the 38% ISC stream was chemostatic with a slope not significantly different from zero, so it is likely that this watershed had a large and consistent anthropogenic source of nitrate in the watershed derived from the urban sources mentioned for the 19% ISC stream. This shift in nitrate sources with watershed ISC from a natural, seasonally variable, groundwater-transported source as seen in the less developed streams to a consistent, transport-limited source has been shown in previous studies (Duncan et al., 2017; Thompson et al., 2011). The relationships between discharge and concentration were similar to those of the 19% ISC stream for orthophosphate and PN (excluding differences in CV_C/CV_Q for particulate metrics), so PN and orthophosphate sources mobilized during stormflow were likely the results of stream channel and bank erosion.

4.4.3. Urban Watershed With Retention-Based Stormwater Management

Nearly the entire watershed of the 33% ISC stream was drained by stormwater ponds, and these stormwater ponds appear to have been important transformers of dissolved nitrogen and large sources of PN. The 33% ISC stream had a positive DON *C*-*Q* slope similar to the two less developed streams, but low DON concentrations suggests a that a diluted natural source of DON during baseflow (lack of wetlands in watershed) may have been supplemented during storm events by DON from stormwater ponds within the watershed. Stormwater ponds can be sources of DON downstream (Bell et al., 2019), have strong autochthonous nitrogen and carbon signatures (Williams et al., 2013), transform inorganic nitrogen to DON and PN (Gold et al., 2017b), and increase the biodegradability of DON (Lusk & Toor, 2016a). The 33% ISC stream also had ammonium *C*-*Q* slopes that were similar to the less developed streams, so stormwater ponds may have also been sources of ammonium like natural wetlands in the less developed watersheds. Stormwater ponds were clearly large sources of algal biomass that was exported during storm events when ponds were flushed, and this algal biomass contributed to increased PN export. The 33% ISC stream had positive *C*-*Q* slopes for both PN and algal biomass, and while high flows were important times of export for both particulate N and algal biomass, the timing of algal biomass export was similar to PN export (opposite that of all other study streams). A previous study showed that a stormwater pond in the 33% ISC watershed had significantly higher Chl *a* concentrations than the draining stream (Gold et al., 2017b), and stormwater ponds in similar areas have also been shown to harbor high concentrations of algal biomass (DeLorenzo et al., 2012; Lewitus et al., 2008; Reed et al., 2016). Nitrate export was chemostatic with a dilution pattern, but nitrate was likely not supplied by the stormwater ponds given that nitrate concentrations in these ponds and other coastal stormwater ponds during baseflow conditions have been low to nonexistent (Gold et al., 2017b; Reed et al., 2016). Stormwater ponds can promote denitrification downstream if the area drained by ponds is less impervious, but denitrification downstream can be dampened if the drained area is very impervious (Rivers et al., 2018), possibly leading to higher nitrate concentrations during baseflow. Urban streams can also have increased rates of net nitrogen mineralization and nitrification (Reisinger et al., 2016), so this may have influenced the elevated nitrate concentrations during baseflow. For orthophosphate, a strong enrichment pattern shows that stormwater ponds may have been a source of orthophosphate. Stormwater ponds can decrease erosion in the draining stream (Tillinghast et al., 2011), thus decreasing orthophosphate export, but they can also be sources of orthophosphate during certain seasons due to low-oxygen conditions in pond sediments that cause desorption (Duan et al., 2016).

4.4.4. Additional Impacts of Changing Nutrient Sources

While rates of DON export were similar between most of the study streams, the growing importance of urban sources of DON with watershed ISC could increase the availability of DON to downstream ecosystems. The dilution of natural DON sources and increase in the urban DON sources presented here has been observed previously with measurements of DON bioavailability, which increases in urban streams (Lusk & Toor, 2016b; Pellerin et al., 2006; Petrone et al., 2009; Stanley & Maxted, 2008). Further, DON and DOM are derived from similar sources in blackwater streams, and dissolved organic matter sources have also been shown to shift with increased watershed ISC (Hosen et al., 2014; Parr et al., 2015). Bioassay experiments have shown that urban sources of DON, such as wastewater effluent or stormwater, are more easily utilized by estuarine algae than natural sources of DON (Hounshell et al., 2017; Seitzinger et al., 2010), suggesting that a similar amount of DON export from urban streams compared to more natural streams may supply more bioavailable nitrogen.

