ENVIRONMENTAL QUALITY OF WILMINGTON AND NEW HANOVER COUNTY WATERSHEDS, 2012

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Michael A. Mallin, Lauren E. Bohrer, Matthew R. McIver and Stephanie Protopappas

CMS Report 13-01
Center for Marine Science
University of North Carolina Wilmington
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www.uncw.edu/cms/aelab/

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The City of Wilmington through the Water Resources Research Institute of the University of North Carolina, NCSU No. 2010-1651-01

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Executive Summary

This report represents combined results of Year 14 of the Wilmington Watersheds Project. Water quality data are presented from a watershed perspective, regardless of political boundaries. The 2012 program involved 8 watersheds and 22 sampling stations. In this summary we first present brief water quality overviews for each watershed from data collected between January and December 2012.

Barnards Creek – Barnards Creek drains into the Cape Fear River Estuary. It drains a 4,161 acre watershed that consists of about 17% impervious surface coverage, and a population of approximately 12,200. Water column sampling was not funded during 2012.

Bradley Creek – Bradley Creek drains a watershed of 4,631 acres, including much of the UNCW campus, into the Atlantic Intracoastal Waterway (ICW). The watershed contains about 23% impervious surface coverage, with a population of about 16,470. Three sites were sampled, all from shore. In 2012 there was one significant algal bloom recorded in the south branch of the creek on Wrightsville Avenue (BC-SB). Average dissolved oxygen was fair to poor at the three sites. All three sites sampled were rated poor due to high fecal coliform bacteria, with the south branch site BC-SB and the College Acres station BC-CA both having especially high counts.

Burnt Mill Creek – Burnt Mill Creek drains a 4,252 acre watershed which is extensively urbanized (34% impervious surface coverage) into Smith Creek. Three locations were sampled during 2012. This creek had very poor water quality, with algal blooms occurring on occasion at all of the three sites sampled. High fecal coliform counts occurred, with two of the three sites exceeding the human contact standard > 60% of occasions sampled. These levels of pollution have characterized the system for the past several years. Dissolved oxygen concentrations were fair to poor in 2012.

The effectiveness of Ann McCrary wet detention pond on Randall Parkway as a pollution control device for upper Burnt Mill Creek was mixed for 2012. Comparing inflows to outflows, there was a significant increase in dissolved oxygen and pH, and a significant decrease in fecal coliform counts; whereas there was no change in nutrient concentrations. Several water quality parameters showed a worsening in pollutant levels along the creek from where it exited the detention pond to the downstream Princess Place sampling station, including dissolved oxygen, fecal coliform bacteria, nitrogen and phosphorus.

Futch Creek – Futch Creek is situated on the New Hanover-Pender County line and drains a 3,106 acre watershed into the ICW. UNC Wilmington was not funded to regularly sample this creek in 2012. The County employed a consulting firm to sample this creek and data are available on the County website.

Greenfield Lake – This lake drains a watershed of 2,551 acres, covered by about 36% impervious surface area with a population of about 10,630. This urban lake has, over the years, suffered from low dissolved oxygen, algal blooms, periodic fish kills and high fecal bacteria counts. The lake was sampled for physical parameters at three tributary sites and for all parameters at three in-lake sites. The three tributaries of Greenfield Lake (near Lake Branch Drive, Jumping Run Branch, and Lakeshore Commons Apartments) all suffered from low dissolved oxygen problems. In 2012 there was good to fair dissolved oxygen at two of the in-lake stations (especially nearest the SolarBees), but low dissolved oxygen concentrations were common at GL-2340, in the upper lake.

Algal blooms are periodically problematic in Greenfield Lake, and have occurred during all seasons, but are primarily a problem in spring and summer. In 2012 algal blooms did occur on several occasions in the lake, but they were decreased from 2011. In the period 2007-2012 there was a statistically significant relationship within the lake between chlorophyll *a* and BOD5, meaning that the algal blooms are likely an important cause of low dissolved oxygen in this lake, along with stormwater runoff of BOD materials into the streams feeding the lake. In 2012 all three in-lake sites had fecal coliform counts that exceeded the State standard on 33% or more of occasions sampled. Station GL-2340 maintained geometric mean concentration of 235 CFU/100 mL, exceeding the standard of 200 CFU/100 mL, and exceeded the standard on four of six occasions sampled. In early July 2012 there was a fish kill in Greenfield Lake, consisting of a variety of species. High water temperatures coupled with lack of rain and flushing likely led to decreases in dissolved oxygen that caused the kill.

From 2005 to 2012 several steps were taken by the City of Wilmington to restore viability to the lake. Sterile grass carp were introduced to the lake to control (by grazing) the overabundant aquatic macrophytes, and four SolarBee water circulation systems were installed in the lake to improve circulation and force dissolved oxygen from the surface downward toward the bottom. Also, on many occasions a contract firm and City staff applied herbicides to further reduce the amount of aquatic macrophytes. These actions led to a major reduction in aquatic macrophytes lake wide.

Greenfield Lake sediments were sampled at seven sites on October 23. Two in-lake stations, GL-P and GL-YD had elevated concentrations of copper and lead; GL-YD additionally had high zinc concentrations (Table 6.4). Metals were not at excessive concentrations in the streams feeding the lake. Total PAH concentrations were excessive in the sediments of all three in-lake stations, as well as two stream sites; GL-LB (Lake Branch), and especially GL-SS1, the head of the Silver Stream wetland/detention pond complex along Candlewood Dr. Individual PAHs that were excessive in the lake sediments included Phenanthrene, Fluoranthene and Chrysene (Table 6.4). All stream sites had elevated concentrations of Fluoranthene; Lake Branch also had high Chrysene concentrations. Total PCBs were below detection limit at all sites.

<u>Hewletts Creek</u> – Hewletts Creek drains a large (7,435 acre) watershed into the Intracoastal Waterway. This watershed has about 19% impervious surface coverage with a population of about 20,210. In 2012 the creek was sampled at four tidal sites and one non-tidal freshwater site. Incidents of severe hypoxia did not occur in 2012 as no concentrations sampled were below 4.0 mg/L. Turbidity was low, and algal blooms were not problematic in 2012. Fecal coliform bacteria counts were high in three stations sampled in the creek. Counts exceeded State standards 100% of the time at MB-PGR,

83% of the time at NB-GLR and 67% of the time at PVGC-9. The geometric mean at PVGC-9 decreased from 2011.

During 2007 the 7.6 acre JEL Wade wetland (located at the end of Bethel Road) was constructed to treat stormwater runoff from a 589 acre watershed within the Hewletts Creek drainage. Drainage for this wetland enters the south branch of the creek, upstream of the SB-PGR sampling site. This constructed wetland has continued to function extremely well in reduction of nutrients and fecal bacteria from stormwater inputs. Additionally, sampling data collected downstream of the wetland at Station SB-PGR shows a statistically significant decline in ammonium, nitrate and fecal coliform bacteria after completion of the wetland, demonstrating the wetland's benefits to the creek system as a whole.

Howe Creek – Howe Creek drains a 3,518 acre watershed into the ICW. This watershed hosts a population of approximately 6,460 with about 19% impervious surface coverage. Three stations were sampled in Howe Creek in 2012. Two minor algal blooms were seen, both at the uppermost station HW-DT. The uppermost station HW-DT was rated poor for high fecal coliform bacteria counts, exceeding the state standard on 67% of the times sampled, while HW-GP and HW-FP were rated fair and good, respectively. Dissolved oxygen concentrations were rated poor at the two upper stations in 2012 from being below 5.0 mg/L on 50% of occasions sampled, although the levels seen did not represent extreme hypoxia. Since wetland enhancement was performed in 1998 above Graham Pond the creek below the pond at Station HW-GP has had fewer and smaller algal blooms than before the enhancement.

Motts Creek – Motts Creek drains a watershed of 3,328 acres into the Cape Fear River Estuary with a population of about 9,530. This creek was not sampled by UNCW in 2012.

Pages Creek – Pages Creek drains a 3,039 acre watershed into the ICW. UNC Wilmington was not funded to sample this creek from 2008-2012. The County employed a private firm to sample this creek and data are available on the County website.

Smith Creek – Smith Creek drains into the lower Northeast Cape Fear River just upstream of where it merges with the Cape Fear River. It has a watershed of 13,896 acres that has about 33% impervious surface coverage, with a population of about 31,780. One estuarine site on Smith Creek, SC-CH, was sampled by UNCW under the auspices of the Lower Cape Fear River Program (LCFRP). Water quality at this site was poor in 2012, with the dissolved oxygen standard of 4.0 mg/L violated 25% of the time and the turbidity standard of 25 NTU violated on 17% of occasions sampled. Fecal bacteria pollution remained poor in 2012, violating the contact standard 42% of occasions sampled.

Sediment toxin sampling showed that there were no problematic metals or toxin concentrations in either the north or south branches of Smith Creek as sampled at Kerr Avenue (SC-KAN and SC-KAS). However, the lower station at Castle Hayne Road

(SC-CH) had elevated concentrations of two PAHs, Fluoranthene and Chrysene; both were at problematic levels, according to established toxic ranges.

Whiskey Creek – Whiskey Creek is the southernmost large tidal creek in New Hanover County that drains into the ICW. It has a watershed of 2,095 acres, a population of about 8,000, and is covered by approximately 19% impervious surface area. One station, on Masonboro Loop Road, was sampled from shore along this creek in 2012. This site had low to moderate nutrient concentrations and no algal bloom problems. Dissolved oxygen was substandard (below 5.0 mg/L) on 67% of occasions sampled, whereas fecal coliform bacteria counts were below standard on all occasions sampled.

Study of Potential Sewage Inputs into Burnt Mill Creek - The UNCW Aquatic Ecology Laboratory at The Center for Marine Science conducted sampling at or near several stormwater sites entering Burnt Mill Creek for potential sewage inputs; these sites were sampled for fecal coliform bacteria and optical brightener concentrations. This project was conducted from June 4th through the month of August 2012, with emphasis toward rain events. Of the seven sites that UNCW collected significant data on, three showed possible sewage influence. These were: BMC-MDW and BMC-MDE, located on Rankin St. between 12th and 13th - these are stormwater pipes flowing into McCumbers Ditch, a tributary to Burnt Mill Creek; and Station 21-NB, located in close proximity to the mouth of Burnt Mill Creek where it meets up with the Northeast Cape Fear River. This site is a small bridge directly underneath a street storm drain located off of 21st St. between Noble and Brandon.

Water Quality Station Ratings – The UNC Wilmington Aquatic Ecology Laboratory utilizes a quantitative system with four parameters (dissolved oxygen, chlorophyll *a*, turbidity, and fecal coliform bacteria) to rate water quality at our sampling sites. If a site exceeds the North Carolina water quality standard for a parameter less than 10% of the time sampled, it is rated Good; if it exceeds the standard 10-25% of the time it is rated Fair, and if it exceeds the standard > 25% of the time it is rated Poor for that parameter. We applied these numerical standards to the water bodies described in this report, based on 2012 data, and have designated each station as good, fair, and poor accordingly (Appendix B).

Fecal coliform bacterial conditions for the entire Wilmington City and New Hanover County Watersheds system (19 sites sampled for fecal coliforms) showed 21% to be in good condition, 5% in fair condition, but **74%** in poor condition, similar to 2011. Dissolved oxygen conditions system-wide (22 sites) showed 18% of the sites were in good condition, 23% were in fair condition, and 59% were in poor condition, a worse showing than in 2011. For algal bloom presence, measured as chlorophyll *a*, 61% of the 18 stations sampled were rated as good, 28% as fair and 11% as poor (Greenfield Lake) an improvement from 2011. In terms of turbidity 21 of the 22 sites sampled were rated as good, while one site, Smith Creek at Castle Hayne Rd. was rated fair. It is important to note that the two water bodies with the worst water quality in the system also have the most developed watersheds with the highest impervious surface coverage; Burnt Mill Creek – 34% impervious coverage; Greenfield Lake – 36% impervious coverage.

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Plate 1. Wilmington and New Hanover County watersheds (map by M. Hayes, Wilmington Stormwater Services).

1.0 Introduction

In 1993 scientists at the UNC Wilmington Center for Marine Science Research began studying five tidal creeks in New Hanover County. This project, funded by New Hanover County, the Northeast New Hanover Conservancy, and UNCW, yielded a comprehensive report detailing important findings from 1993-1997, and produced a set of management recommendations for improving creek water quality (Mallin et al. 1998a). Data from that report were later published in the peer-reviewed literature (Mallin et al. 2000a; Mallin et al. 2001) and were used 2006-2009 by the N.C. General Assembly (Senate Bill 1967) as the scientific basis to redefine low density coastal areas as 12% impervious surface coverage instead of the previously used 25% impervious cover. In 1999-2000 Whiskey Creek was added to the matrix of tidal creek watersheds analyzed in our program.

In October 1997 the Center for Marine Science began a project (funded by the City of Wilmington Engineering Department) with the goal of assessing water quality in Wilmington City watersheds under base flow conditions. Also, certain sites were analyzed for sediment heavy metals concentrations (EPA Priority Pollutants). In the past fourteen years we have produced several combined Tidal Creeks – Wilmington City Watersheds reports (Mallin et al. 1998b; 1999; 2000b; 2002a; 2003; 2004; 2006a; 2007; 2008) In fall 2007 New Hanover County decided to stop funding UNCW sampling on the tidal creeks and UNCW has subsequently produced several reports largely focused on City watersheds (2009a; 2010a; 2011; 2012). In the present report we present results of sampling conducted during 2012, with principal funding by the City of Wilmington. In fall 2008 we were pleased to obtain funding from a private company dedicated to environmentally sound development, the Newland Corporation. The Newland Corporation is designing and building a large residential project called River Lights along River Road between Barnards and Motts Creeks. Through this funding we reinitiated sampling of Motts and Barnards Creeks along River Road. This sampling continued until July 2010, when plans for development of the site were delayed due to the economic slowdown and funding was suspended. As such, there has been no construction near either creek as of yet related to this project.

Water quality parameters analyzed in these nine watersheds include water temperature, pH, dissolved oxygen, salinity/conductivity, turbidity, total suspended solids (TSS), nitrate, ammonium, total Kjeldahl nitrogen (TKN), total nitrogen (TN), orthophosphate, total phosphorus (TP), chlorophyll *a* and fecal coliform bacteria. Biochemical oxygen demand (BOD5) is measured at selected sites. In 2010, a suite of metals, PAHs and PCBs were assessed in the sediments of Burnt Mill Creek and Hewletts Creeks, in 2011 the sediments of Barnards and Bradley Creeks were sampled, and in 2012 the sediments of Smith Creek and Greenfield Lake were sampled for those parameters.

In 2010 Wilmington Stormwater Services also began a collaboration with UNCW to investigate potential sewage spills and leaks and illicit sanitary connections potentially polluting city waterways. The results of samples collected under that effort are also presented.

1.1 Water Quality Methods

Samples were collected on six occasions at 22 locations within the Wilmington City watersheds between January and December 2012. Field parameters were measured at each site using a YSI 6920 Multiparameter Water Quality Probe (sonde) linked to a YSI 650 MDS display unit. Individual probes within the instrument measured water temperature, pH, dissolved oxygen, turbidity, salinity, and conductivity. YSI Model 85 and 55 dissolved oxygen meters were available as back-up meters. The YSI 6920 was calibrated prior to each sampling trip to ensure accurate measurements. The UNCW Aquatic Ecology laboratory is State-Certified for field measurements (temperature, conductivity, dissolved oxygen and pH). At 19 locations samples were collected on-site for laboratory analysis of ammonium, nitrate+nitrite (referred to within as nitrate), total Kjeldahl nitrogen (TKN), orthophosphate, total phosphorus, total suspended solids (TSS), fecal coliform bacteria, and chlorophyll *a*.

The analytical method used by the UNCW Aquatic Ecology Laboratory to measure chlorophyll *a* (EPA Method 445.0) is based on Welschmeyer (1994) and US EPA (1997). Chlorophyll *a* concentrations were determined from the 0.7 micrometer glass fiber filters used for filtering samples for nitrate+nitrite and orthophosphate analyses. All filters were wrapped individually in aluminum foil, placed in an airtight container and stored in a freezer. During the analytical process, the glass filters were separately immersed in 10 ml of a 90% acetone solution and allowed to extract the chlorophyll from the material for three hours; filters were ground using a Teflon grinder prior to extraction. The solution containing the extracted chlorophyll was then analyzed for chlorophyll *a* concentration using a Turner AU-10 fluorometer. This method uses an optimal combination of excitation and emission bandwidths that reduces errors in the acidification technique. UNCW Aquatic Ecology Laboratory is State-certified for laboratory chlorophyll *a* measurements.

