Comparative Impacts of Stormwater Runoff on Water Quality of an Urban, a Suburban, and a Rural Stream

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Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream

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Abstract Water quality data at 12 sites within an urban, a suburban, and a rural stream were collected contemporaneously during four wet and eight dry periods. The urban stream yielded the highest biochemical oxygen demand (BOD), orthophosphate, total suspended sediment (TSS), and surfactant concentrations, while the most rural stream yielded the highest total organic carbon concentrations. Percent watershed development and percent impervious surface coverage were strongly correlated with BOD (biochemical oxygen demand), orthophosphate, and surfactant concentrations but negatively with total organic carbon. Excessive fecal coliform abundance most frequently occurred in the most urbanized catchments. Fecal coliform bacteria, TSS, turbidity, orthophosphate, total phosphorus, and BOD were significantly higher during rain events compared to nonrain periods. Total rainfall preceding sampling was positively correlated with turbidity, TSS, BOD, total phosphorus, and fecal coliform bacteria concentrations. Turbidity and TSS were positively correlated with phosphorus, fecal coliform bacteria, BOD, and chlorophyll *a*, which argues for better sedimentation controls under all landscape types.

Keywords Creeks · Pollutants · Rainfall · Fecal bacteria · BOD · Impervious

Introduction

Urban stormwater is a leading cause of pollution to fresh and brackish receiving waters, especially fecal bacteria (NOAA 1998; Smith and Perdek 2004). Elevated fecal bacteria, viruses, and protozoans in recreational waters are a direct human health threat as these microbes can cause illness if they are exposed to vulnerable areas such as the mouth, nose, eyes, and open wounds. Wet weather and subsequent increased surface and subsurface runoff has been shown to increase health hazards to humans by increasing the presence of fecal microbial pathogens in marine and estuarine waters (Lipp et al. 2001; Noble et al. 2003). In coastal waters, fecal microbes are a further health threat

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and cause economic loss as they can contaminate shellfish beds that could otherwise be harvested and consumed by humans. Urban stormwater runoff has been cited as a contributing cause to 40% of the shellfish closures in US waters (NOAA 1998). However, less is known about the impact of stormwater runoff in largely rural areas. The exception to this is agricultural areas (i.e., livestock grazing areas) where fecal microbial contamination of waterways results from manure deposition by the animals (Howell et al. 1995; Smith and Perdek 2004) and from the spraying or spreading of manure as fertilizer or waste disposal (Edwards and Daniel 1992, 1994; Sims and Wolf 1994).

Nutrients (nitrogen and phosphorus) are problematic pollutants in urban stormwater runoff (Bannerman et al. 1993; Line et al. 2002). Likewise, in agricultural areas, rainfall-driven runoff of phosphorus into streams is problematic (Edwards and Daniel 1992) and occurs both from the erosion of particulate phosphorus and surface or subsurface movement of dissolved phosphorus (Sims et al. 1998; Nash and Halliwell 2000). Rural sources of nitrogen subject to surface runoff are chemical fertilizers, manure fertilizers, swine and poultry waste disposal, and settling of ammonia generated by swine and poultry lagoons and sprayfields (Edwards and Daniel 1994; Sims and Wolf 1994; Gangbazo et al. 1995; Burkholder et al. 2007).

The degree of watershed development, often expressed as the percent watershed impervious coverage, has been associated with changes in stream hydrology and morphology and the degradation of water quality and biotic condition: impairment is frequently noted within the range of 10–15% impervious cover level (Schueler 1994; Arnold and Gibbons 1996; Miltner et al. 2004). More recently, watershed development and impervious surface coverage has been positively correlated with fecal bacterial contamination in freshwater urban streams (Young and Thackston 1999) and tidal creek ecosystems (Mallin et al. 2000; Holland et al. 2004). A set of fresh-to-brackish creeks located within several kilometers of each other in coastal North Carolina presented an opportunity to assess water quality over a range of subwatersheds ranging from 5% to >25% impervious surface coverage.

Burnt Mill Creek and Smith Creek are two examples of urban and suburban streams that are experiencing water quality problems. Known problems in these waters include low dissolved oxygen, fecal bacterial contamination, periodic algal blooms, and occasional turbidity pulses. Burnt Mill Creek is presently on the North Carolina Division of Water Quality 303(d) list as impaired due to impaired biological community (NCDENR 2005). Prince Georges Creek is a more rural water body with previously untested water quality that was analyzed for comparative purposes. The objectives of the study were to assess water quality differences in three fresh-to-brackish tidal creeks of differing degrees of urbanization, determine the impact of landscape utilization on creek water quality, and determine the impacts of rainfall on parameter concentrations for the whole data set and for individual creeks. Known stormwater runoff pollutants including fecal bacteria and nutrients were tested, and we also analyzed a number of parameters whose relationship to stormwater runoff are less well studied, including total organic carbon (TOC), biochemical oxygen demand (BOD), surfactants, and grease and oil.

Site description

The sample sites were located in New Hanover and Pender Counties in southeastern North Carolina, USA (Fig. 1). These are counties that border the Atlantic Ocean and are part of the Coastal Plain province, which is characterized by sandy soils, lowland riparian swamp forests, and blackwater streams. The City of Wilmington is the largest municipality in the area with a population of approximately 120,000.

Burnt Mill Creek is a second-order freshwater creek located entirely within the City of Wilmington. It joins lower Smith Creek approximately 3 km upstream of Smith Creek's juncture with the Northeast Cape Fear River (Fig. 1). Tide gates prevent brackish water from entering Burnt Mill Creek on the incoming tide. It drains a 1,730-ha watershed that is highly urbanized (KCI Associates 2001). Five stations were sampled in this watershed: BMC-KA3 is a first-