PN removal is rarely measured when assessing nitrogen removal from stormwater ponds (Rosenzweig et al., 2011), but this may be a pathway of nitrogen export to streams in certain areas. Stormwater wet ponds are designed to retain water, nutrients, and suspended sediments, but total suspended solid measurements that are often used as a measure of effectiveness are poor predictors of performance due to phytoplankton growth in stormwater ponds that can drive internal nutrient processing (Williams et al., 2013). There are few studies that assess PN export from coastal plain urban streams, but a previous study found that elevated particulate phosphorus concentration in an urban stream was likely due to urban pond phytoplankton export (Tufford et al., 2003). Low N:P ratios and high rates of nitrogen uptake within coastal stormwater pond waters indicate that nitrogen uptake may be dominated by assimilative uptake by algae in the water column (Gold et al., 2017a; Reed et al., 2016). Assimilative uptake by coastal stormwater pond sediments, as opposed to denitrification, may be high when DIN:DIP ratios are low (as shown by differences in pond age) or during hot and dry periods (Gold et al., 2017a), and assimilated nitrogen could be remineralized. The nutrient cycling within stormwater ponds likely changes with season and physiographic region, and could influence the retention of dissolved versus particulate forms of nutrients. Stormwater ponds are often promoted as nitrogen sinks, although the processes of nitrogen removal have not been well characterized (Gold et al., 2019b), and this topic requires further study to determine if and when algal biomass is the dominant pathway of nitrogen uptake in stormwater ponds and if it is a source of PN downstream in other physiographic areas.

4.5. Implications for Coastal Water Quality Management

The results of this study indicate that multiple management actions could be used to address or prevent excessive stream nutrient export stemming from coastal plain urbanization. The first management action is stormwater volume reduction, which should aim to reduce the volume of stormwater to restore the predevelopment water balance and hydrologic flow paths (Askarizadeh et al., 2015; Dietz, 2007). The second management action is to preserve or restore wetland area within the watershed to act as DIN sinks. The third management action is to reduce contemporary anthropogenic sources of nutrients that may be contributing to increased nutrient export.

Reducing the overall volume of discharge would reduce nutrient export (Jefferson et al., 2017), and a stormwater volume reduction approach may be more effective than retention-based stormwater management in this region. Retention-based stormwater management is designed to decrease peak flows and extend the storm hydrograph (Hancock et al., 2010), but this study shows that by retaining nutrient-rich stormwater in nitrogen-limited stormwater ponds in the study area, a large amount of algal biomass was produced and exported downstream as PN. Based on these negative water quality impacts of retention-based stormwater management and increased flow across all rates of discharge in the urban study streams, stormwater volume reduction with an emphasis on stormwater harvesting may be a more effective mitigation strategy in the study area than a retention-based approach. A well-known way to reduce stormwater volume is to utilize low-impact development structures that promote evapotranspiration of stormwater, the reuse of stormwater through harvesting, and stormwater infiltration. However, extensive stormwater infiltration practices in urbanizing areas can sometimes lead to increases in baseflow due to decreased evapotranspiration and increased infiltration (Barron et al., 2013; Bhaskar, Hogan, et al., 2016). This increase in baseflow with excessive infiltration could be a concern for development in this study region based on the observed increases in discharge across all flows and dampened seasonal patterns in discharge with watershed ISC. Stormwater harvesting would help reduce discharge during baseflow as well as discharge volume over annual and seasonal time scales (Askarizadeh et al., 2015; Jefferson et al., 2017), but it may not address decreased stormflow lag times as effectively as retention-based or infiltration-based stormwater management (Jefferson et al., 2017). A combination of stormwater harvesting and infiltration would likely be effective at reducing discharge and nutrient export (Askarizadeh et al., 2015), but additional studies in this area are needed. Low-impact development structures have not been extensively studied in coastal plain regions, but the few studies on this topic suggest that bioretention cells (Page et al., 2015), permeable pavement (Bean et al., 2007; Page et al., 2015), and regenerative stormwater conveyance systems (Cizek et al., 2017; Fanelli et al., 2017) may be able to improve water quality and reduce the volume of stormwater.