Nutrients (nitrate, ammonium, total Kjeldahl nitrogen, total nitrogen, orthophosphate, and total phosphorus) and total suspended solids (TSS) were analyzed by a state-certified contract laboratory using EPA and APHA techniques. We also computed inorganic nitrogen to phosphorus molar ratios for relevant sites (N/P). Fecal coliform concentrations were determined using a membrane filtration (mFC) method (APHA 1995).

For a large wet detention pond (Ann McCrary Pond on Burnt Mill Creek) we collected data from input and outfall stations. We used these data to test for statistically significant differences in pollutant concentrations between pond input and output stations. The data were first tested for normality using the Shapiro-Wilk test. Normally distributed data parameters were tested using the paired-difference t-test, and non-normally distributed data parameters were tested using the Wilcoxon Signed Rank test. Statistical analyses were conducted using SAS (Schlotzhauer and Littell 1997).

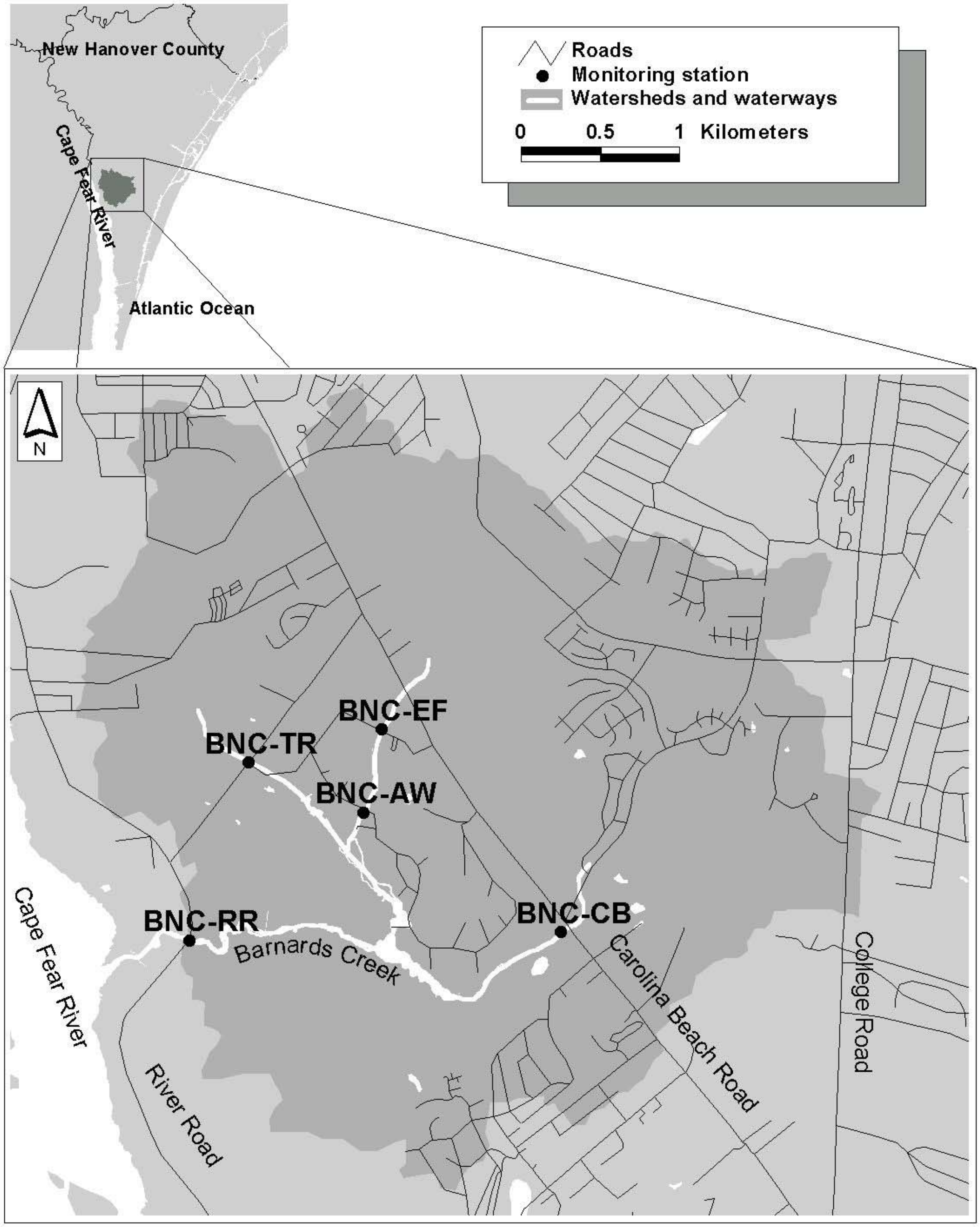
For comparative purposes, North Carolina water quality standards are listed in Appendix A.

2.0 Barnards Creek

Snapshot
Watershed area: 4,161 acres (1,684 ha)
Impervious surface coverage: 17%
Watershed population: Approximately 12,200
Overall water quality: not measured in 2011

The water quality of lower Barnard's Creek is an important issue as single family and multifamily housing construction has occurred upstream of Carolina Beach Rd. in the St. Andrews Dr. area and along Independence Boulevard near the Cape Fear River. Another major housing development (River Lights) is planned for the area east of River Road and between Barnards and Motts Creeks, although no project construction has yet occurred near Barnards Creek. In 2012 UNCW was not funded for water quality studies on lower Barnards Creek. We do have extensive data for this site under a previous funding arrangement from 1999 – 2007 (see the following website for reports on-line: http://www.uncw.edu/cms/aelab/.

Figure 2.1 Barnards Creek watershed



3.0 Bradley Creek

Snapshot
Watershed area: 4,631 acres (1,874 ha)
Impervious surface coverage: 23%
Watershed population: Approximately 16,470
Overall water quality: fair-poor
Problematic pollutants: fecal bacteria, occasional low dissolved oxygen, occasional algal blooms

The Bradley Creek watershed has been a principal location for Clean Water Trust Fund mitigation activities, including the purchase and renovation of Airlie Gardens by the County. There is currently ongoing redevelopment of the former Duck Haven property bordering Eastwood Road, which is of concern in terms of its potential water quality impacts to the creek. This creek has been one of the most polluted in New Hanover County, particularly by fecal coliform bacteria (Mallin et al. 2000a) and has suffered from sewage leaks (Tavares et al. 2008) and stormwater runoff. Three upstream stations (BC-SB, BC-NB and BC-CA) were sampled in the past year, both fresh and brackish (Fig. 3.1).

Turbidity was not a problem during 2012; the standard of 25 NTU was not exceeded on any sampling occasion (Table 3.1). Total suspended solids (TSS) were elevated on two occasions at BC-NB; in June when it was 23.9 mg/L and August when it was 31.6 mg/L (there are no NC ambient standards for TSS, but UNCW considers 25 mg/L high for the Coastal Plain). There were minor issues with low dissolved oxygen (hypoxia), at station BC-CA and Station BC-SB having DO < 5.0 mg/L on one occasion each during the six, but BC-NB was rated Poor for DO due to have DO below the standard on 50% of occasions sampled (Appendix B).

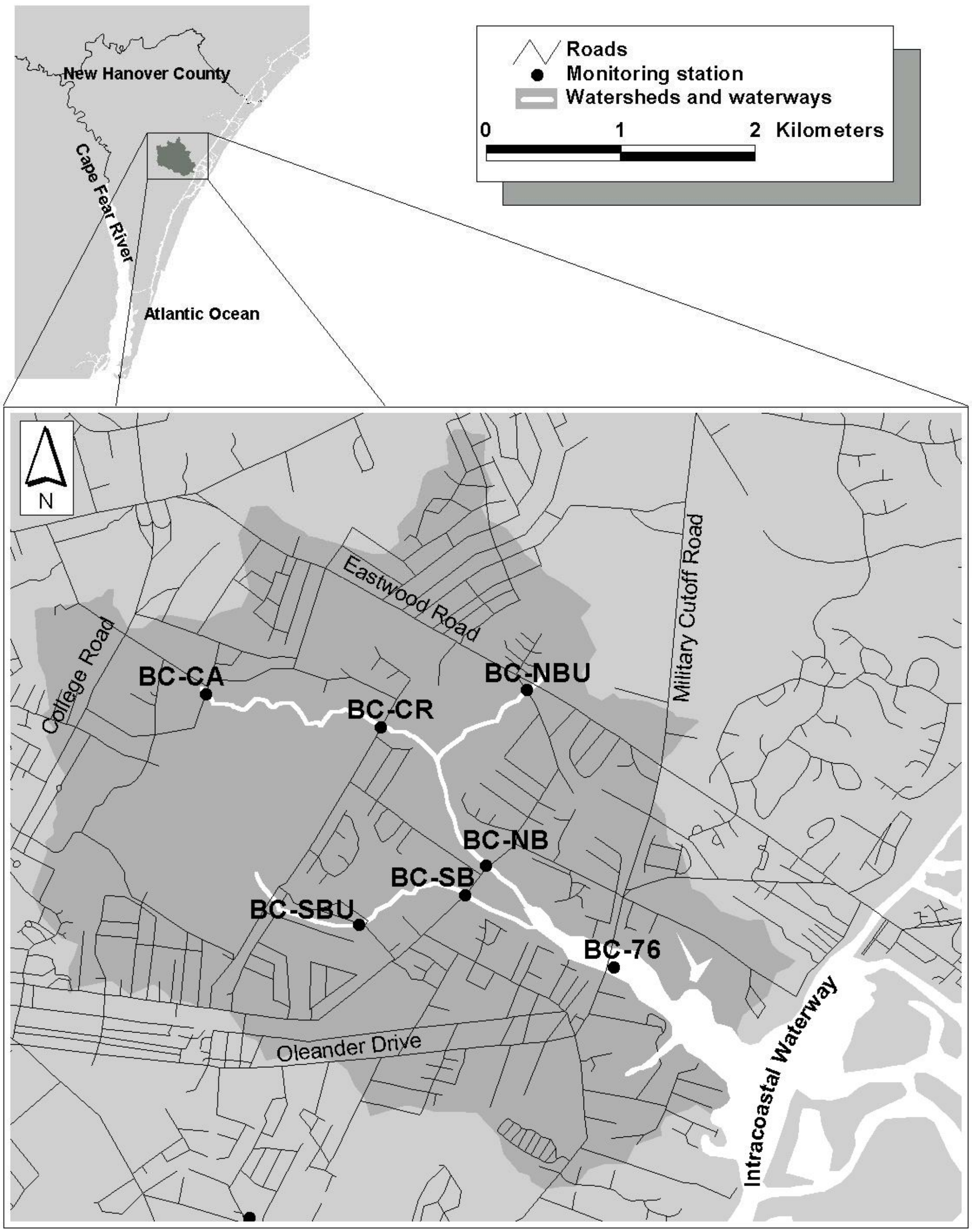
Ammonium concentrations were generally low, but somewhat higher than during 2011. Nitrate concentrations were highest at station BC-CA, but low in general and lower than during 2011 (Table 3.1). Total nitrogen concentrations were low to moderate at all times sampled, and slightly higher than in 2011. Orthophosphate concentrations were low and similar to 2011; TP followed a similar pattern as orthophosphate. Bradley Creek station BC-SB hosted one significant algal bloom of 75 μg/L chlorophyll *a* in June. Median nitrogen to phosphorus ratios at BC-NB and BC-SB were low (3-6) indicating that inputs of inorganic nitrogen are likely to stimulate the algal blooms.

Fecal coliform bacteria counts were excessive at all three stations sampled during 2012. The NC contact standard was exceeded on 100% of occasions sampled at BC-SB and BC-CA, and 33% of occasions sampled at BC-NB. The geometric means of the fecal coliform counts ranged from under the standard (192 CFU/100 mL at BC-NB) to >9X the standard (3,746 CFU/100 mL at BC-CA, Table 3.1). Fecal coliform contamination in 2012 was worse than the previous year at BC-CA.

Table 3.1 Water quality parameter concentrations at Bradley Creek sampling stations, 2012. Data as mean (SD) / range, N/P ratio as mean/median, fecal coliform bacteria as geometric mean / range, n = 6 months.

Station	BC-CA	BC-NB	BC-SB
Salinity	0.1 (0.0)	25.5 (4.6)	14.4 (6.8)
(ppt)	0.1-0.1	18.4-31.7	8.1-26.7
Dissolved Oxygen	5.8 (1.1)	6.0 (2.8)	6.0 (2.0)
(mg/L)	4.6-7.3	3.6-9.6	3.8-8.8
Turbidity	6 (4)	9 (7)	10 (7)
(NTU)	1-11	0-21	2-22
TSS	4.0 (3.9)	18.8 (8.4)	14.2 (5.2)
(mg/L)	1.4-11.6	6.7-31.6	6.8-21.4
Nitrate	0.093 (0.069)	0.013 (0.008)	0.025 (0.021)
(mg/L)	0.050-0.230	0.010-0.030	0.010-0.060
Ammonium	0.097 (0.069)	0.024 (0.021)	0.053 (0.081)
(mg/L)	0.020-0.200	0.005-0.050	0.005-0.210
TN	0.868 (01.326)	0.405 (0.506)	0.508 (0.519)
(mg/L)	0.100-3.550	0.060-1.410	0.140-1.510
Orthophosphate	0.095 (0.091)	0.010 (0.000)	0.018 (0.012)
(mg/L)	0.010-0.260	0.010-0.010	0.010-0.040
TP	0.133 (0.095)	0.033 (0.023)	0.045 (0.031)
(mg/L)	0.040-0.300	0.010-0.060	0.010-0.090
N/P	10.4	6.5	5.9
	10.0	6.1	3.9
Chlorophyll *a*	10 (5)	6 (7)	17 (29)
(μg/L)	5-17	1-20	1-75
Fecal coliforms	3,746	192	531
(CFU/100 mL)	440-60,000	64-546	310-819

Figure 3.1. Bradley Creek watershed and sampling sites.