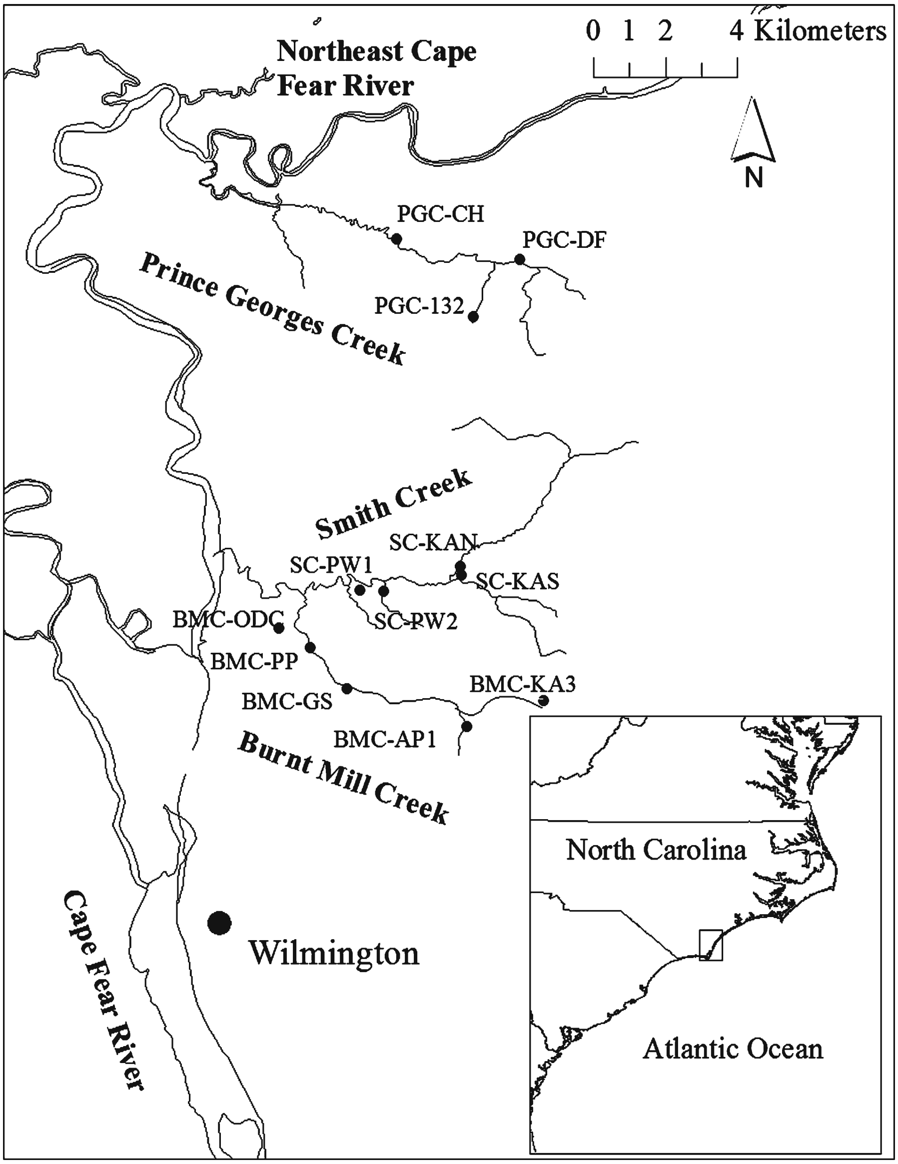

Fig. 1 Map of stream sampling sites in New Hanover County, North Carolina, USA

order stream that drains a small largely commercial watershed, BMC-AP1 (also first order) is located 1.2 km downstream from KA3 and drains a residential and commercial area, BMC-PP (second order) is on the main channel of Burnt Mill Creek 4 km downstream for BMC-AP1, BMC-GS is a first-order tributary that enters the main channel 1.3 km upstream of BMC-PP and drains a small largely multifamily residential area, and BMC-ODC is another first-order tributary of the creek that drains an urban area. The individual stations drain catchments ranging from approximately 21% to 26% impervious cover with the watershed as a whole approximately 22% impervious cover (Table 1).

Smith Creek is a third-order tidal creek located partially within the City of Wilmington, North Carolina. It drains into the Northeast Cape Fear River, a fifth-order blackwater river that is generally oligohaline to mesohaline at its confluence with Smith Creek (Fig. 1). The creek drains a catchment of approximately 6,028 ha (KCI Associates 2001). It is fresh in the headwaters, becoming generally more brackish near the mouth.

Table 1 Percent land use coverage by key categories of urban Burnt Mill Creek, suburban Smith Creek, and rural Prince Georges Creek watersheds, by station (2002 data)

Station	Area (ha)	%Resid.	%AGFOR	%BMIS	%Undevel.	%IMP
BMC-KA3	15.0	0.0	0.0	86.7	13.3	22.5
BMC-GS	14.3	98.6	0.0	0.7	0.7	25.8
BMC-ODC	211.4	43.7	0.0	44.2	12.1	23.0
BMC-PP	1,160.9	52.1	0.1	30.4	17.4	21.7
BMC-AP1	293.0	48.7	0.0	33.0	18.3	21.7
SC-KAS	635.5	33.3	0.1	40.8	25.8	20.3
SC-KAN	3,512.2	30.3	8.3	9.3	52.1	10.6
SC-PW2	121.2	29.3	0.0	20.1	50.6	13.0
PGC-CH	2,126.1	22.9	7.0	11.3	58.8	9.5
PGC-132	365.3	27.0	14.1	18.9	40.0	13.4
PGC-DF	822.8	17.9	7.9	0.2	74.0	4.8

Delineation of watershed boundaries of SC-PW1 was not possible due to the small catchment area and its highly modified surface water drainage network

%Resid. percent of watershed under residential usage, *%AGFOR* percent of watershed used for either agriculture (including pastureland) or forestry, *% BMIS* percent of watershed covered by retail business, manufacturing, institutions or services, *%Udevel.* percent of undeveloped land, *%IMP* percent of watershed covered by impervious surfaces

Station KAN is the upper second-order portion of the stream in freshwater, draining a watershed with about 30% residential and 52% undeveloped land; it is joined by the first-order SC-KAS which drains a more developed catchment (Table 1). The main branch is then joined by two first-order tributaries, PW1 and PW2, which drain small catchments that are mixed residential and undeveloped. Percent impervious surface coverage of the individual station catchments ranged from 10.5% to 20.3%, while impervious coverage for the whole watershed was approximately 19.8% (Table 1).

Prince Georges Creek is a second-order tidal creek located in Pender County that enters the Northeast Cape Fear River 17 km upstream of Smith Creek. It drains a catchment of approximately 4,576 ha (KCI Associates 2001). It was sampled approximately 10 km upstream of the river at Station PGC-DF, draining a primarily undeveloped area, and downstream at PGC-CH, draining an area that is still primarily undeveloped but with some residential and commercial areas. PGC-132 is a first-order tributary that drains an area with significant agriculture as well as mixed development (Table 1). Percent impervious surface coverage of the station catchments ranged from 4.8% to 13.4%, with total watershed impervious coverage just under 10% (Table 1). All stations in the three-stream matrix were located sufficiently far upstream to be considered freshwater (average salinities <0.5 psu).

For the purposes of this analysis, we refer to Burnt Mill Creek as urban, Smith Creek as suburban, and Prince Georges Creek as rural. While such definitions are unavoidably somewhat arbitrary, Burnt Mill Creek is one of the two most developed watersheds in Wilmington, has >20% impervious coverage, significant amounts of business and industrial land use, and no agricultural or forestry usage (Table 1). Smith Creek has <20% impervious coverage, some business and industrial land use, and yet retains some minimal amount of agricultural land use (Table 1). Prince Georges Creek is the only watershed of the three with significant agricultural and forestry usage, very little business and industrial usage, <10% impervious coverage, and large amounts of undeveloped land (Table 1).

Methods

Sampling was conducted biweekly July through October 2001, with additional samples collected in November and December 2001, and January and April 2002. Sampling on July 12, August 14, September 25, and December 11 was conducted during or just after rain events of 2.0, 4.2, 1.5, and 2.4 cm, respectively. All stations were sampled on

12 occasions with the exception of stations BMC-AP1 and BMC-PP, which were sampled on seven occasions each.