Adding wetland area within the watershed (or conserving wetlands during urbanization) provides an inorganic nitrogen sink for the removal of current nutrient pollution and “legacy” nutrient pollution (Basu et al., 2010; Collins et al., 2010) and could shift DON toward natural sources (Flint & McDowell, 2015; Petrone et al., 2011). Chemostatic behavior of nitrate and orthophosphate suggests that there may be a legacy store within the watershed that could keep nutrient export elevated for a long period of time (Basu et al., 2010; Goyette et al., 2018; Van Meter & Basu, 2015), and wetlands throughout the watershed, especially in areas with short travel times to the stream (Van Meter & Basu, 2015), may help lower values of export (Basu et al., 2010). This addition of wetlands would likely be part of a larger stormwater volume reduction strategy as discussed above.

Finally, reducing nonpoint sources (e.g., fertilizers, lawn waste, pet waste) and point sources (e.g., leaky sewers; Hobbie et al., 2017; Kaushal et al., 2011) remains an effective approach to reduce nutrient export. Nitrate from nonpoint urban sources was evident from chemostatic export and positive C-Q slopes in the more urban watersheds. Also, leaky sewers can contribute large amounts of water and nutrients to streams, as shown by the 38% ISC watershed, and should be repaired to reduce nutrient export.

5. Conclusions

This study found that urban coastal plain streams had higher rates of annual discharge, more cumulative discharge at high flows, and dampened seasonal patterns of discharge compared to less impacted streams. Differences in hydrology at high flows were attributed to increased watershed ISC, and differences at low flows were attributed to decreased evapotranspiration with watershed ISC, leaky wastewater infrastructure, and stormwater ponds. The magnitude of nutrient export for all measured nutrients increased with watershed ISC due to elevated stream discharge and increased concentrations of PN and DIN that varied by watershed and were more reliant on high flows. The relative importance of DON to total nitrogen export decreased with watershed ISC due to increased DIN and PN export, but DON was the dominant form of nitrogen in all but one study stream. Nitrogen export in the urban watershed drained by stormwater ponds was dominated by PN export due to pond algal production. Based on these findings, this study suggests that stormwater volume reduction emphasizing stormwater harvesting and evapotranspiration rather than retention-based management, the preservation or addition of wetland area, and the reduction of anthropogenic nutrient sources could reduce nutrient export from urban coastal plain streams.

Effective management of urban areas benefits from an understanding of ecological processes in more natural systems. By including a wide spectrum of development with a more natural end-member, this study provides new information and insights that can be used to manage coastal plain watersheds and improve downstream water quality.

Acknowledgments
We are extremely thankful to Scott Ensign for reviewing a previous draft of the manuscript and Olivia Torano, Mollie Yacano, Jaye Cable, Rachel Noble, Ariane Peralta, and two anonymous reviewers for the constructive discussion and helpful comments. This work was supported by the Strategic Environmental Research and Developmental Program - Defense Coastal/Estuarine Research Program (project RC-2245). The views expressed are solely those of the authors and do not represent the policies or opinions of the U.S. Department of Defense or associated services. Data from this study are freely available for download at Zenodo.org, doi: 10.5281/zenodo.2571549 (Gold et al., 2019a).

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