4.0 Burnt Mill Creek

Snapshot
Watershed area: 4,252 acres (1,721 ha)
Impervious surface coverage: 34%
Watershed population: Approximately 23,700
Overall water quality: poor
Problematic pollutants: Fecal bacteria, algal blooms, some low dissolved oxygen, high sediment PAH, lead, zinc and mercury concentrations

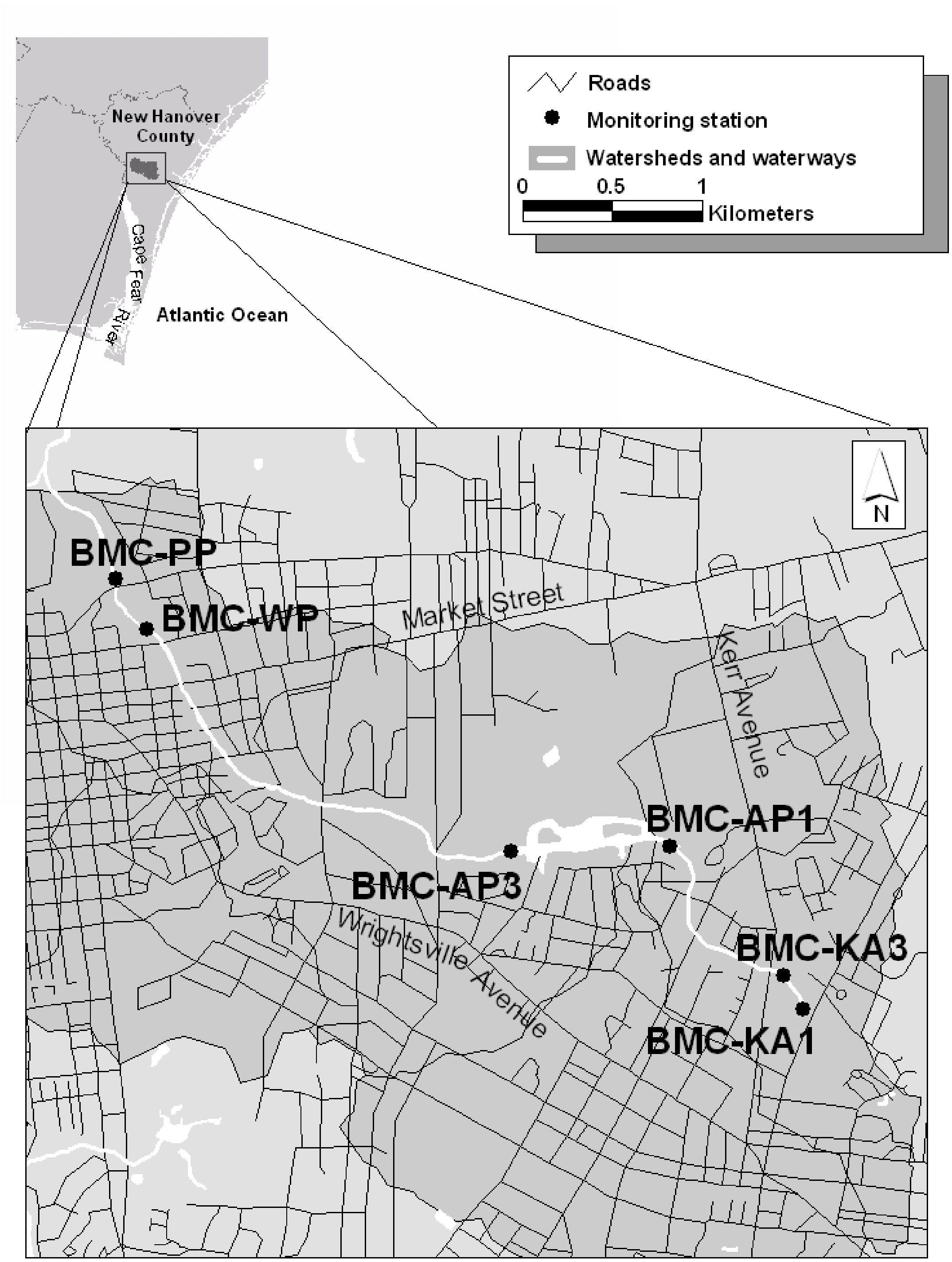
Introduction

A prominent feature in the Burnt Mill Creek watershed (Fig. 4.1) is the Ann McCrary Pond, which is a large (28.8 acres) regional wet detention pond draining 1,785 acres, with a large apartment complex (Mill Creek Apts.) at the upper end. The pond itself has periodically hosted thick growths of submersed aquatic vegetation, with *Hydrilla verticillata, Egeria densa, Alternanthera philoxeroides, Ceratophyllum demersum* and *Vallisenaria americana* having been common at times. There have been efforts to control this growth, including addition of triploid grass carp as grazers. The ability of this detention pond to reduce suspended sediments and fecal coliform bacteria, and its failure to reduce nutrient concentrations, was detailed in a scientific journal article (Mallin et al. 2002b). Numerous waterfowl utilize this pond as well. Burnt Mill Creek has been studied by a number of researchers, and recent water quality results of these continuing studies have been published in technical reports and scientific journals (Perrin et al. 2008; Mallin et al. 2009a; Mallin et al. 2009b; Mallin et al. 2010a; 2011).

Methods

Sampling Sites: During 2012 samples were collected from three stations on the creek (Fig. 4.1). In the upper creek Ann McCrary Pond, a large regional wet detention pond on Randall Parkway was sampled just upstream (BMC-AP1) and about 40 m downstream (BMC-AP3) of the pond (Fig. 4.1). Several km downstream of Ann McCrary Pond is Station BMC-PP, located at the Princess Place bridge over the creek, respectively (Fig. 4.1). This is a main stem station in what is considered to be the mid-to-lower portion of Burnt Mill Creek, in a mixed residential and retail area.

Figure 4.1. Burnt Mill Creek watershed and water quality sampling sites.



Results and Discussion

The Upper Creek

About one km downstream from Kerr Avenue along Randall Parkway is the large regional wet detention pond known as Ann McCrary Pond. Data were collected at the input (BMC-AP1) and outflow (BMC-AP3) stations on six occasions in 2012. Dissolved oxygen concentrations fell below the State standard of 5.0 mg/L on three occasions at BMC-AP1. The State standard for turbidity in freshwater is 50 NTU; there were no exceedences of this value in our 2012 samples. Suspended solids concentrations were unusually high on one sampling occasion at BMC-AP1 (24.3 mg/L in May) while concentrations were low at BMC-AP3 leaving this large regional pond; there was no statistical difference between inflow and outflow (Table 4.1). Fecal coliform concentrations entering Ann McCrary Pond at BMC-AP1 were very high (Table 4.1), possibly a result of pet waste (very visible to the observer) runoff from the Mill Creek apartment complex and runoff from urban upstream areas (including the Kerr Avenue wetland). Over the sampling period five of the six samples collected at BMC-AP1 had counts exceeding 200 CFU/100 mL, whereas two of the samples from BMC-AP3 exceeded the standard. This resulted in a statistically significant decrease in fecal coliform counts from passage through the regional detention pond (Table 4.1). The Wilmington Stormwater Services Department is aware of the problem in upper Burnt Mill Creek and UNCW continues to work with them to determine sources of fecal contamination to the upper creek.

There was one major algal bloom at BMC-AP1 that exceeded the North Carolina water quality standard; 42 ug/L in May, whereas at BMC AP-3 there was one bloom that exceeded the State standard (60 µg/L in July), and several lesser blooms between 29-36 µg/L in three other months. Statistically, there were no significant differences in chlorophyll *a* concentrations exiting the pond compared with entering the pond (Table 4.1). Concentrations of ammonium, nitrate, total nitrogen, orthophosphate and total phosphorus also did not significantly differ between entering and exiting the pond. Average dissolved oxygen significantly increased through the pond (nearly doubling), probably because of in-pond photosynthesis and aeration by passage over the final dam at the outfall. There was a significant increase in pH, probably due to utilization of CO_2 during photosynthesis in the pond.

Lower Burnt Mill Creek: The Princess Place location (BMC-PP) was the only lower creek station sampled in 2012. One parameter that is key to aquatic life health is dissolved oxygen. Dissolved oxygen at BMC-PP in 2012 was substandard on four or six occasions. Turbidity concentrations at BMC-PP did not exceed the State standard on any of our sampling occasions. Total suspended solids (TSS) concentrations have no ambient state standard. Based on our long term observances in the lower Cape Fear River area, for the lower Coastal Plain a reasonable TSS “interest concentration” is 25 mg/L; in 2012 this level was not approached at BC-PP.

In 2012 BMC-PP showed one major algal bloom that exceeded the North Carolina water quality standard for chlorophyll *a* of 40 µg/L. In May chlorophyll *a* was 44 µg/L

(Table 4.1); otherwise this station showed unusually low algal biomass. Algal blooms can cause disruptions in the food web, depending upon the species present (Burkholder 2001).

An important question is what drives algal bloom formation in Burnt Mill Creek? Nitrate concentrations were somewhat elevated at BMC-PP, while phosphorus concentrations were low. Examination of inorganic nitrogen to phosphorus ratios (Table 4.1) shows that median N/P ratios were 15.5 and mean ratios were 15.1. In waters where the N/P ratio is well below 16 (the Redfield Ratio for algal nutrient composition) it is generally considered that algal production is limited by the availability of nitrogen (i.e. phosphorus levels are sufficient); where N/P ratios are well above 16, additions of phosphate should encourage algal blooms. If such values are near the Redfield Ratio, as at BMC-PP, inputs of either N or P could drive an algal bloom. Thus, control of inputs of both N and P would help reduce algal blooms in lower Burnt Mill Creek.

Important from a public health perspective are the excessive fecal coliform bacteria counts, which maintained geometric means at BMC-PP well in excess of the State standard for human contact waters (200 CFU/100 mL). Fecal coliform counts were greater than the State standard on 83% of occasions sampled at Princess Place. It is notable that fecal coliform bacteria counts increased along the passage from BMC-AP3 (geometric mean 96 CFU/100 mL) to the Princess Place location (geometric mean 823 CFU/100 mL; Fig. 4.2), as in previous years. It is likewise notable that nutrient concentrations increased from the outflow from Ann McCrary Pond downstream to the lower main stem station (Table 4.1; Fig. 4.3).

Table 4.1. Water quality data in Burnt Mill Creek, 2012, as mean (standard deviation)/range. Fecal coliforms as geometric mean; N/P as mean/median.

Parameter	BMC-AP1	BMC-AP3	BMC-PP
DO (mg/L)	4.8 (1.4) 1.9-6.2	10.1 (1.4)** 8.1-12.5	4.4 (2.3) 2.1-8.3
Cond. (μS/cm)	232 (38) 191-281	195 (48) 131-255	311 (55) 229-371
pH	7.2 (0.3) 6.9-7.7	8.1 (0.5)* 7.6-8.8	7.3 (0.1) 7.1-7.5
Turbidity (NTU)	8 (10) 1-28	8 (6) 3-18	5 (5) 1-13
TSS (mg/L)	7.0 (8.8) 1.4-24.3	6.2 (3.4) 1.4-11.3	4.0 (2.5) 7.4-1.4
Nitrate (mg/L)	0.137 (0.145) 0.010-0.410	0.020 (0.017) 0.010-0.050	0.187 (0.115) 0.040-0.390
Ammonium (mg/L)	0.055 (0.024) 0.020-0.090	0.032 (0.026) 0.010-0.070	0.052 (0.170) 0.040-0.170
TN (mg/L)	0.845 (0.886) 0.140-2.460	1.087 (1.756) 0.110-4.630	0.628 (0.351) 0.210-1.190
OrthoPhos. (mg/L)	0.018 (0.008) 0.010-0.030	0.012 (0.004) 0.010-0.020	0.052 (0.031) 0.030-0.110
TP (mg/L)	0.055 (0.032) 0.010-0.100	0.042 (0.023) 0.010-0.080	0.090 (0.047) 0.050-0.170
N/P molar ratio	34.5 17.2	9.8 7.2	15.1 15.5
Chlor. *a* (μg/L)	15 (18) 1-42	29 (20) 5-60	12 (16) 1-44
FC (CFU/100 mL)	1,763 19-60,000	96* 5-455	832 46-60,000

* Statistically significant difference between inflow and outflow at $p<0.05$; ** $p < 0.01$.

Figure 4.2. Fecal coliform bacteria geometric means for Burnt Mill Creek, 2012

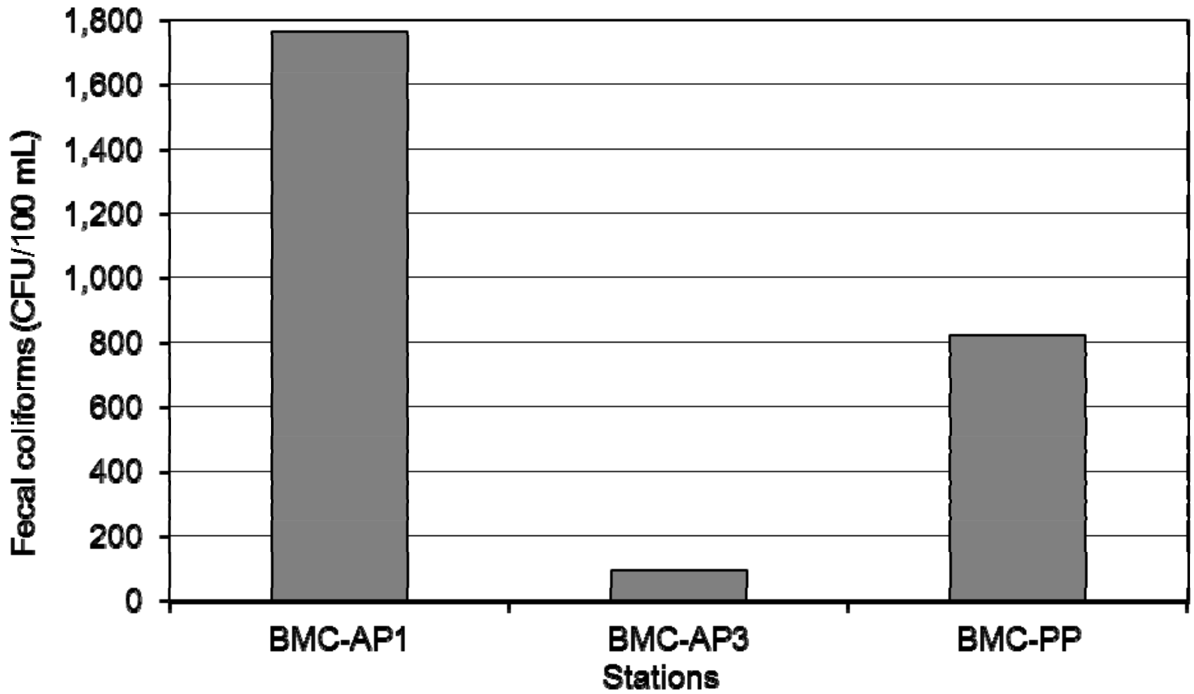
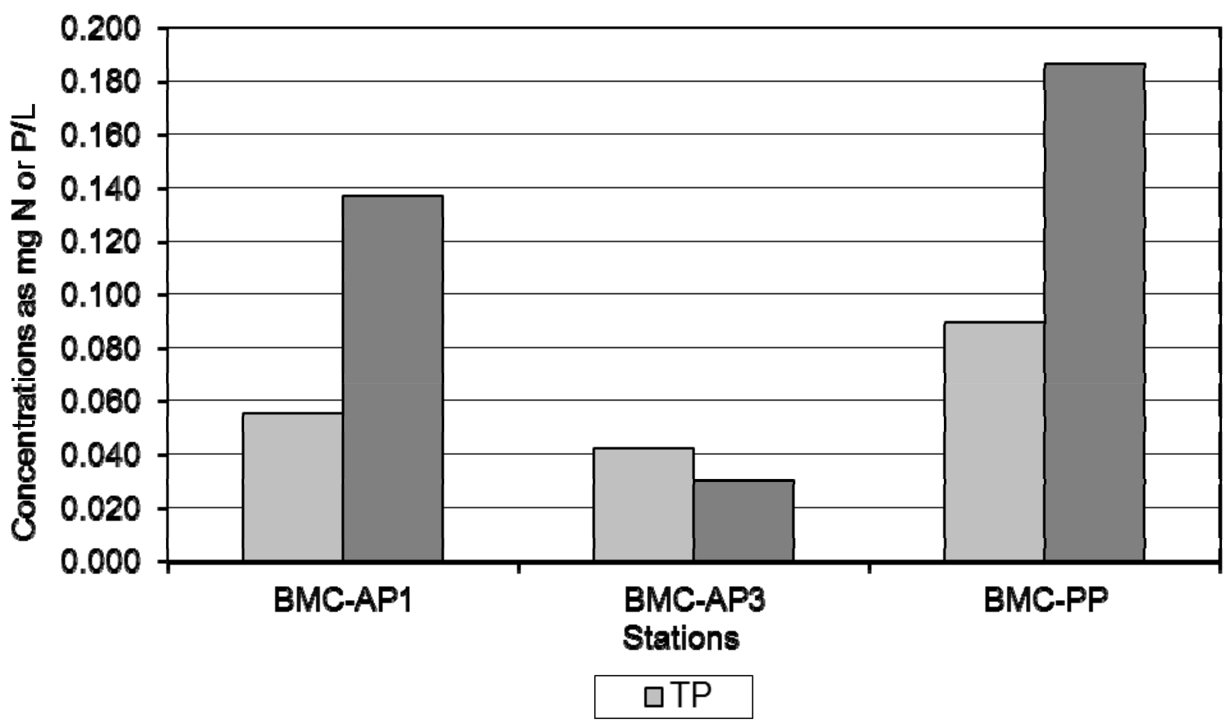


Figure 4.3. Average total phosphorus and nitrate concentrations by station for Burnt Mill Creek, 2012