Data were collected on site for water temperature, conductivity, salinity, dissolved oxygen, pH, and turbidity using a YSI 6920 Multiparameter Water Quality Probe (sonde) linked to a YSI 650 MDS display unit. Most sites were sampled from bridges; others were accessed from prominent physical features on shore. While on site, sample bottles were either hand dipped directly into the creek or clipped to a telescoping pole and dipped into the creek as such. Samples were collected at 0.1 m depth for total suspended sediments, total nitrogen, nitrate-N, ammonium-N, total phosphorus, orthophosphate-P, total organic carbon, fecal coliform bacteria, biochemical oxygen demand (BOD5 and BOD20), grease and oil, surfactants, and chlorophyll *a*. Samples were immediately stored on ice and returned to the laboratory. Most laboratory analyses were conducted using protocols described in Standard Methods (APHA 1995) and included nitrate (Method 4500-NO3 F), ammonium (Method 4500-NH3 H), total Kjeldahl nitrogen (TKN-Method 4500-Norg B), orthophosphate (Method 4500-P E), and total phosphorus (TP-Method 4500-P E with persulfate digestion), total suspended solids (Method 2540-D), surfactants (Method 5540C), and total grease and oil (Method 5520B). Total nitrogen (TN) was computed as TKN plus nitrate. Fecal coliform bacteria concentrations were determined using a membrane filtration (mFC) method that utilizes a 24 h incubation time at 44.5°C and an enriched lactose medium (Method 9222-D; APHA 1995), and reported as colony-forming units (CFU) 100 mL^{-1}, with an upper counting limit of 6,000 CFU/100 mL. The analytical method used to measure chlorophyll *a* is described in Welschmeyer (1994); an acetone extraction analyzed for chlorophyll *a* concentration using a Turner AU-10 fluorometer.

Geospatial statistics of catchment area and land use within watersheds upstream of water quality sampling locations were derived using Arcview geographic information system software (ESRI, Redlands, CA, USA). Latitude and longitude of sampling locations was collected using a handheld, differentially corrected Global Positioning System. The catchment area drained by each location was determined using the Arcview Watershed Delineator extension and 7.5 min digital elevation models produced by the US Geologic Survey at 30 m resolution (http://ned.usgs.gov/). Land use within each delineated catchment was summarized from land parcel ownership digital spatial data provided by the New Hanover County Planning Office (data within are 2001 or earlier). Land parcel polygons within each delineated drainage basin were selected and summarized by area and land use type. Conversion factors utilized by the New Hanover County Planning Department were multiplied by the area covered by each land use type to obtain impervious surface coverage for the subcatchments. Impervious ratios utilized by the county included 50.0% for utilities, transportation and right-of-ways, 26% for retail, manufacturing, services, institutional, and residential, 1.5% for recreational areas, and 0% for undeveloped including agriculture and forestry. Land use types utilized in this analysis are developed land (DEV) which includes residential, retail business, manufacturing, institutional and services; BMIS, which includes retail business, manufacturing, institutional and services; AGFOR, which denotes land area devoted to agriculture and forestry; IMP, which denotes land covered by impervious surfaces, and Undevel., or undeveloped land.

Statistical analyses

Physical, chemical, biological, and meteorological parameters were tested for normality using the Shapiro–Wilk test. All parameters with the exception of water temperature and dissolved oxygen were not normally distributed and required log transformation before further analyses. Analysis of variance was used to test for significant differences in the mean concentrations of all parameters between the three streams. Where significant differences occurred, creeks were ranked using the least significant difference (LSD) procedure (Day and Quinn 1989). Daily rainfall data were obtained from the Wilmington Airport (National Weather Service Cooperative Observer Station 319457) and applied to three temporal forcing groups for each sampling date: RAIN24 was total rain that fell on the day of sampling plus the previous 24 h; RAIN48 was the rain that fell on the day of sampling plus the previous 48 h; and RAIN72 was the total rain that fell on the day of sampling plus the previous 72 h. The effects of wet versus dry (no rainfall in the previous 72 h) antecedent conditions on parameter concentrations was examined by grouping observations from each regime and testing for differences using *t* tests. Correlation analyses were run among response parameters and rainfall inputs for the entire data set, as well as for the three creeks individually. To test for landscape influences, additional correlation analyses were run among mean response parameters and the various watershed land use percentages for the individual station's respective watersheds. The land use categories included percent developed land, percent impervious surface coverage, percent agricultural (including grazing land) and forestry combined, and an additional category combining percent of land devoted to retail business, services, manufacturing, and institutions (such as university facilities). Station SC-PW1 was excluded from this latter analysis because of unavailability of accurate landscape data due to the small catchment area and its highly modified surface water drainage network. The Statistical Analysis System (SAS, Schlotzhauer and Littell 2001) was used for all the above analyses, and all statistical tests were performed using a significance level of $a = 0.05$.

Results

Water quality among stream types

Two of the three streams, the urbanized Burnt Mill Creek (BMC) and the rural Prince Georges Creek (PGC), were frequently impacted by low dissolved oxygen. The State of North Carolina has a water quality standard of 5.0 mg/L, and several of the sites within these creeks fell below that standard on more than 50% of the sampling events. Stations BMC-ODC and PGC-CH were particularly low in dissolved oxygen, with values below 5 mg/L on 75% and 67% of the sampling trips, respectively. Smith Creek (SC) had no major hypoxia problems during this study (Table 2). None of the three streams suffered from excessive turbidity on a consistent basis (Table 2). The North Carolina freshwater turbidity standard of 50 NTU was exceeded on only one sample date (a rain date) in BMC and SC; however, it was exceeded on three dates at rural PGC-132. There was no significant difference in average turbidities among the three creeks overall. There were, however, significant total suspended sediment (TSS) differences among the creeks, with SC higher than PGC but not significantly different from BMC (Table 2).

There were no significant differences among creeks for ammonium, nitrate, or TN (Table 2). High concentrations (defined here as >500 μg N/L; see Mallin et al. 2004a) of ammonium occurred on only one date each in BMC and SC and on two dates in PGC, and nitrate exceeded this concentration on only one date in PGC. On most dates, TN remained below 1,000 μg N/L, with maxima of 2,500, 3,000 and 2,300 μg N/L seen at BMC, SC, and PGC, respectively (Table 2). Orthophosphate concentrations were significantly higher in urban BMC than rural PGC, with no significant difference between BMC and SC (Table 2). There were no significant intercreek differences in average TP concentrations (Table 2). TP concentrations exceeding 100 μg P/L are sometimes considered problematic in fresh and estuarine receiving waters (Correll 1998). Creek mean TP concentrations exceeded this level for all three creeks (Table 2), while median TP exceeded this level only for Burnt Mill Creek and for several individual stations within the matrix including BMC-KA3, BMC-GS, BMC-ODC, SC-PW1, and PGC-132. Total organic carbon showed an opposite pattern with concentrations at PGC significantly higher than both BMC and SC (Table 2). Average TOC values in the rural creek were approximately double those of the more urbanized creeks.

Some of the sites were subject to algal blooms exceeding 30 μg chlorophyll *a* per liter (see Dodds et al. 1998). Such blooms occurred on four occasions at BMC-ODC (maximum 49 μg/L), twice at SC-PW1 (maximum 37 μg/L), and once each at BMC-PP (89 μg/L), SC-KAN (maximum 32 μg/L), SC-PW2 (30 μg/L), PGC-CH (35 μg/L), and PGC-132 (63 μg/L, see also Fig. 2).

Table 2 Water quality parameter concentrations among an urban, a suburban, and a rural creek, collected July 2001–April 2002

Parameter	Burnt Mill Creek *N* = 50	Smith Creek *n* = 48	Prince Georges Creek *n* = 36
Dissolved oxygen (mg/L)	5.5 ± 2.0 A	6.2 ± 1.4 A	4.5 ± 1.7 A
	1.3–9.8	4.0–10.5	0.9–8.2
Turbidity (NTU)	12.1 ± 16.0 A	14.7 ± 24.2 A	19.6 ± 32.6 A
	1–101	1–125	1–156
TSS (mg/L)	8.6 ± 9.0 AB	64.4 ± 79.3 A	8.0 ± 11.8 BC
	1.0–56.0	1.6–108.0	1.2–67.0
Ammonium (μg N/L)	88.3 ± 109.3 A	64.4 ± 79.3 A	118.6 ± 170.6 A
	5.0–689.0	5.0–550.0	20.0–730.0
Nitrate (μg N/L)	140.0 ± 96.8 A	131.7 ± 77.1 A	142.9 ± 178.7 A
	20.0–390.0	5.0–330.0	20.0–1,050.0
Total nitrogen (μg N/L)	715.2 ± 607.9 A	670.4 ± 662.3 A	721.4 ± 573.1 A
	80.0–2,500.0	90.0–3,000.0	168.0–2,300.0
Orthophosphate (μg P/L)	69.8 ± 39.6 A	54.0 ± 45.0 AB	48.6 ± 39.5 BC
	5.0–180.0	5.0–252.0	5.0–195.0
Total phosphorus (μg P/L)	135.2 ± 111.5 A	126.8 ± 115.8 A	122.7 ± 128.6 A
	8.0–630.0	20.0–570.0	5.0–540.0
Total organic carbon (mg C/L)	7.1 ± 2.6 B	7.4 ± 2.1 B	14.5 ± 4.6 A
	3.8–15.0	4.1–15.0	6.9–26.0
Chlorophyll *a* (μg/L)	10.8 ± 15.6 A	8.4 ± 8.4 A	6.4 ± 11.5 B
	0.7–89.3	0.7–36.6	0.6–63.0
BOD5 (mg/L)	3.6 ± 1.4 A	2.5 ± 1.2 B	2.6 ± 1.4 B
	1.0–6.9	0.4–5.7	0.2–6.1
BOD20 (mg/L)	11.6 ± 6.2 A	9.0 ± 6.0 B	8.6 ± 4.9 B
	3.7–26.1	3.1–27.6	4.1–22.4
Fecal coliforms (CFU/100 mL)	955 A	493 A	536 A
	2 to >6,000	40 to >6,000	1 to >6,000
Surfactants (μg/L)	238.6 ± 225.5 A	160.0 ± 116.0 B	117.1 ± 74.3 B
	50.0–1,400.0	50.0–500.0	50.0–300.0
Grease and oil (mg/L)	123.8 ± 184.3 A	98.0 ± 130.4 A	84.5 ± 77.4 A
	5.1–756.6	5.1–817.5	3.4–357.1

Presented as mean ± standard deviation/minimum and maximum. Means with the same letter designation were not significantly different between creeks (log-transformed data except DO), where different, A > B > C; ranked using the LSD test

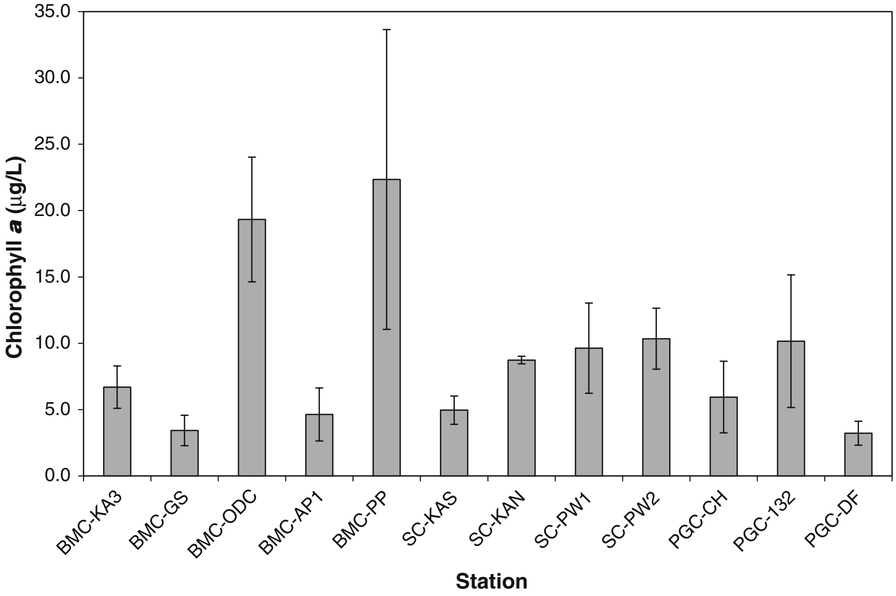

Fig. 2 Chlorophyll *a* concentrations by station for urban Burnt Mill Creek (*BMC*), suburban Smith Creek (*SC*), and rural Prince Georges Creek (*PGC*), wet and dry weather samples combined, presented as mean ± standard error of the mean

Comparing average chlorophyll *a* concentrations among creeks, both BMC and SC were significantly higher than PGC (Table 2). Biochemical oxygen demand showed a distinct urban signature, with average concentrations of both BOD5 and BOD20 significantly higher at BMC than either SC or PGC (Table 2). Stations with highest BOD5 concentrations were BMC-KA3 (median 3.9 mg/L, mean 4.2 mg/L) and BMC-ODC (median 3.8 mg/L, mean 3.5 mg/L), and the lowest was SC-PW1 (median 1.9 mg/L, mean 2.0 mg/L). For BOD20, the highest concentrations occurred at BMC-KA3 (median 12.2 mg/L, mean 14.0 mg/L) and BMC-ODC (median 12.6 mg/L, mean 13.1 mg/L) and the lowest were at SC-PW1 (median 5.6 mg/L, mean 7.5 mg/L).

Fecal coliform bacteria concentrations were characterized by frequent excessive concentrations, particularly at some of the most urbanized sites in Burnt Mill Creek (Fig. 3). As a reference, the North Carolina freshwater fecal coliform bacteria standard for human contact waters is 200 CFU/100 mL. Periodic high counts occurred at some rural and suburban locations as well, and the high variability among creeks masked any statistical differences (Table 2). The upper count limit of 6,000 CFU was exceeded seven times at BMC-ODC, four times at BMC-GS, three times at BMC-KA3, and twice each at SC-KAS and PGC-132. It is notable that, for each creek, the catchments having the least undeveloped area (Table 1) were also those with the highest fecal coliform counts (Fig. 3). Surfactant concentrations were significantly greater at urbanized BMC than either SC or PGC, and maximum surfactant concentrations were 1,400, 500, and 300 μg/L at BMC, SC, and PGC, respectively (Table 2). Grease and oil concentrations were highly variable and showed no significant inter-creek differences (Table 2), although maximum values in BMC, especially BMC-KA3 (728 mg/L), BMC-GS (747 mg/L), and BMC-ODC (757 mg/L) were far higher than in Smith and Prince Georges Creeks. With the exception of a peak at SC-PW1 of 818 mg/L, maximum grease and oil at these other creek sites were below 360 mg/L, approximately half the maximum values for Burnt Mill Creek.