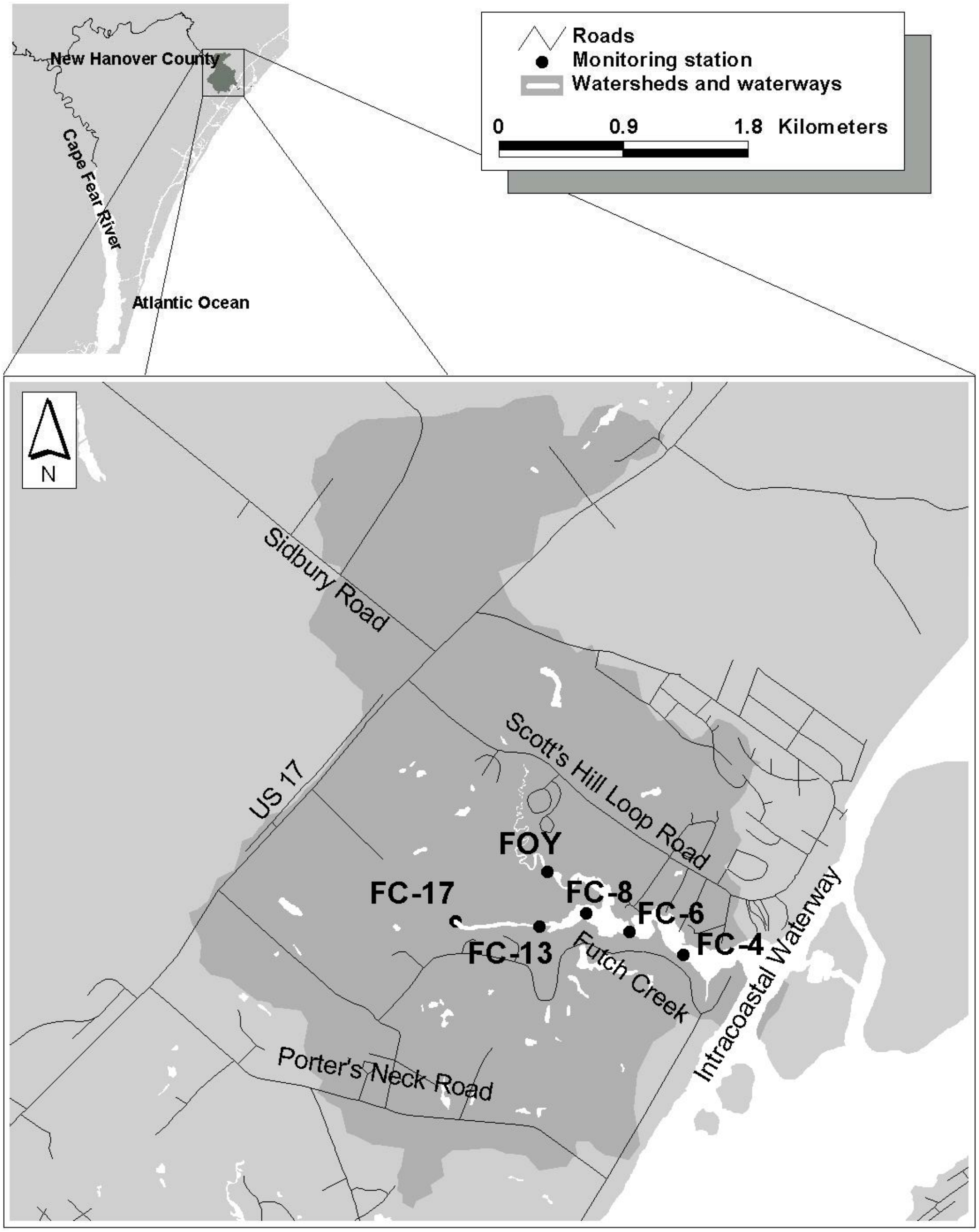
To summarize, in most years Burnt Mill Creek has problems with low dissolved oxygen (hypoxia) at some of the stations. Algal blooms remained a problem in the creek during 2012. The N/P ratios in the creek indicate that inputs of either nitrogen or phosphorus are likely to stimulate algal bloom formation, depending upon season and inputs of nitrogen. It is notable that nutrient concentrations increase from the lower portion of the regional Ann McCrary wet detention pond as one moves downstream toward the lower creek. An important human health issue is the high fecal bacteria counts found at most sampling stations, with the exception of BMC-AP3 below the detention pond. As NPDES point source discharges are not directed into this creek, the fecal bacteria (and nutrient) loading appears to be caused either by non-point source stormwater runoff, illegal discharges, or leakage from sanitary sewer lines. We note that strong statistical correlations between fecal coliform counts, TSS, BOD and rainfall have been demonstrated for this creek (Mallin et al. 2009b). As this is one of the most heavily-developed creeks in the Wilmington area, it also remains one of the most polluted.

5.0 Futch Creek

Snapshot
Watershed area: 3,247 acres (1,314 ha)
Impervious surface coverage: >11%
Watershed population: 4,620

Six stations were sampled by the University of North Carolina Wilmington in Futch Creek from 1993 through 2007. UNCW was not funded by the County to sample Futch Creek in 2011. We present the above information and map below purely for informational purposes. Water quality information for 2008-2011 is available on the County Planning Department website: http://www.nhcgov.com/AgnAndDpt/PLNG/Pages/WaterQualityMonitoring.aspx.

Figure 5.1. Futch Creek watershed and sampling sites.



6.0 Greenfield Lake Water Quality

Snapshot
Watershed area: 2,551 acres (1,032 ha)
Impervious surface coverage: 36%
Watershed population: 10,630
Overall water quality: Poor
Problematic pollutants: Fecal bacteria, low dissolved oxygen in tributaries and the upper lake, high BOD, algal blooms: In early July 2012 there was a fish kill in Greenfield Lake, consisting of a variety of species. High water temperatures coupled with lack of rain and flushing likely led to decreases in dissolved oxygen that caused the kill.

Three tributaries of Greenfield Lake were sampled only for physical field parameters in 2012 (Table 6.1, Fig. 6.1). All three tributaries suffered from hypoxia, as all three sites, GL-LB (creek at Lake Branch Drive), GL-LC (creek beside Lakeshore Commons) and GL-JRB (Jumping Run Branch) showed average dissolved oxygen concentrations below the state standard (DO < 5.0 mg/L). Dissolved oxygen levels were below the state standard of 5.0 mg/L on five of six occasions at GL-LB, two of five occasions at GL-LC, and on five of six occasions at Jumping Run Branch GL-JRB (Table 6.1; Appendix B). Turbidity concentrations were generally low in the tributary stations, with no violations of the freshwater standard of 50 NTU (Table 6.1).

Table 6.1. Mean and (standard deviation) / range of selected field water quality parameters in tributary stations of Greenfield Lake, 2012. n = 6.

Parameter	GL-JRB	GL-LB	GL-LC
DO (mg/L)	2.8 (1.9) 1.0-5.0	1.2 (0.9) 0.4-2.7	4.0 (1.8) 1.2-6.1
Turbidity (NTU)	3 (2) 0-6	3 (2) 0-5	4 (3) 1-7

Three in-lake stations were sampled (Figure 6.1). Station GL-2340 represents an area receiving a considerable influx of urban/suburban runoff, GL-YD is downstream and receives some outside impacts, and GL-P is at Greenfield Lake Park, away from inflowing streams but in a high-use waterfowl area (Fig. 6.1). Low dissolved oxygen was only a problem at GL-2340, with concentrations below the state standard of 5.0 mg/L on four of six occasions, and DO was above standard on all occasions at the other two sites (see also Section 6.1). Turbidity was below the state standard on all sampling occasions. Fecal coliform concentrations worsened from 2011 and were particularly problematic at GL-2340 where they exceeded the State standard on four of six sampling occasions; there were three of six violations at GL-P and two of six at GL-YD.

Concentrations of nitrate were highest at the upstream station GL-2340, which receives input from tributaries. Ammonium levels in the lake were generally low, as were nitrate concentrations. Total nitrogen was highest at GL-P, near the park area, probably due to organic N locked up in organic matter such as algae. Total phosphorus (TP) concentrations were also highest at GL-P among stations, although none of the TP values were remarkable, and orthophosphate was generally low (Table 6.2). Inorganic N/P molar ratios can be computed from ammonium, nitrate, and orthophosphate data and can help determine what the potential limiting nutrient can be in a water body. Ratios well below 16 (the Redfield ratio) can indicate potential nitrogen limitation, and ratios well above 16 can indicate potential phosphorus limitation (Hecky and Kilham 1988). Based on the low mean and median N/P ratios (Table 6.2), phytoplankton growth in Greenfield Lake was limited by nitrogen (i.e. inputs of nitrogen can cause algal blooms) except in the uppermost station GL-2340. Our previous bioassay experiments indicated that nitrogen was usually the limiting nutrient in this lake (Mallin et al. 1999).

Phytoplankton blooms are periodically problematic in Greenfield Lake (Table 6.1), and usually consist of green or blue-green algal species, or both together. These blooms have occurred during all seasons, but are primarily a problem in spring and summer. Three blooms exceeding the North Carolina water quality standard of 40 μg/L of chlorophyll *a* occurred at GL-YD, two at GL-P, and one at GL-2340 in 2012, which is a decrease from 2011. Average biochemical oxygen demand (BOD5) for 2012 was lower (1.5-3.2) among the three sites sampled (Table 6.1), which was lower compared to the elevated BOD concentrations found last year. As phytoplankton (floating algae) are easily-decomposed sources of BOD, the blooms in this lake continue to be a periodic source of low dissolved oxygen.

In 2012 all three in-lake sites had fecal coliform counts that exceeded the State standard on 33% or more of occasions sampled. Station GL-2340 maintained geometric mean concentration of 235 CFU/100 Ml, exceeding the standard of 200 CFU/100 mL, and exceeded the standard on four of six occasions sampled.

Table 6.2. Mean and (standard deviation) / range of water quality parameters in Greenfield Lake sampling stations, 2012. Fecal coliforms given as geometric mean, N/P ratio as mean / median; n = 6 samples collected.

Parameter	GL-2340	GL-YD	GL-P
DO (mg/L)	4.9 (1.2) 3.6-7.2	6.8 (1.5) 5.4-9.4	9.1 (0.7) 8.1-10.1
Turbidity (NTU)	3 (3) 0-9	8 (7) 1-21	10 (13) 1-35
TSS (mg/L)	3.8 (3.0) 1.4-9.4	6.0 (2.5) 2.9-10.1	7.8 (5.3) 1.3-16.2
Nitrate (mg/L)	0.17 (0.14) 0.01-0.33	0.03 (0.05) 0.01-0.13	0.03 (0.05) 0.01-0.13
Ammonium (mg/L)	0.07 (0.05) 0.01-0.16	0.08 (0.10) 0.01-0.25	0.05 (0.06) 0.01-0.15
TN (mg/L)	0.83 (0.86) 0.16-2.52	0.75 (0.48) 0.41-1.41	1.25 (1.34) 0.41-3.91
Orthophosphate (mg/L)	0.02 (0.01) 0.01-0.03	0.05 (0.03) 0.01-0.10	0.06 (0.05) 0.01-0.12
TP (mg/L)	0.05 (0.02) 0.03-0.07	0.09 (0.04) 0.05-0.17	0.11 (0.05) 0.05-0.17
N/P molar ratio	30.8 26.6	12.1 2.5	3.3 3.0
Fec. col. (CFU/100 mL)	235 91-340	88 5-364	162 37-546
Chlor. *a* (µg/L)	20 (23) 7-65	40 (23) 11-76	41 (31) 9-85
BOD5	1.5 (0.8) 1.0-3.0	3.2 (1.1) 2.0-5.0	3.2 (0.6) 2.4-4.0

Sediment Metals and Chemical Toxins in Greenfield Lake

Wilmington Stormwater Services and the UNCW Aquatic Ecology Laboratory are interested in potential toxicants buried in or adhering to the creek sediments in City watersheds. Thus, we collected sediment samples on one occasion throughout Greenfield Lake for analysis of sediment metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) as well some basic chemical parameters including total nitrogen, total phosphorus and total organic carbon. The State of North Carolina has no official guidelines for sediment concentrations of metals and organic pollutants in reference to protection of invertebrates, fish and wildlife. However, academic researchers (Long et al. 1995) have produced guidelines (Table 2.2) based on extensive field and laboratory testing that are used by the US Environmental Protection Agency in their National Coastal Condition Report II (US EPA 2004).

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds with a fused ring structure. PAHs with two to five rings are of considerable environmental concern. They are compounds of crude and refined petroleum products and coal and are also produced by incomplete combustion of organic materials (US EPA 2000). They are characteristic of urban runoff as they derive from tire wear, automobile oil and exhaust particles, and leaching of asphalt roads. Other sources include domestic and industrial waste discharge, atmospheric deposition, and spilled fossil fuels. They are carcinogenic to humans, and bioconcentrate in aquatic animals. In these organisms they form carcinogenic and mutagenic intermediaries and cause tumors in fish (US EPA 2000).

Polychlorinated biphenyls (PCBs) have been banned for use in the United States since 1979. They are closely related to many chlorinated hydrocarbon pesticides, and were used industrially as insulating fluids, heat transfer fluids, plasticizers, lubricants and hydraulic fluids (US EPA 2000). They are persistent in the environment and bioaccumulate in the food chain, and individual PCBs cause health problems including developmental impacts in children, hepatotoxicity, neurotoxicity and carcinogenicity (US EPA 2000).

Table 6.3. Guideline values for sediment metals and organic pollutant concentrations potentially harmful to aquatic life (Long et al. 1995; U.S. EPA 2004). ERL = (Effects range low). Concentrations below the ERL are those in which harmful effects on aquatic communities are rarely observed. ERM = (Effects range median). Concentrations above the ERM are those in which harmful effects would frequently occur. Concentrations between the ERL and ERM are those in which harmful effects occasionally occur.

Metal	ERL	ERM
	Dry wt., ppm = µg/g = mg/kg	
Arsenic (As)	8.2	70.0
Cadmium (Cd)	1.2	9.6
Chromium (Cr)	81.0	370.0
Copper (Cu)	34.0	270.0
Lead (Pb)	46.7	218.0
Mercury (Hg)	0.15	0.71
Nickel (Ni)	20.9	51.6
Silver (Ag)	1.0	3.7
Zinc (Zn)	150.0	410.0
	Dry wt., ppb = ng/g = µg/kg	
Total PCBs	22.7	180.0
Total DDT	1.6	46.1
Total PAHs	4,020	44,800
Anthracene	85.3	1,100
Phenanthrene	240	1,500
Pyrene	665	2,600
Flouranthene	600	5,100
Benzo(a)pyrene	430	1,600
B(a)anthracene	261	1,600
Chrysene	384	2,800

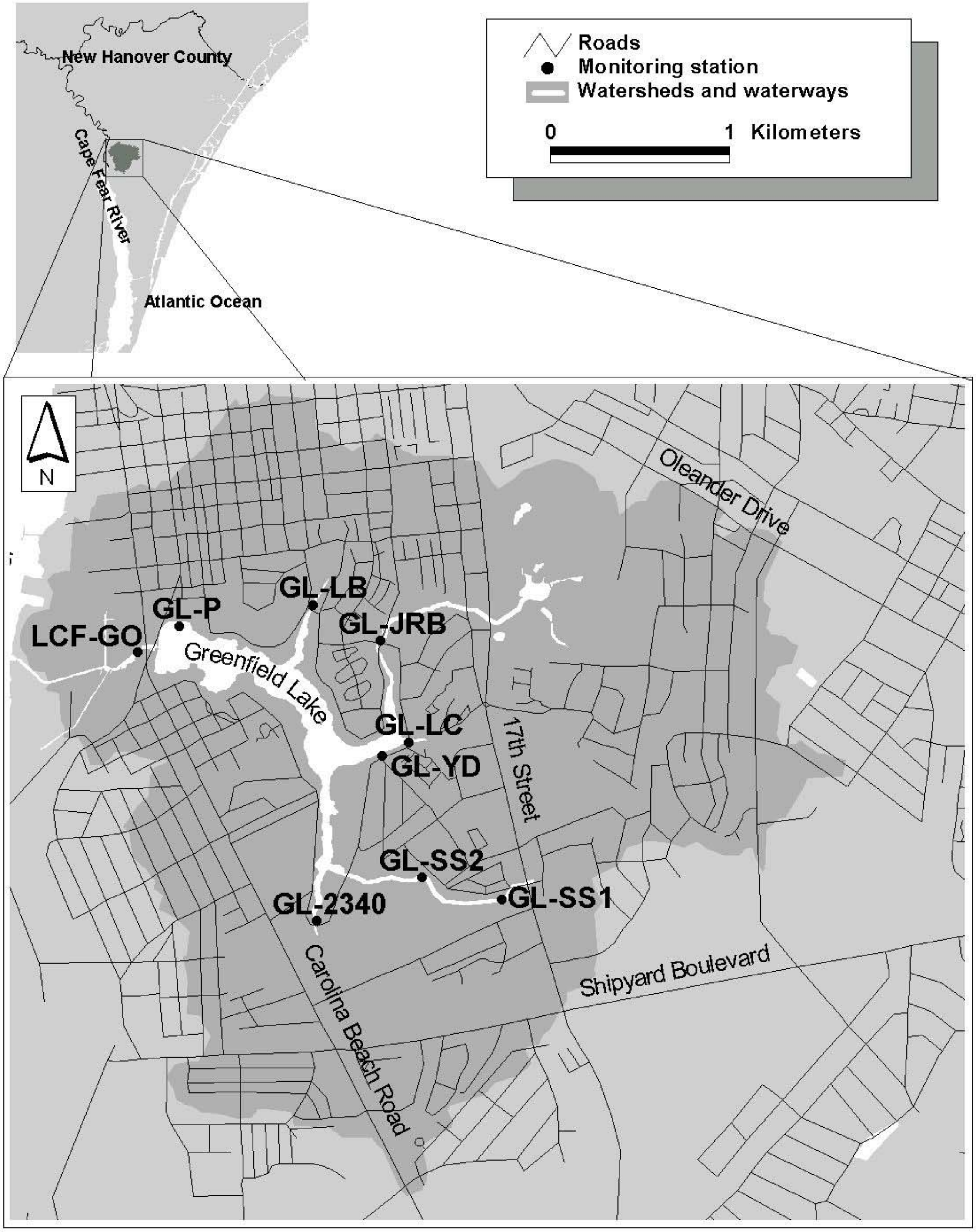
Greenfield Lake sediments were sampled at seven sites on October 23. Two in-lake stations, GL-P and GL-YD had elevated concentrations of copper and lead; GL-YD additionally had high zinc concentrations (Table 6.4). Metals were not at excessive concentrations in the streams feeding the lake. Total PAH concentrations were excessive in the sediments of all three in-lake stations, as well as two stream sites; GL-LB (Lake Branch), and especially GL-SS1, the head of the Silver Stream wetland/detention pond complex along Candlewood Dr. Individual PAHs that were excessive in the lake sediments included Phenanthrene, Fluoranthene and Chrysene (Table 6.4). All stream sites had elevated concentrations of Fluoranthene; Lake Branch also had high Chrysene concentrations. Total PCBs were below detection limit at all sites.