Landscape impacts on water quality

Correlation analyses were applied over all catchment data combined to assess relationships between land use indicators and water quality. The percent of watershed developed land and percent impervious surface coverage were both strongly correlated with orthophosphate, BOD5, and surfactant concentrations (Table 3). The nonresidential development category BMIS was strongly

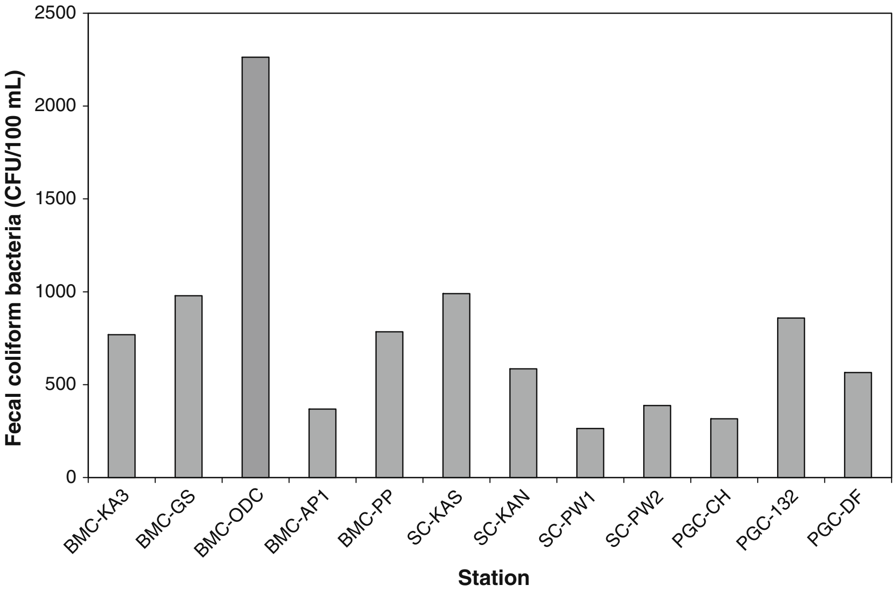

Fig. 3 Fecal coliform bacteria concentrations by station for urban Burnt Mill Creek (*BMC*), suburban Smith Creek (*SC*), and rural Prince Georges Creek (*PGC*), wet and dry weather samples combined, presented as geometric mean

Table 3 Results of correlation analyses between landscape use and chemical and biological parameters, all stations combined, presented as Pearson correlation coefficient (*r*—top line)/probability (*p*—bottom line)

	OP	BOD5	BOD20	Surfactants	FC	TOC
%DEV	0.636	0.723		0.694		−0.786
	0.036	0.028	ns	0.018	ns	0.012
%IMP	0.628	0.698		0.696		−0.628
	0.039	0.036	ns	0.018	ns	0.012
%BMIS		0.818	0.778		0.778	
	ns	0.007	0.014	ns	0.005	ns
%AGFOR						0.792
	ns	ns	ns	ns	ns	0.011

OP orthophosphate, *FC* fecal coliform bacteria, *%DEV* percent of watershed that is developed, *%IMP* percent of watershed covered by impervious surfaces, *%BMIS* percent of watershed covered by retail business, manufacturing, institutions or services, *%AGFOR* percent of watershed used for either agriculture (including pastureland) or forestry, *ns* not significant

correlated with BOD5, BOD20, and fecal coliform bacterial concentrations. In contrast, TOC concentrations were negatively correlated with percent developed land and percent impervious cover, and TOC had a strong positive correlation with percent agriculture and forestry coverage (Table 3).

Wet versus dry periods

Rainfall had a major impact on stream water quality. For all sites combined, total rainfall within the 72-h period preceding sample collection was highly significantly correlated with turbidity, TSS, fecal coliform bacteria, orthophosphate, TP, BOD5, and BOD20 but negatively correlated with ammonium and grease and oil concentrations (Table 4). Rainfall in the 24- and 48-h periods preceding sampling were also tested; correlation coefficients were very similar to those of RAIN72 so they are not presented here. When correlation analyses were performed by individual creek system, similar results were seen with the exception of BOD5 and BOD20, which were not correlated with rainfall in urbanized BMC, as well as BOD5 in PGC (Table 4). Also, in the more rural PGC, ammonium and grease and oil were not negatively correlated with rainfall, nor was grease and oil correlated with rainfall in SC.

Combined parameter concentrations collected during the eight dry periods were compared to

Table 4 Significant correlations between total rainfall during the 72 h prior to sampling and physical, chemical, and biological parameters for the entire data set (all stations combined—column 1) and for individual creek, presented as Pearson correlation coefficient (*r*—top line)/probability (*p*—bottom line)

	All sites	Burnt Mill Creek	Smith Creek	Prince George Creek
Turbidity	0.624	0.550	0.789	0.553
	0.001	0.001	0.001	0.001
TSS	0.450	0.342	0.596	0.436
	0.001	0.015	0.001	0.008
FC	0.576	0.473	0.827	0.517
	0.001	0.001	0.001	0.001
Ortho-P	0.393	0.309	0.446	0.456
	0.001	0.029	0.002	0.005
Total-P	0.331	0.303	0.346	0.357
	0.001	0.033	0.016	0.032
BOD5	0.266		0.462	
	0.003	ns	0.016	ns
BOD20	0.565		0.679	0.777
	0.001	ns	0.001	0.001
Ammonium	−0.363	−0.492	−0.510	
	0.001	0.001	0.001	ns
Grease and oil	−0.333	−0.513		
	0.001	0.001	ns	ns

ns not significant

those collected during the four wet periods, by individual creek and for all sites and creeks combined. Wet-period fecal coliform bacteria counts were significantly higher than dry-period counts for each individual creek (Fig. 4). Geometric mean counts in wet periods were four to ten times greater than during dry periods. Wet-period BOD5 concentrations were significantly higher than dry-period concentrations only at Smith Creek (Fig. 4). However, BOD20 was higher during wet periods for both Smith Creek and Prince Georges Creek samples (Fig. 4). Wet-period TSS concentrations were higher than dry-period concentrations for Smith Creek alone (Fig. 5), and wet-period turbidity was significantly higher than dry-period turbidity at all three individual creeks (Fig. 5). For the entire data set (all sites combined), wet-period concentrations were significantly higher than dry-period concentrations for fecal coliform bacteria, BOD20, TSS and turbidity (not shown).