Table 6.4. Concentrations of sediment metals and polycyclic aromatic hydrocarbons (PAHs) in Greenfield Lake, 2012. Concentrations in bold type exceed the level at which harmful effects to benthic organisms may occur according to Long et al. (1995).

Parameter	GL-P	GL-2340	GL-YD	GL-SS1	GL-JRB	GL-LC	GL-LB
			Dry wt., ppm = µg/g = mg/kg				
Antimony	<0.19	0.713	12.8	1.39	0.909	2.55	4.86
Arsenic	0.21	<0.148	<0.48	<0.132	<0.140	<0.140	<0.16
Beryllium	<0.19	<0.148	<0.48	<0.132	<0.140	<0.140	<0.16
Cadmium	<0.19	<0.148	<0.48	<0.132	<0.140	<0.140	<0.16
Chromium	9.76	1.06	71.8	3.62	0.894	17.2	2.36
Copper	**211.0**	3.18	**579.0**	5.66	5.55	7.18	7.94
Lead	**51.3**	9.24	**160.0**	8.34	5.77	19.0	41.1
Mercury	0.014	0.006	0.020	0.0053	0.103	0.006	<0.0066
Nickel	1.95	<0.623	9.21	0.941	0.467	1.04	1.51
Selenium	<0.19	<0.148	1.59	<0.132	<0.140	<0.140	<0.16
Silver	<0.19	<0.148	<0.48	<0.132	<0.140	<0.140	<0.16
Thallium	<0.19	0.42	<0.148	<0.48	<0.132	<0.140	<0.16
Zinc	62.20	21.5	**168.0**	40.3	16.4	19.4	47.9
			Dry wt., ppb = ng/g = µg/kg				
Total PAH	**6,810**	**12,940**	**4,910**	**51,580**	3,130	3,060	**8,380**
Anthracene	1,960	BDL	BDL	**2,850**	BDL	BDL	BDL
Phenanthrene	BDL	**3,410**	**3,410**	**4,000**	BDL	BDL	BDL
Fluoranthene	**2,490**	**5,110**	BDL	**9,920**	**3,130**	**3,060**	**4,260**
Pyrene	BDL	BDL	BDL	**7,110**	BDL	BDL	BDL
B(a)anthracene	BDL	BDL	BDL	**3,900**	BDL	BDL	BDL
Chrysene	**2,360**	**4,420**	BDL	**5,890**	BDL	BDL	**4,120**
B(a)pyrene	BDL	BDL	BDL	**4,080**	BDL	BDL	BDL
Total PCBs	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TN	208.0	4.81	670.0	72.0	2.09	423.0	147.0
TP	80.8	533.0	7.28	2,550	396.0	455.0	794.0
TOC	52.2	167.0	1,260	96.1	266.0	149.0	268.0

BDL = below detection limit

Figure 6.1 Greenfield Lake watershed



6.1 A Continuing Assessment of the Efficacy of the 2005-2012 Greenfield Lake Restoration Measures

Introduction

Greenfield Lake is a 37 ha blackwater system located in the City of Wilmington, North Carolina. It was first dammed and filled as a millpond in 1750, and purchased for a city park in 1925. It has an average depth of 1.2-1.5 m, it is about 8,530 m around the shoreline, and its watershed drains approximately 1,032 ha (2,551 acres). The lake has one outfall, but is fed by six perennial inflowing streams (as well as intermittent ditches). The lake is surrounded by a watershed that is comprised mainly of residential, office, institutional and commercial areas, with an overall watershed impervious surface coverage of 36%.

In recent decades a number of water quality problems have become chronic within the lake, including high fecal coliform bacterial counts, low dissolved oxygen problems, nuisance aquatic macrophyte growths, algal blooms and fish kills. Some of these problems are typically related to eutrophication, a process driven by loading of excessive nutrients to a body of water. The State of North Carolina Division of Water Quality has considered the lake to have a problem with aquatic weeds (NCDENR 2005). Periodic phytoplankton blooms have occurred in spring, summer and fall. Some of the bloom forming taxa are the cyanobacterium *Anabaena cylindrica* and the chlorophytes *Spirogyra* and *Mougeotia* spp. The free-floating macrophyte *Lemna* sp. (duckweed) is frequently observed on the surface, and below a massive *Lemna* bloom in summer 2004 dissolved oxygen concentrations at the park station were nearly anoxic. In-situ monitoring instruments have demonstrated that dissolved oxygen concentrations can decrease by as much as 45% at night compared with daytime DO measurements.

Beginning in 2005 several steps were taken by the City of Wilmington to restore viability to the lake (David Mayes, City of Wilmington Stormwater Services, personal communication). During February one thousand sterile grass carp were introduced to the lake to control (by grazing) the overabundant aquatic macrophytes. During that same month four SolarBee water circulation systems were installed in the lake to improve circulation and force dissolved oxygen from the surface downward toward the bottom. Finally, from April through June 2005 a contract firm applied the herbicide Sonar to further reduce the amount of aquatic macrophytes. On March 29-31 2006 City crews applied 35 gallons of K-Tea algaecide and on July 18 applied 6.3 gallons of habitat aquatic herbicide. A contract firm stocked the lake with 500 additional grass carp on April 4, 2006 and applied 40 gallons of Nautique aquatic herbicide on April 25, and treated the lake with Nautique again on July 31, 2007. The firm also added 200 more grass carp March 28, 2007, but no further fish were added in 2008. City crews added spot applications of herbicide in April, September, October and November 2007 and April, May and June 2008. Herbicide was also added in March, April, July, August and September 2009 in various locations, the herbicide sonar was added in June 2010, several herbicides were added on various occasions from April – June 2011, and some again in September 2011. In 2012, on March 15th, edges of the lake were sprayed with 2 gallons of Reward and 5 gallon of K-tea; on May 11th the boat ramp area was sprayed with 5 gallons of K-tea, 5 gallons of knockout, and 0.5 gallon of Komeen; on June 22nd

various shallows were sprayed with 2.5 gallons of Rodeo; and on July 29th lake edge areas were sprayed with 10 gallon of Knockout and 10 gallon of K-tea.

Since 1998 the University of North Carolina Wilmington's Aquatic Ecology Laboratory, located at the Center for Marine Science, has been performing water quality sampling and associated experiments on Greenfield Lake. The City of Wilmington Stormwater Services has funded this effort. Monitoring of various physical, chemical, and biological parameters has occurred monthly. These data allow us to perform assessments of the effectiveness of the City's lake restoration efforts by comparing summer data from 2003 and 2004 (before restoration efforts) with data from the summers of 2005 through 2012 (after restoration efforts have been underway).

Results

To assess the results so far we have chosen several parameters to examine over time. One parameter that is only estimated visually is surface coverage by nuisance macrophyte vegetation. In the summers of 2003 and 2004 extensive mats of duckweed (*Lemna* sp.), mixed with algae and other vegetation covered large areas of the lake's surface, with visible estimates for some coves exceeding 95% coverage. In summer of 2005 surface coverage was minimal; with most lake areas 95% clear of surface mats. Some coverage returned in 2006 and some coverage, particularly in backwater areas has been seen in 2007 through 2012. Coverage is currently being monitored by Cape Fear River Watch; excessive coverage leads to spot herbicide treatments as above..

Dissolved oxygen (DO): During 2003 and 2004 hypoxia (DO < 4.0 mg/L) was common in surface waters. Areas beneath thick *Lemna* mats were anoxic (DO of zero) or nearly so, especially at GL-P, the main Park area (Fig. 6.1). Following the onset of herbicide addition in April 2005, the May DO (mean of the three in-lake stations) showed a distinct decrease; however, it subsequently rose in June and remained at or above the State standard of 5 mg/L through the rest of the summer of 2005 (Fig. 6.2). In summer of 2006 the average lake DO levels decreased compared with 2005, but were still higher than in 2003 and 2004 (Fig. 6.2). This was because Station GL-2340 experienced low DO levels from 1.2 to 3.8 mg/L from July through September, although the other two in-lake stations (GL-P and GL-YD) maintained good DO levels. In 2007 through 2009 GL-2340 continued to have substandard dissolved oxygen problems and the other two in-lake stations had generally good dissolved oxygen (Table 6.2). In 2010 average DO conditions were below standard in August (the warmest month) but well above standard the rest of the year, whereas in 2011 average DO conditions were lowest in August and September (Fig. 6.2). In 2012 Stations GL-P and GL-YD were in good shape, while GL-2340 was slightly below the state standard on four occasions.

Turbidity: Turbidity was not excessive in the lake during the two years prior to restoration efforts (Mallin et al. 2006a). It has remained low (below the North Carolina freshwater standard) following these efforts throughout 2012 (Table 6.2).

Ammonium: Ammonia, or ammonium is a common degradation product of organic material, and is an excretory product of fish and other organisms. The addition of grass carp and the herbicide usage did not raise ammonium concentrations in the lake for several years (Fig. 6.3). However, in early 2008 there was a large increase in average ammonium lake-wide, which decreased in late spring (Fig. 6.3). There were no herbicide sprayings immediately before this pulse, and no fish kills, so the reason for this remains unknown. In 2009 there were generally low ammonium levels except for an unusually large peak in July, which subsequently decreased (Fig. 6.3). There was no herbicide application within three months prior to this 2009 ammonium peak. In 2010 average ammonium concentrations were low, with a minor increase in December, whereas in 2011 and 2012 ammonium concentrations were low all year (Fig. 6.3).

Nitrate: Nitrate is an inorganic form of nitrogen that is known to enter the lake during rainfall and runoff periods (Mallin et al. 2002). The concentration of nitrate in the lake does not appear to have been influenced by the restoration efforts (Table 6.2). Nitrate concentrations are generally impacted by stormwater runoff, and the low rainfall in 2007 likely provided minimal nutrient inputs to the lake. During 2008 there was a sharp increase in nitrate concentrations, especially in the upper and middle lake stations, which we suspect was largely stormwater runoff-driven. Concentrations in 2009 through 2012 were elevated at GL-2340 but low at the other two sites (Table 6.2). Pulses of nitrate within stormwater runoff likely cause the elevated concentrations at GL-2340.

Total nitrogen: Total nitrogen (TN) is a combination of all inorganic and organic forms of nitrogen. Average lake concentrations and concentrations at individual stations appeared to show no overall trend over time, although there was an unusually large peak in May of 2009 (Table 6.2; Fig. 6.4). In 2010 TN concentrations were among the lowest seen in the past seven years. Concentrations of TN jumped considerably in summer 2011; since inorganic N was low this was likely organic nitrogen in the form of phytoplankton during the large summer algal bloom (Fig. 6.4). In 2012 (Fig. 6.4) there were high concentrations of TN in July (coincident with algal blooms and the fish kill) and high concentrations in November (with no apparent source).

Orthophosphate: Orthophosphate is the most common inorganic form of phosphorus, and is utilized as a key nutrient by aquatic macrophytes and phytoplankton. Orthophosphate concentrations have not experienced any major changes in the water column either before (Mallin et al. 2006a) or after the restoration effort (Table 6.2). Earlier research found that a significant quantity of phosphorus in the lake is contributed by waterfowl through excretion.

Total phosphorus: Total phosphorus (TP) is a combination of all organic and inorganic forms of phosphorus in the water. Although pulses of TP occurred in summer 2005 and spring 2006, they were similar in magnitude to pulses of TP seen in 2003 and 2004 (Fig. 6.5). Pulses in 2007 were smaller than the previous years (Figure 6.5). In 2008 there was a jump in TP, which may in part by caused by high phytoplankton biomass and the phosphorus locked up as cell tissue (see next section). Another reason may include increased runoff of phosphorus into the lake with increased rainfall. In 2009 there was decreased TP compared with 2008, although it was not as low as in 2007. In 2010 TP concentrations were lower than both 2008 and 2009. In 2011 there was a large peak in TP that consisted of organic phosphorus tied up in phytoplankton biomass during the summer algal bloom in the lake, but in 2012 low to moderate TP concentrations prevailed (Fig. 6.5).

Chlorophyll *a*: Chlorophyll *a* is the principal measure used to estimate phytoplankton biomass (algal bloom strength) in water bodies. As mentioned above, algal blooms have been a common occurrence in this lake. They are generally patchy in space, usually occurring at one or two stations at a time. However, in summer 2005 extensive phytoplankton blooms occurred at all three in-lake stations, with levels well exceeding the State standard of 40 μg/L (Fig. 6.6). Blooms continued throughout 2006 as well (Fig. 6.6). The overall reduction in macrophyte coverage may also encourage phytoplankton growth because there is less competition for nutrients, and less shading of the water column by the macrophytes cover. A positive signal was that blooms within the lake in 2007 were fewer than in previous years (Fig. 6.6), either because of continuing restoration efforts or lower stormwater driven inputs of nitrate to feed the blooms. Unfortunately the latter was the likely explanation, as in 2008 the blooms returned in force (Fig. 6.6; also see previous section). In 2009 several blooms exceeding the state standard occurred (at GL-P and GL-YD); however, on average, overall bloom activity in the lake showed a slight decrease from 2008 (Fig. 6.6). There were some blooms in 2010 but on average the chlorophyll *a* abundance was low relative to the previous two years. In 2011 there was a large blue-green algal bloom that was present from July through September (Fig. 6.6); as noted above, this bloom also accounted for the high TN and TP concentrations during this period. In 2012 highest chlorophyll occurred during the July algal blooms (Fig. 6.6).

Algal blooms are the result of nutrient inputs, either from outside the lake or from release from decaying material. Algal blooms, when they die, cause a BOD (biochemical oxygen demand) load (Mallin et al. 2006b). This is organic material that natural lake bacteria feed on and multiply, using up dissolved oxygen in the lake as they do so. We performed regression analysis on our 2007 chlorophyll *a* concentrations with the corresponding BOD concentrations for the three in-lake stations, and found that, statistically speaking, approximately 40% of the variability in Greenfield Lake BOD was caused by algal blooms. We performed similar analysis in succeeding years using our chlorophyll *a* and BOD data (Fig. 6.7). The results showed significant positive correlations between the two parameters, although regression analysis indicated that only 26% and 31% of the variability in dissolved oxygen was accounted for by chlorophyll *a* in 2008 and 2009, respectively. In 2010 there was an extremely strong regression ($p<0.0001$) with chlorophyll *a* explaining 77% of the variability in BOD5; in 2011 chlorophyll *a* explained 50% of the variability, and in 2012 53% of the variability in BOD5 (Fig. 6.7). Thus, the algal blooms can lead to low dissolved oxygen in the lake, but there are other factors that contribute as well. Research conducted on Burnt Mill Creek, Smith Creek, and Prince Georges Creek (Mallin et al. 2009b) showed that BOD was also strongly correlated with watershed rainfall and TSS concentrations, indicating that runoff of oxygen-demanding materials (organic waste, debris, various chemicals) can make a significant contribution to reducing dissolved oxygen in aquatic systems.