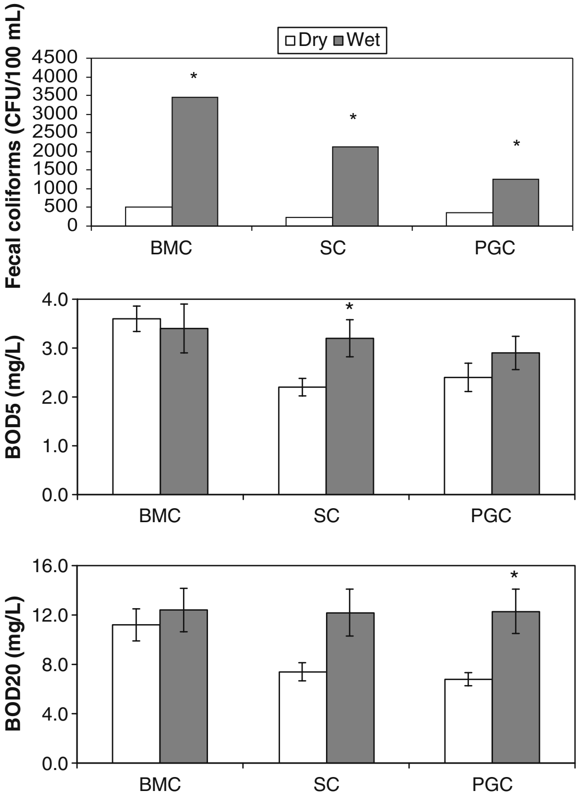

Fig. 4 Dry versus wet-period concentrations of fecal coliform bacteria (geometric mean), BOD5, and BOD20 (mean ± standard error of the mean) for Burnt Mill Creek (*BMC*), Smith Creek (*SC*), and Prince Georges Creek (*PGC*); significantly different at $^*p < 0.05$

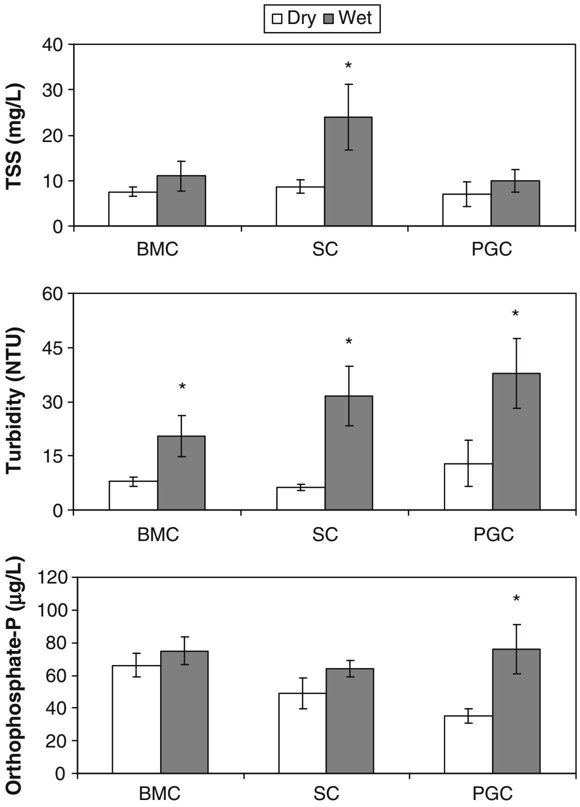

Fig. 5 Dry versus wet-period concentrations of TSS turbidity, and orthophosphate-P (mean ± standard error of the mean) for Burnt Mill Creek (*BMC*), Smith Creek (*SC*), and Prince Georges Creek (PGC); significantly different at $^*p < 0.05$

Wet-period orthophosphate concentrations were significantly higher than dry-period concentrations for Prince Georges Creek (Fig. 5), but wet-period TP was higher for both Smith Creek and Prince Georges Creek (Fig. 6). In contrast, TN was significantly higher during dry periods for Smith Creek alone (Fig. 6), and grease and oil dry-period concentrations were greater than wet-period concentrations for Burnt Mill Creek alone (Fig. 6). The only other parameter with a significant period difference was dissolved oxygen at Smith Creek (dry 6.5 ± 1.5 mg/L; wet 5.5 ± 0.8 mg/L). For all sites combined, both orthophosphate and TP had higher wet-period concentrations, and TN and grease and oil had higher dry-period concentrations (not shown).

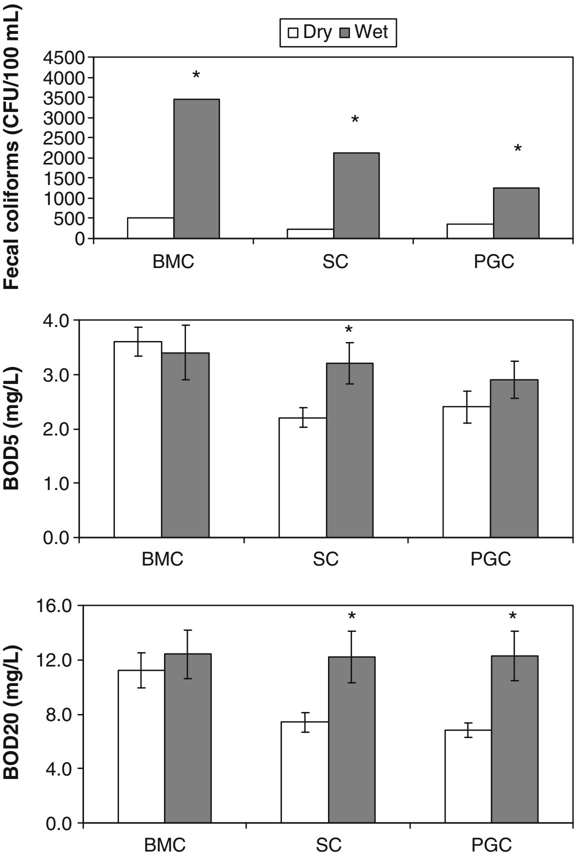

Fig. 6 Dry versus wet-period concentrations of total phosphorus, grease and oil, and surfactants (mean ± standard error of the mean) for Burnt Mill Creek (*BMC*), Smith Creek (*SC*), and Prince Georges Creek (*PGC*); significantly different at $^*p < 0.05$

There were no significant wet- vs. dry-period differences for either ammonium or nitrate.

Pollutant association with particulate matter

Table 5 Results of correlation analyses among suspended particulate matter and select physical, chemical, and biological parameters, all 12 stations combined, presented as Pearson correlation coefficient (*r*—top line)/probability (*p*—bottom line)

	Turbidity	TSS
Orthophosphate-P	0.335	0.381
	0.001	0.001
Total P	0.303	0.372
	0.001	0.001
Fecal coliforms	0.388	0.269
	0.001	0.001
Total organic C	0.292	
	0.002	ns
Chlorophyll *a*	0.285	0.388
	0.001	0.001
BOD5	0.198	0.327
	0.030	0.001
BOD20	0.452	0.549
	0.001	0.001
Ammonium-N	−0.358	−0.239
	0.001	0.005
Grease and oil	−0.390	−0.267
	0.001	0.001

ns not significant

Several pollutant parameters were positively correlated with measures of suspended particulate matter (TSS and turbidity). For all data combined (Table 5), these included orthophosphate, TP, fecal coliforms, TOC (with turbidity only), chlorophyll *a*, BOD5, and BOD20, while ammonium and grease and oil were negatively correlated with these measures. For the individual creeks, either TSS or turbidity was positively correlated with the same variables except for fecal coliforms in Burnt Mill Creek and chlorophyll *a* in Prince Georges Creek. Ammonium was not negatively correlated with either of these measures in Prince Georges Creek (Table 6).

Discussion

Effects of landscape characteristics on water quality

Land use correlations indicate that increased urban development (both residential and commercial) and greater impervious surface coverage carry increased concentrations of BOD, fecal coliform bacteria, orthophosphate, and surfactants to surface waters. All of these compounds can be attributed largely to anthropogenic sources, and hence their correlation with landscape characteristics confirms their utility as indicators of urban pollution. Of the three watersheds surveyed, the most urbanized, Burnt Mill Creek, demonstrated significantly higher BOD and surfactants than the other creeks. The watershed least affected by development, Prince Georges Creek, was significantly lower in orthophosphate and chlorophyll *a* than the other systems. Overall, the results of this

Table 6 Results of correlation analyses among suspended particulate matter and select physical, chemical, and biological parameters by individual creek, presented as Pearson correlation coefficient (*r*—top line)/probability (*p*—bottom line)

	Burnt Mill Creek		Smith Creek		Prince Georges Creek	
	Turbidity	TSS	Turbidity	TSS	Turbidity	TSS
Ortho-P		0.311	0.471	0.455		0.424
	ns	0.028	0.001	0.001	ns	0.001
Total P	0.305	0.320	0.441	0.373	0.359	0.439
	0.031	0.024	0.001	0.009	0.032	0.007
F. coliforms			0.618	0.393	0.443	0.360
	ns	ns	0.001	0.005	0.007	0.031
BOD5		0.337	0.365	0.387		0.371
	ns	0.044	0.011	0.007	ns	0.026
BOD20		0.400	0.662	0.725	0.515	0.584
	ns	0.016	0.001	0.001	0.001	0.001
Chlor. *a*	0.329	0.446		0.353		
	0.020	0.001	ns	0.014	ns	ns
Ammonium	−0.321		−0.647	−0.460		
	0.023	ns	0.001	0.001	ns	ns

ns not significant

study generally agree with a growing body of scientific literature that predicts water quality degradation to result from development, urbanization, and consequent impervious surface coverage.

Biochemical oxygen demand directly contributes to the development of hypoxia in creeks and their estuarine end-members, making it a useful parameter for the evaluation of creek ecological integrity (Mallin et al. 2006). This study demonstrated that BOD can be significantly increased by urbanization. Some of this increased BOD in BMC and SC may have been associated with algal production in these creeks (Mallin et al. 2006). In the present analysis, both BOD5 and BOD20 were positively correlated ($p \leq 0.010$) with chlorophyll *a* for all sites combined and for Smith Creek alone. Other urban sources of BOD may include pet and urban wildlife manure and petrochemicals from automobiles. Line et al. (1996) found elevated BOD concentrations in runoff draining industrial sites, especially scrap and recycling, vehicle maintenance and auto salvage areas, likely indicating petrocarbon influence on BOD.

Fecal bacteria concentration was correlated with the percent of commercial development in the three watersheds, but correlations with impervious coverage and watershed development were not statistically significant. The lack of correlation with the later two variables stands in contrast to the conclusions of similar studies. For example, in urban creeks in Nashville, Tennessee, Young and Thackston (1999) found increasing fecal coliform counts associated with degree of urbanization. In a large sampling of estuarine tidal creeks in North Carolina (Mallin et al. 2000) and South Carolina (Van Dolah et al. 2008), strong correlations were found between fecal coliform concentration and watershed population, degree of urbanization, and especially percent impervious surface coverage. Likewise, Holland et al. (2004) found a similar strong correlation between fecal coliform counts and watershed impervious surface percent cover in a set of 22 tidal estuarine creeks in Charleston, S.C. Analytical limitations of fecal coliform analysis may have obscured the expected correlations in the current study: the maximum concentration countable was 6,000 CFU/100 mL, and the most urbanized creek in the current study, Burnt Mill Creek, exceeded this maximum on 14 occasions, compared to two occasions in each of the other creek systems (Table 2; Fig. 3). The correlations between development, impervious coverage, and fecal coliforms may have been more effective had fecal coliform concentrations above 6,000 CFU/100 mL been estimated. Additionally, there was sufficient agricultural land use in the Prince Georges Creek watershed (i.e., livestock grazing) to impact water quality with elevated fecal bacterial counts. It is notable that the catchment within Prince Georges Creek that had the highest fecal coliform counts (geometric mean = 859 CFU/100 mL) had both the highest percent impervious surface coverage (13.4%) and highest agricultural land coverage (14.1%) in that creek system.

Orthophosphate is the most common inorganic form of phosphate and a potential pollutant to surface waters due to its stimulation of bacteria (Mallin et al. 2004a) and phytoplankton growth (Mallin et al. 2004b). Percent of urban development and impervious surface were positively correlated with orthophosphate in the three watersheds studied, suggesting a combination of anthropogenic sources of orthophosphate in these watersheds and increased delivery efficiency to surface waters. Previous research has demonstrated that, in residential areas, lawns and driveways contribute large phosphorus loads to stormwater runoff (Bannerman et al. 1993). In urbanized areas, the high impervious surface coverage exacerbates the runoff of P from lawns, gardens, and landscaped areas by increasing the "flashiness" or erratic and rapid inputs of runoff into creeks (Holland et al. 2004) and providing a rapid conduit for P and other pollutants to enter receiving waters. These mechanisms of orthophosphate enrichment in urban streams in the current study are also supported by the significantly higher concentrations in the urban stream than the rural stream (Table 1).

Surfactants are chemicals used in soaps and detergents that reduce the surface tension at the air/water interface, essentially causing grease globules to be broken up into finer pieces to be more readily washed away (Pankow 1991). Common in wastewater, surfactants should also be found in urban/suburban runoff situations where soaps and detergents are used in auto washing, window and building cleaning, floor cleaning, etc. Their strong correlation with impervious surface coverage and percent developed area demonstrates that increased surfactants are clearly a water quality signal of increasing urbanization.

Total organic carbon in rural Prince Georges Creek was double the TOC concentration in Burnt Mill and Smith Creeks (Table 2). In the lowland predominantly blackwater rivers that characterize most of the coastal drainages in the Southeast US, the TOC is often comprises >90% dissolved organic carbon (DOC; Meyer 1992). The sandy soils in these watersheds do not retain DOC, and hence their creeks are characterized by high DOC concentrations. Higher TOC is indicative of undeveloped regions or non-urban human use such as forestry, and thus, low TOC concentrations in this study area can indicate disruption of the natural biogeochemical and hydrologic pathways. Data from the current study bolster previous research (e.g., Vernberg et al. 1992; Kawaguchi et al. 1997; Wahl et al. 1997) showing that organic carbon concentrations are reduced in urbanized, developed watersheds. The food webs of coastal plain blackwater rivers are based on TOC, and therefore, reduced inputs of organic matter may negatively impact these ecosystems. Additionally, lower DOC inputs to estuarine waters downstream of urbanized areas can affect marine food webs. Dissolved organic matter chelates iron, making it more available to phytoplankton; thus, urbanization reduces iron (an essential algal micronutrient) availability to the algae and may result in changes to algal community structure (Kawaguchi et al. 1997).