Fecal coliform bacteria: Fecal coliform bacteria are commonly used to provide an estimate of the human or animal derived microbial pollution in a water body. Greenfield Lake is chronically polluted by high fecal coliform counts, well exceeding the state standard of 200 CFU/100 mL during many months (Table 6.2; Fig. 6.8). In summer 2005 there were particularly large fecal coliform counts at each in-lake station, though the individual stations did not have pulses during the same months. Excessive fecal coliform counts occurred to a lesser degree in 2006 in the lake, mainly at GL-2340 (Table 6.2). In 2007 high fecal coliform counts occurred within the lake on about 43% of the occasions sampled (Fig. 6.8). In 2008 the lake was highly polluted by fecal coliforms (Fig. 6.8), with stormwater runoff likely the principal source. In September 2008 at the upper station, GL-2340, there was a high concentration (60,000 CFU/100 mL) of fecal coliform bacteria. City staff was unaware of any sewage spills in that area, so the source remains unknown. In 2009 there were again high counts (Table 6.2) especially for July (Fig. 6.8) with other months not unusually high. In 2010 average fecal coliform counts were low in comparison to 2008 and 2009; whereas in 2011 counts were not high with the exception of a large lakewide pulse in August, and in 2012 counts were only somewhat elevated (Fig. 6.8). We note that fecal coliform counts were not targeted by the type of restoration efforts currently ongoing in the lake. Efforts to reduce runoff into tributary streams would likely have a positive benefit in reducing fecal bacteria counts.

Discussion

A risk that is taken when applying herbicides to lakes is the creation of biochemical oxygen demand (BOD) from decomposing organic matter that is a product of dead or dying plant material. As mentioned above, this would serve to drive the lake DO concentrations downward. DO levels in summer 2005 were nearly twice what they were during summers of 2003 and 2004, and DO levels in 2006 were also higher than 2003 and 2004. It is very likely that the use of the SolarBee circulation systems maintained elevated DO even when there was an obvious BOD source. The in-lake station with lowest DO levels in 2006 was GL-2340, which is located quite a distance from the SolarBees. This pattern has continued from 2007-2012. We note that DO in the lake overall remains considerably better than the period before restoration efforts began (Fig. 6.2).

Water column nutrient concentrations did not appear to change notably after the introduction of grass carp or use of herbicide. Certainly ammonium, an excretory and decomposition product would be expected to rise following the consumption and death of large quantities of plant material. Likewise phosphorus did not increase, although it is a common excretory product. However, ammonium (like orthophosphate) is readily used as a primary nutrient by phytoplankton. Nutrient addition bioassay experiments have demonstrated that phytoplankton growth in this lake is limited by nitrogen (Mallin et al. 1999). It is likely that ammonium produced by fish excretion or dying plant material was utilized by phytoplankton to produce the excessive algal blooms that characterized the lake in 2005 and 2006. The phytoplankton blooms were dominated by blue green algae (cyanobacteria) including species containing heterocytes (formerly called heterocysts). These species have the added ability to utilize these structures to fix atmospheric nitrogen into a useable form when phosphorus is replete. Thus, while large amounts of macrophyte material disappeared from the lake, some of the resultant nutrients were utilized by phytoplankton to produce the blooms in the two years after the largest treatments.

The continuing problems with high fecal coliform bacteria do not appear to be related to any of the restoration activities. Fecal coliform bacteria enter the environment from the feces of warm blooded animals, so it is possible that increases in waterfowl, or dogs brought to the lake by their owners, or feral cats could lead to increased fecal coliform bacteria counts, but we have no data to support this speculation either way. Likewise on rare occasions large pulses of fecal bacteria have appeared in the lake or tributaries, potentially related to either sewage leaks or spills, or illicit connections. We do re-emphasize that fecal coliform counts in 2010 were the lowest in several years. In 2011 and 2012 Greenfield Lake had generally low fecal coliform counts except for a large peak in August 2011(Fig. 6.8).

Figure 6.2. Average dissolved oxygen concentrations in Greenfield Lake, 2003-2012.

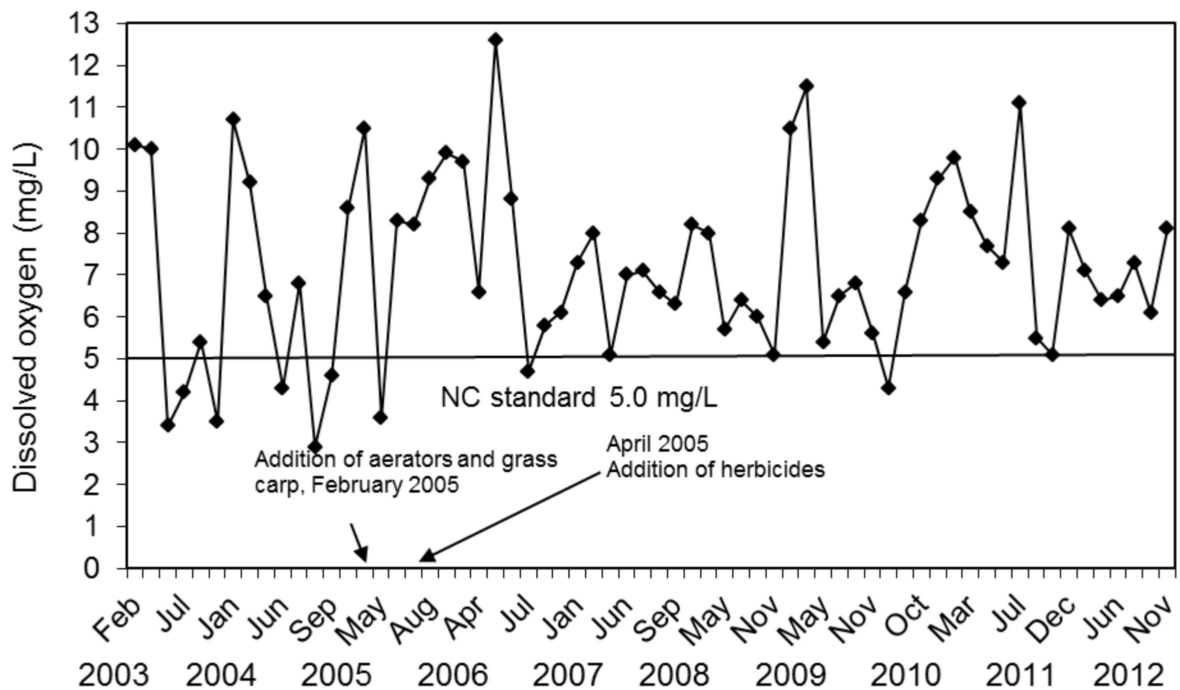


Figure 6.3. Average ammonium concentrations in Greenfield Lake 2003 - 2012.

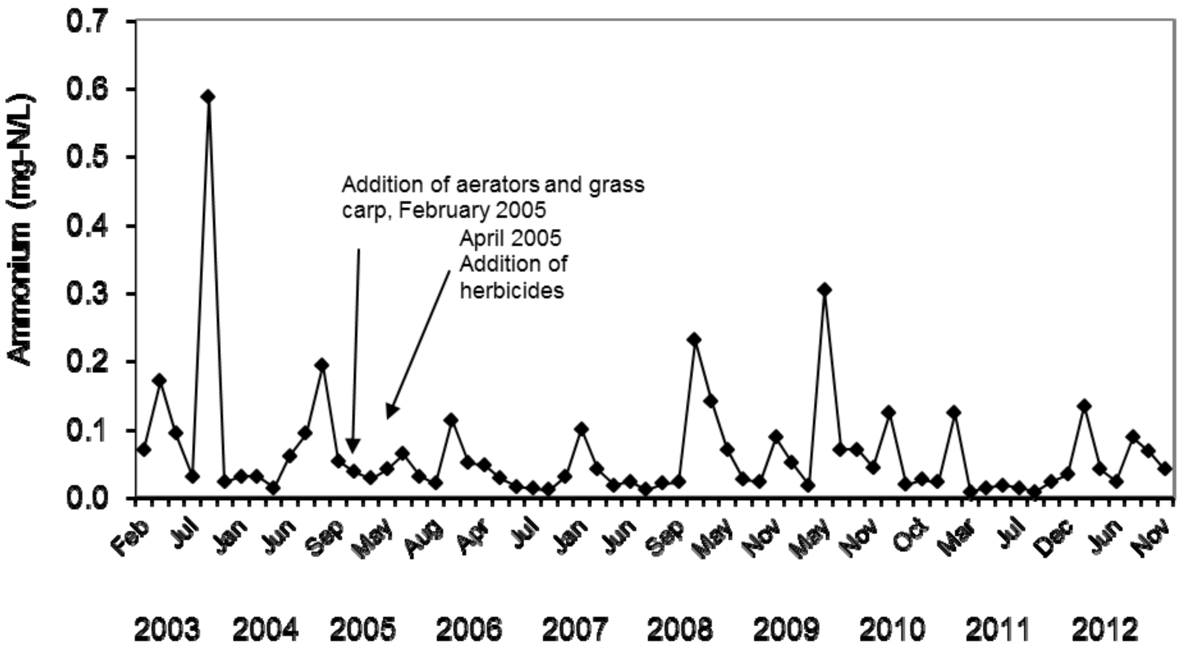


Figure 6.4. Average TN concentrations in Greenfield Lake, 2003-2012.

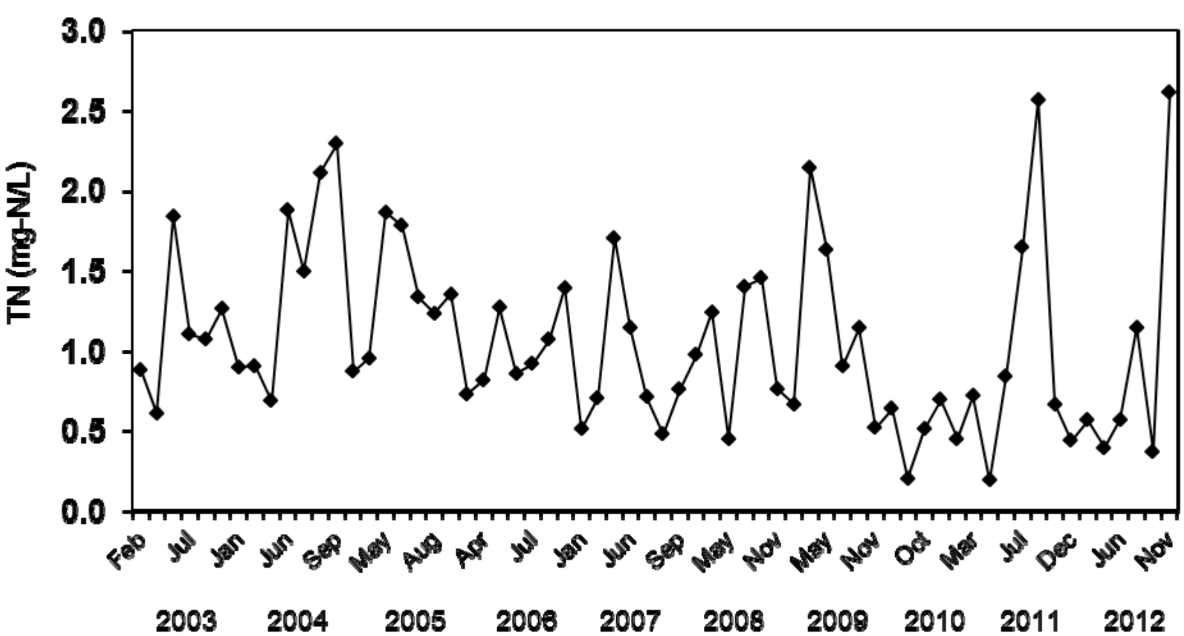


Figure 6.5. Average TP concentrations in Greenfield Lake, 2003-2012.

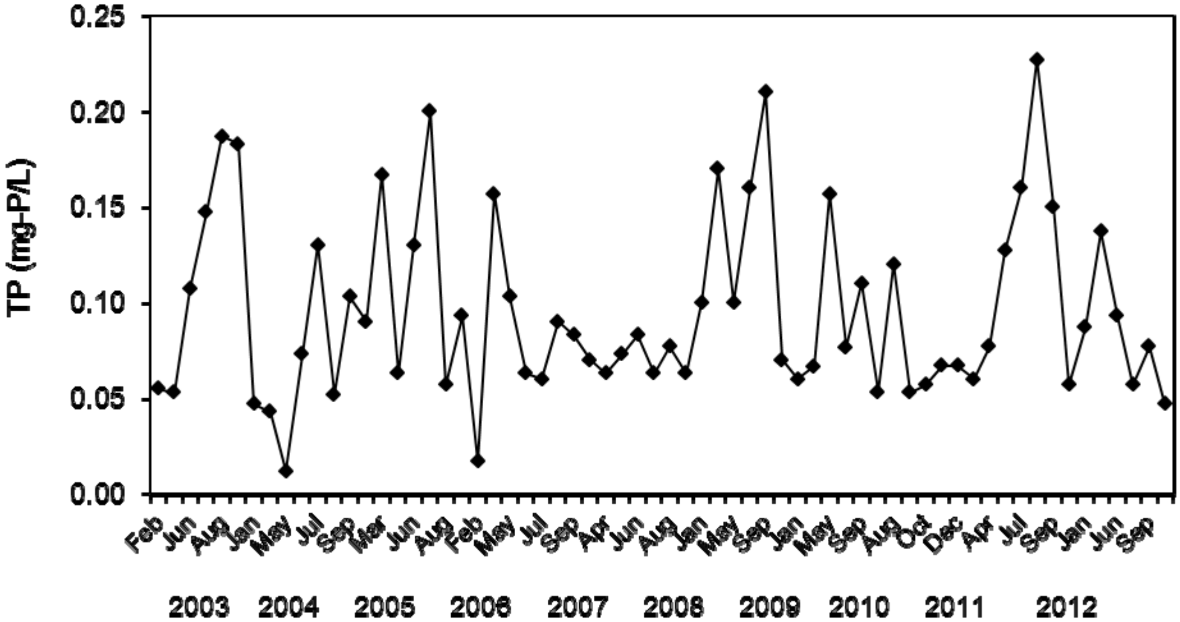


Figure 6.6. Average chlorophyll *a* concentrations in Greenfield Lake, 2003-2012.

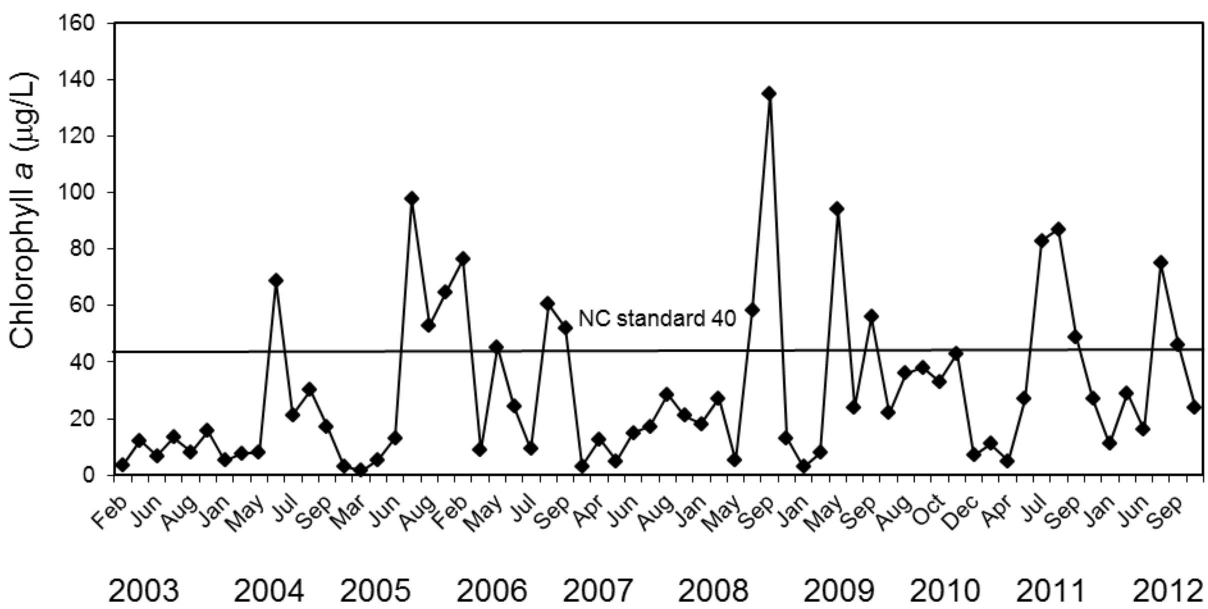


Figure 6.7. BOD5 as a function of chlorophyll *a* in Greenfield Lake, 2012

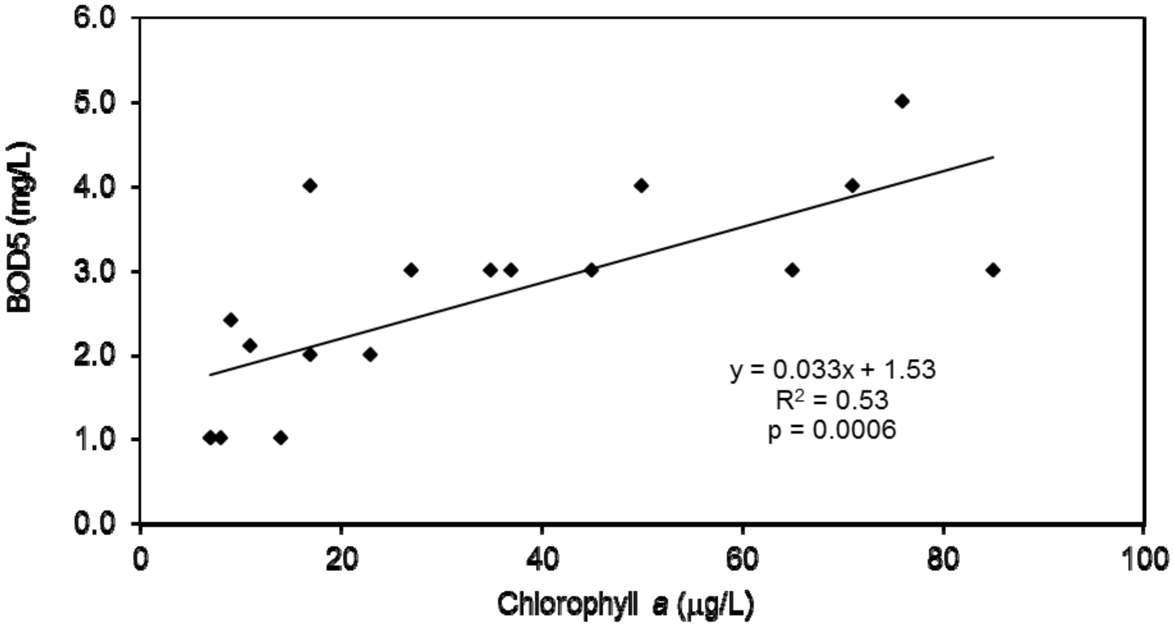
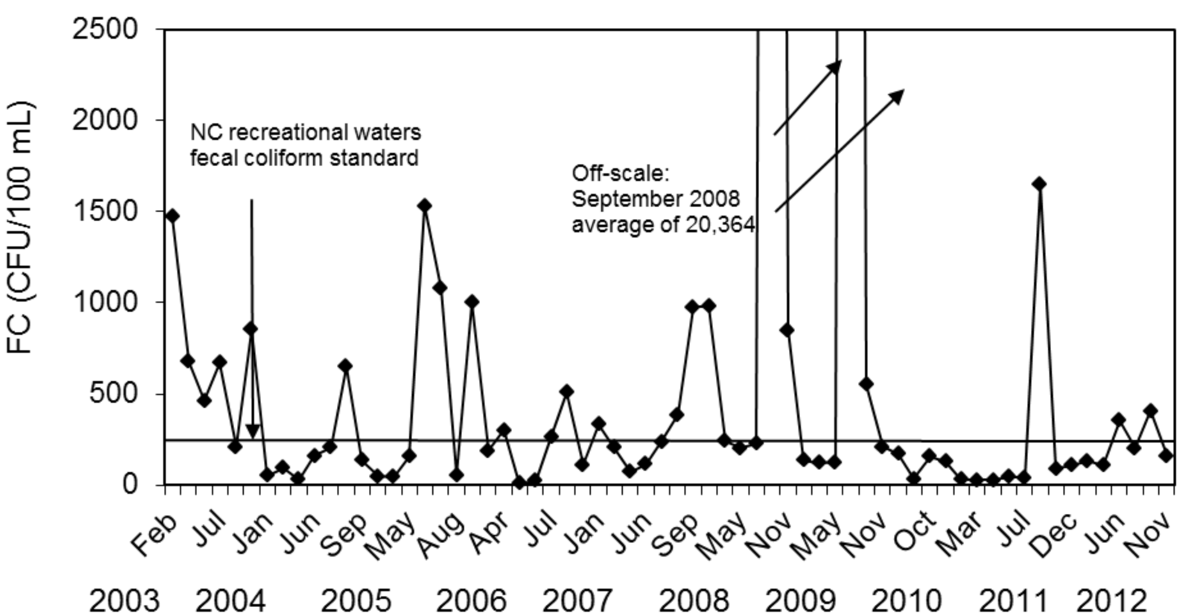


Figure 6.8. Average fecal coliform concentrations in Greenfield Lake, 2003-2012.



7.0 Hewletts Creek

Snapshot
Watershed area: 7,435 acres (3,009 ha)
Impervious surface coverage: 19%
Watershed population: Approximately 20,200
Overall water quality: Fair
Problematic pollutants: high fecal bacteria, minor dissolved oxygen issues

Hewletts Creek was sampled at four tidally-influenced areas (HC-3, NB-GLR, MB-PGR and SB-PGR) and a freshwater stream station draining Pine Valley Country Club (PVGC-9 - Fig. 7.1). At all sites the physical data indicated that turbidity was well within State standards during this sampling period during all sampling events, and TSS levels were below 25 mg/L at all times sampled (Table 7.2). Hypoxia occurred on two of six occasions at NB-GLR and HC-3, and on three of six occasions at SB-PGR, although not severely. Nitrate concentrations were elevated leaving the golf course at PVGC-9 relative to the other stations (Tables 7.1 and 7.2). From there the next station is MB-PGR, which also receives inputs from the Wilmington Municipal Golf Courses (Fig. 7.1; Mallin and Wheeler 2000). Nitrate was somewhat elevated at MB-PGR; however, none of the other stations had elevated nitrate concentrations. In general nitrate concentrations creek-wide were slightly higher than in 2011. Ammonium concentrations were increased from previous years at some of these sites; total nitrogen also increased over 2011. Orthophosphate concentrations were low, as were total phosphorus concentrations. The N/P ratios were high in the middle branch coming from the golf course, but were low at the lower creek sites indicating that inputs of inorganic nitrogen could cause algal blooms; however, as mentioned nitrate and ammonium were low in the lower creek areas in 2012. The chlorophyll *a* data (Tables 7.1 and 7.2) showed that the Hewletts Creek samples were free of major algal blooms in 2012. This is positive news as algal blooms have been common in upper Hewletts Creek in the past (Mallin et al. 1998a; 1999; 2002a; 2004; 2005; 2006a; 2008; Duernberger 2009).

Fecal coliform bacteria counts were high in three stations sampled in the creek. Counts exceeded State standards on 100% of the time at MB-PGR, 83% of the time at NB-GLR and 67% of the time at PVGC-9 (Tables 7.1 and 7.2). The geometric mean at PVGC-9 decreased from 2011. There was an excessive rain event in August that led to NB-GLR, MB-GLR and PVGC-9 all having high counts that month.

Figure 7.1 Hewletts Creek watershed

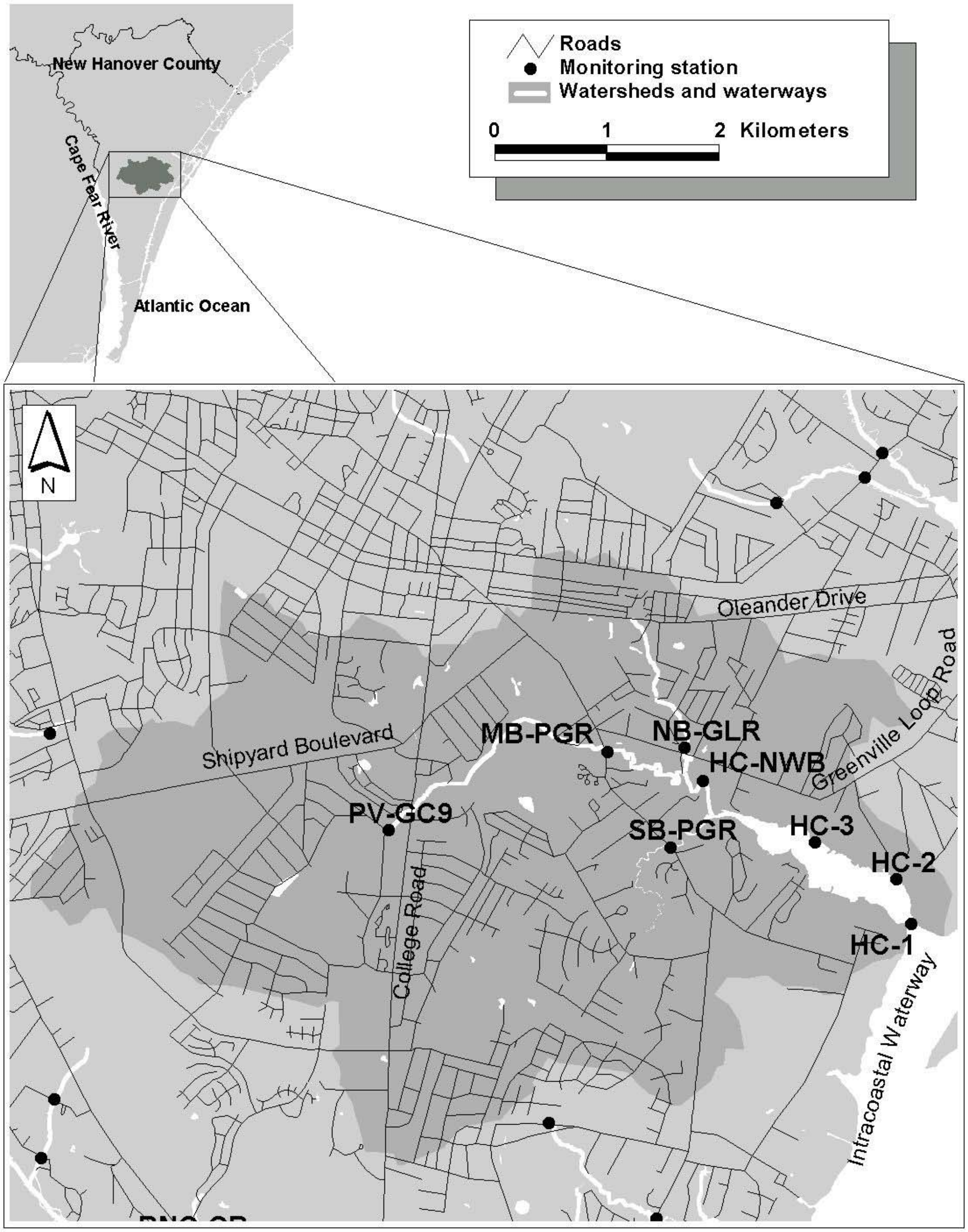


Table 7.1. Selected water quality parameters at upper and middle creek stations in Hewletts Creek watershed 2012 as mean (standard deviation) / range, N/P ratios as mean / median, fecal coliform bacteria presented as geometric mean / range, n = 6.

Parameter	PVGC-9	MB-PGR
Salinity (ppt)	0.1 (0) 0.1-0.1	0.4 (0.7) 0.1-1.8
Turbidity (NTU)	2 (2) 0-4	2 (2) 0-5
TSS (mg/L)	1.4 (0.0) 1.4-1.5	1.4 (0.1) 1.4-1.5
DO (mg/L)	5.3 (1.5) 3.0-6.7	7.3 (1.5) 5.9-9.9
Nitrate (mg/L)	0.570 (0.168) 0.400-0.840	0.267 (0.041) 0.200-0.310
Ammonium (mg/L)	0.049 (0.051) 0.005-0.140	0.036 (0.025) 0.005-0.070
TN (mg/L)	0.953 (0.303) 0.600-1.500	0.550 (0.316) 0.310-1.150
Orthophosphate (mg/L)	0.012 (0.004) 0.010-0.020	0.017 (0.010) 0.010-0.030
TP (mg/L)	0.032 (0.024) 0.010-0.070	0.027 (0.015) 0.010-0.050
N/P	127.9 125.7	53.5 68.1
Chlorophyll *a* (µg/L)	4 (7) 1-18	1 (1) 1-4
Fecal col. (CFU/100 mL)	254 5-1,546	767 370-1,364

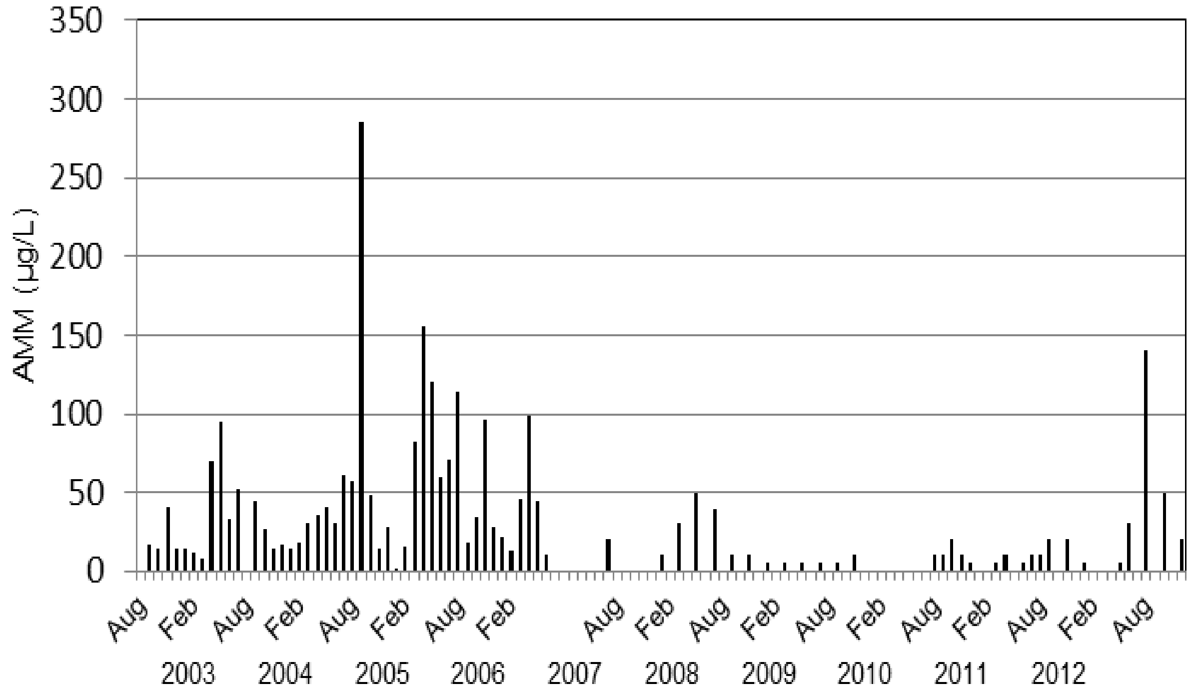
Table 7.2. Selected water quality parameters at stations in Hewletts Creek watershed, 2012, as mean (standard deviation) / range, fecal coliforms as geometric mean / range, n = 6 months.