Effects of rainfall on water quality

Rainfall runoff had major impacts on the water quality of all three systems. Positive correlations occurred between rainfall and TSS, turbidity, fecal coliform abundance, phosphorus, and BOD, with the correlation between BOD20 and rainfall stronger than that with BOD5 (Table 4). As discussed above, these water quality constituents can originate from anthropogenic sources, but the observed correlations in all watersheds indicates increased loading of these constituents from a combination of anthropogenic and natural sources during storms. Furthermore, most of these constituents were correlated with TSS which provides a means of transport for many of these particles and ions. In rural areas, agricultural land is a major source of TSS and turbidity in receiving stream waters (Waters 1995). In urban and suburban watersheds, sources include landscaping activities, road construction, dust from road shoulders, lot clearing, home building, and any other earthmoving activity (Waters 1995).

Fecal bacteria are frequently associated with TSS and/or turbidity (Tables 5 and 6; Mallin et al. 2000, 2002) and can either be deposited on the channel bottom or carried long distances downstream to pollute coastal waters. Excessive fecal coliform counts occurred in Burnt Mill Creek not only following rain events but during dry periods as well. Sources of fecal microbial contamination in urban areas include domestic animals and urban wildlife including pets, waterfowl, pigeons, rats, and raccoons (Hussong et al. 1979; Smith and Perdek 2004); other potential sources include illicit sewer connections to storm drain systems and leaks in sanitary sewer systems. In contrast to Burnt Mill Creek, in Smith Creek and especially Prince Georges Creek, the peak fecal coliform counts were associated almost entirely with wet periods. Some rural areas of Pender County, where Prince Georges Creek is located, are unsewered, and septic system use is common. Unsuitable soils combined with a high water table may render septic systems as sources of fecal microbial and nutrient contamination to nearby surface water bodies (Reneau et al. 1975; Cahoon et al. 2006). As mentioned, rural grazing areas can contribute elevated fecal bacteria counts to creeks (Howell et al. 1995); at one of our stations in Prince Georges Creek (PGC-DF), pastureland containing horses was clearly visible upcreek of the collection site.

Excessive soil phosphorus levels are commonly found in row crop and pastureland in eastern North Carolina (Cahoon and Ensign 2004), increasing the potentiality of phosphorus runoff entering streams. Suspended sediments readily adsorb phosphate (Burkholder 1992) through chemical and physical reactions and later desorb phosphorus when higher salinity waters are encountered (Froelich 1988). Between 75% and 90% of the phosphorus runoff from cultivated land occurs in association with eroding soils (Sharpley et al. 1993), and most of the annual runoff of phosphorus from cultivated acreage occurs in a few intense rainstorms (Sharpley et al. 1993). In urban situations, phosphorus sources include fertilizer use, pet and urban wildlife manure, phosphate-containing cleaning agents, and leaking sewer systems. As mentioned, residential areas can be important sources of phosphorus (Bannerman et al. 1993). The many urban sources of TSS and turbidity mentioned above, when combined with escalated runoff and erosion caused by increased impervious cover (Schueler 1994), clearly lead to this strong urban runoff coupling of suspended matter and phosphorus.

The reason(s) for the negative correlation between rainfall and ammonium in Burnt Mill Creek and Smith Creek is not clear. Barring sewage spill situations, ammonium concentrations in streams in this area are low to moderate (Mallin et al. 2002, 2004a, b), although rainfall ammonium concentrations have increased in recent years (Willey et al. 2006). Whereas ammonification tends to occur in hypoxic situations such as are likely to occur under stagnant water conditions, the rain events may have led to mixing, better oxic conditions, and enhanced nitrification, although this is speculative since there was not a corresponding positive correlation between rainfall and nitrate. Another potential (again speculative) explanation is that, under higher temperatures and pH levels, formation of ammonium is favored; however, if rainfall cools the water and reduces pH, this may reduce formation and accumulation of ammonium.

There was a negative correlation between grease and oil and rainfall for all sites combined and for Burnt Mill Creek alone. During low-flow periods on Burnt Mill Creek. there is frequently a visible surface sheen from petrochemicals leaking into the system from subsurface urban sources (old dump sites and other contaminated areas) or from what may have been washed into the creek from runoff on earlier occasions. This surface layer may be mixed and diluted following rainfall, making it less concentrated in the near-surface samples used in field collections.

Implications for water quality management

The data presented here indicate that surface water pollution by fecal bacteria and both inorganic and organic chemicals is higher in urban watersheds and that concentrations of these pollutants will be exacerbated following rainfall. The observed trends in entirely anthropogenic constituents such as hydrocarbons (grease and oil) and surfactants indicate the presence of anthropogenic pollution sources and a hydrologic linkage to the watershed's streams. Thus, while the proportion of pollution due to anthropogenic activities cannot be ascertained from the data, it is clear that watershed urbanization is responsible for providing both a source and mechanism for transport of bacteriological and chemical pollutants to surface waters.

In our study, multiple pollutants (fecal bacteria, phosphorus, BOD) showed a clear association with TSS and turbidity. This suggests that strong efforts to reduce TSS loading to water bodies will have multiple benefits. Reducing TSS inputs will: (1) increase water clarity and provide better visibility for sight-predatory fish, (2) increase rooted macrophyte and benthic microalgal growth with better light penetration, (3) lower inputs of fecal bacteria associated with particles and increase destruction of fecal bacteria with more ultraviolet light penetration, (4) lower phosphorus loading and algal blooms in P-limited fresh or brackish waters, (5) increase oxygen concentration by reduction of particle-associated BOD materials, and (6) reduce sedimentation and stress on benthic stream communities.

Conclusions

Over all sampling periods combined, the urban stream yielded the highest BOD, orthophosphate, TSS, and surfactant concentrations, while the most rural stream yielded the highest total organic carbon concentrations of the three creeks.

Percent watershed development and percent impervious surface coverage were strongly correlated with BOD, orthophosphate, and surfactant concentrations but negatively with total organic carbon.

Fecal coliform bacteria, TSS, turbidity, orthophosphate, total phosphorus, and BOD were significantly higher during rain events when compared to nonrain periods, while total nitrogen and grease and oil concentrations were reduced during rain events.

Total rainfall preceding sampling was positively correlated with turbidity, TSS, BOD, total phosphorus, and fecal coliform bacteria concentrations, while ammonium and grease and oil were negatively correlated with rainfall.

TSS and turbidity were positively correlated with phosphorus, fecal coliform bacteria, BOD, and chlorophyll *a* and negatively with ammonium and grease and oil.

Longer-term BOD (BOD20) was more strongly correlated with both rainfall and particulate matter concentrations than 5-day BOD (BOD5).

Strong efforts to reduce TSS loading to water bodies will have multiple benefits including increasing water clarity, less alteration of bottom habitat with less sedimentation, lower inputs of fecal bacteria associated with particles, enhanced die-off of fecal bacteria with more ultraviolet light penetration, lower phosphorus loading and algal bloom problems, and better oxygenation of receiving waters with less input of BOD materials.

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