Parameter	NB-GLR	SB-PGR	HC-3
Salinity (ppt)	16.0 (5.2) 9.2-25.0	28.2 (2.9) 25.3-32.3	33.9 (1.0) 32.0-34.8
Turbidity (NTU)	7 (3) 2-11	8 (5) 1-15	6 (4) 0-12
TSS (mg/L)	11.8 (3.8) 8.3-17.8	16.6 (3.3) 12.1-22.1	13.8 (3.9) 6.9-17.2
DO (mg/L)	5.8 (2.7) 3.3-9.5	5.8 (2.8) 3.3-9.4	6.6 (2.6) 4.3-10.2
Nitrate (mg/L)	0.058 (0.030) 0.030-0.100	0.017 (0.012) 0.010-0.040	0.012 (0.004) 0.010-0.020
Ammonium (mg/L)	0.038 (0.040) 0.005-0.100	0.042 (0.051) 0.005-0.140	0.021 (0.023) 0.005-0.050
TN (mg/L)	0.517 (0.433) 0.150-1.350	0.450 (0.544) 0.070-1.510	0.603 (0.988) 0.070-2.610
Orthophosphate (mg/L)	0.013 (0.008) 0.010-0.030	0.010 (0.000) 0.010-0.010	0.010 (0.000) 0.010-0.010
TP (mg/L)	0.045 (0.019) 0.020-0.070	0.042 (0.023) 0.010-0.070	0.023 (0.012) 0.010-0.040
Mean N/P ratio Median	19.0 14.4	7.8 8.9	7.0 4.4
Chlor *a* (µg/L)	8 (9) 1-20	5 (4) 1-10	3 (3) 1-8
Fecal coliforms (CFU/100 mL)	395 100-819	88 46-200	17 5-136

Dobo Property/Bethel Rd./JEL Wade Park constructed wetland: The New Hanover County Tidal Creeks Advisory Board, using funds from the North Carolina Clean Water Management Trust Fund, purchased a former industrial area owned by the Dobo family in August 2002. This property was bought to be used as a passive treatment facility for the improvement of non-point source runoff drainage water before it enters Hewletts Creek. As such, the City of Wilmington contracted with outside consultants to create a wetland on the property for this purpose. Thus, during 2007 the 7.6 acre JEL Wade wetland was constructed to treat stormwater runoff from a 589 acre watershed within the Hewletts Creek drainage; we note that due to droughts the vegetation did not reach near-full coverage until spring 2010. A rain event sampling program was carried out in 2009-2010 by UNCW to evaluate the efficacy of the wetland in reducing pollutant loads (fecal bacteria, nutrients, suspended solids and metals) from the stormwater runoff passing through the wetland. During the eight storms sampled, the wetland served to greatly moderate the stream hydrograph, retaining and/or removing 50-75% of the inflowing stormwater volume within the wetland. High removal rates of fecal coliform bacteria were achieved (based on “first flush”), with an average load reduction of 99% and overall concentration reduction of > 90%. Particularly high (>90%) load reductions of ammonium and orthophosphate loads also occurred, and lesser but still substantial reductions of total phosphorus (89%) and TSS loads (88%) were achieved. Removal of nitrate was seasonally dependent, with lower removal occurring in cold weather and high percentage (90%+) nitrate load removal occurring in the growing season when water temperatures exceeded 15^{o}C. Since the principal source of impairment in Hewletts Creek is fecal bacteria contamination, and a secondary source of impairment is algal blooms (caused by nitrogen loading in this system), this constructed wetland appears to be very successful in reducing both concentrations and loads of polluting substances to the receiving waters. Details on the wetland and on the sampling results are presented in a peer-reviewed article in a technical journal (Mallin et al. 2012).

Continued monitoring of Hewletts Creek indicates that the wetland is having a positive influence on the main creek. The outflow from JEL Wade wetland enters Hewletts Creek upstream of our Station SB-PGR, so we examined some water quality parameters there for which there are available before-and-after data (Figure 7.2-7.6). Data were log-transformed and t-tests were performed to test for differences between pre-and-post July 2007 data (i.e. 2003-July 2007 vs. August 2007- December 2012) with a probability (p) value of < 0.05 used for significance. Ammonium showed a significant ($p < 0.01$) mean decrease of 60% following the wetland completion (Figure 7.2). The high ammonium peaks seen in earlier years have not been present in our samples since 2007.

Figure 7.2 Ammonium concentrations over time at south branch Station SB-PGR in Hewletts Creek 2003-2012.



From spring 2009 on, creek nitrate concentrations showed peak concentrations that were generally lower than previous to wetland construction (Figure 7.3). There was a statistically-significant ($p < 0.01$) mean decrease in nitrate concentrations of 48% between pre-and-post wetland construction (July 2007). Orthophosphate concentrations were generally low before wetland construction, with no significant change in creek orthophosphate concentrations after wetland construction (Figure 7.4).

Figure 7.3 Nitrate concentration changes over time at south branch Station SB-PGR in Hewletts Creek 2003-2012.

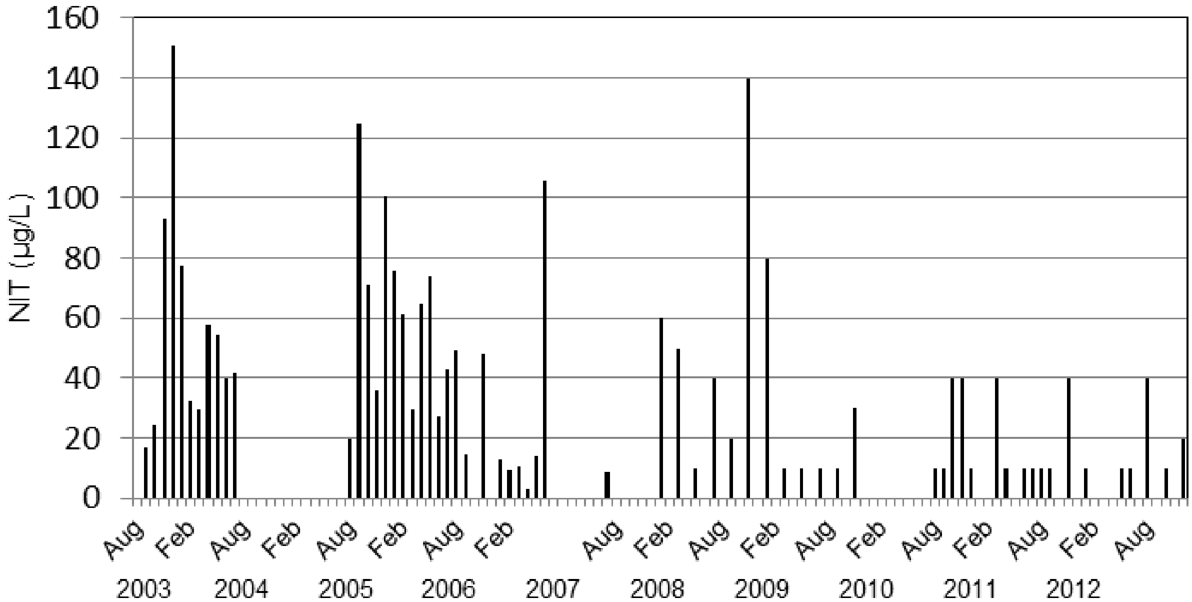
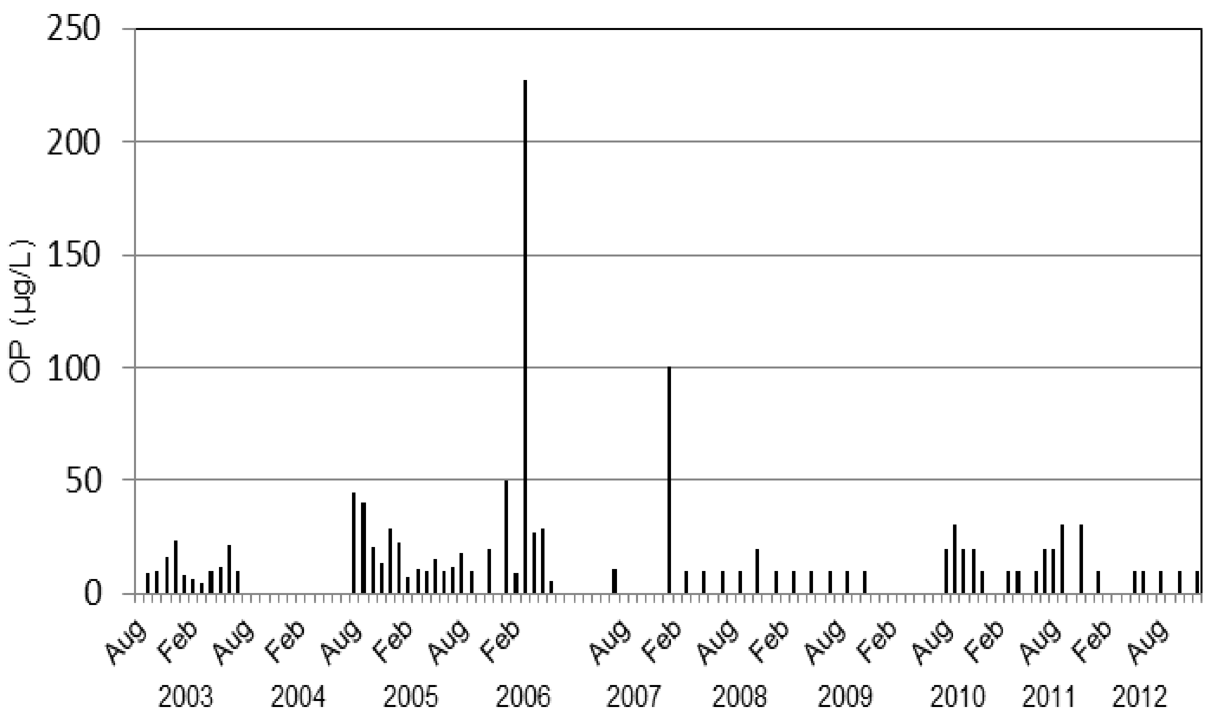
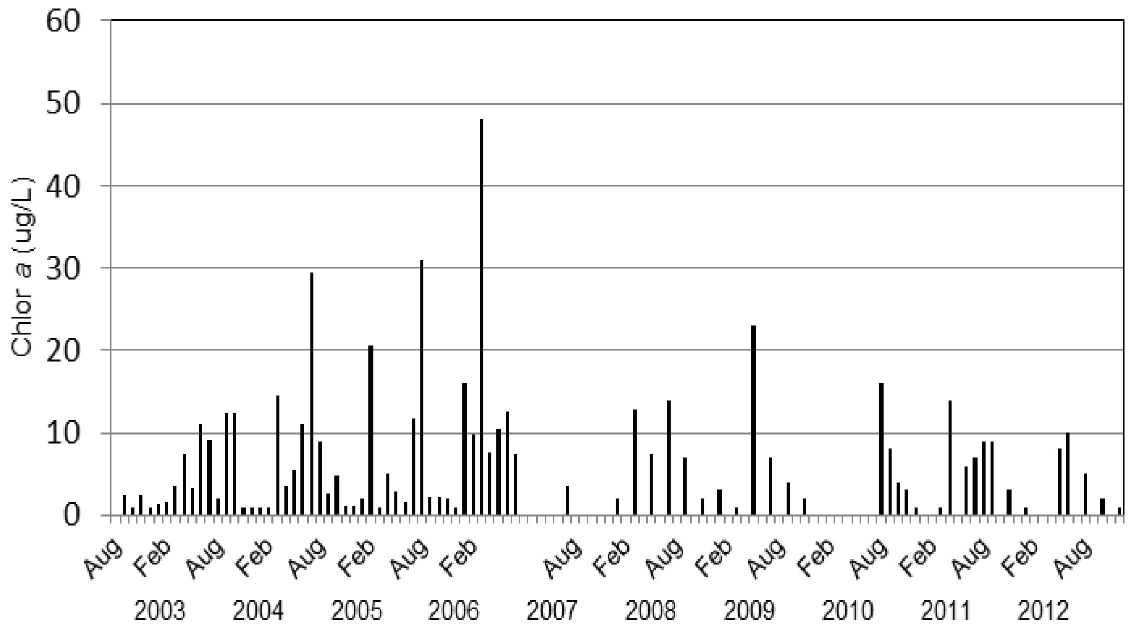


Figure 7.4 Orthophosphate concentration changes over time at south branch Station SB-PGR in Hewletts Creek 2003-2012.



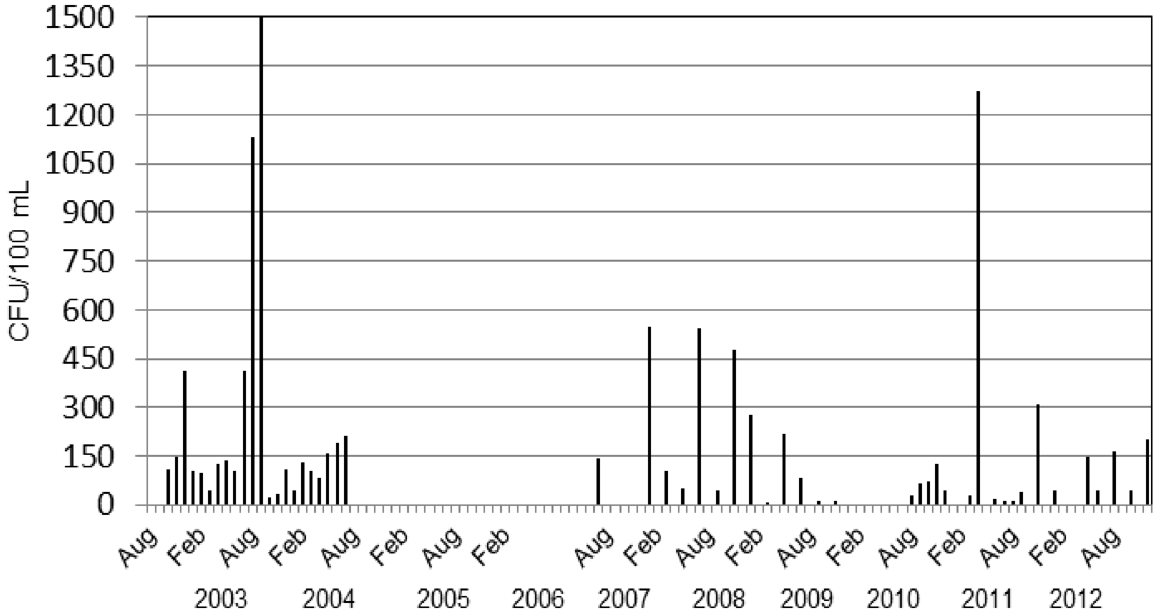
Algal blooms, represented by chlorophyll *a* concentrations, show fewer and smaller peaks in the south branch of Hewletts Creek than prior to wetland construction, but the reductions were not statistically significantly, ($p > 0.05$) (Figure 7.5).

Figure 7.5 Chlorophyll *a* concentration changes over time at south branch Station SB-PGR in Hewletts Creek 2003-2012.



Fecal coliform bacteria concentrations showed some moderately high peaks in the south branch of Hewletts Creek during early wetland operation (2008) but appear to have stabilized at much lower concentrations since summer 2009 with the exception of a sharp peak of 1,273 during an extreme weather event in spring 2011 (Figure 7.6). Fecal coliform bacterial counts were significantly ($p < 0.05$) reduced (geometric mean by 56%) in the downstream receiving waters. Thus, the JEL Wade wetland is both effective in treatment of pollutants entering the wetland, and also having a measurable positive effect on tidal creek water quality downstream as well.

Figure 7.6 Fecal coliform bacteria concentrations over time at south branch Station SB-PGR in Hewletts Creek 2003-2012.



8.0 Howe Creek Water Quality

Snapshot
Watershed area: 3,518 acres (1,424 ha)
Impervious surface coverage: 19%
Watershed population: Approximately 6,460
Overall water quality: Fair
Problematic pollutants: Fecal coliform bacteria, some algal blooms, some low DO

Howe Creek was sampled for physical parameters, nutrients, chlorophyll *a*, and fecal coliform bacteria at three locations on six occasions during 2012 (HW-FP, HW-GP and HW-DT- Fig. 8.1). Turbidity was generally low and did not exceed the North Carolina water quality standard of 25 NTU (Table 8.1; Appendix B). Suspended solids were relatively high (19-22 mg/L) on two occasions each at HW-FP and HW-GP. Dissolved oxygen concentrations were fair at HW-FP, but poor at HW-DT and HW-GP, a worsening from 2011 (Appendix B).

Nitrate and ammonium concentrations were both somewhat higher in 2012 than in 2011 (Table 8.2). Orthophosphate was also low at the three sites. Mean and median inorganic molar N/P ratios were low, indicating that nitrogen was probably the principal nutrient limiting phytoplankton growth at all stations. Previously Mallin et al. (2004) demonstrated that nitrogen was the primary limiting nutrient in Howe Creek. There were two minor algal bloom of 27-37 µg/L as chlorophyll *a* at HW-DT, but the lower two stations did not experience algal bloom problems in 2012 (Table 8.2). Since wetland enhancement was performed in 1998 above Graham Pond the creek below the pond at HW-GP has had fewer and smaller algal blooms than before the enhancement (Fig. 8.2). For fecal coliform bacteria, the creek ranged from no exceedences of the water contact standard of 200 CFU/100 mL at the lower station HW-FP to 17% exceedence at HW-GP, to 67% exceedences at the upper station HW-DT, where the geometric mean of 564 CFU/100 mL was more than double the NC standard (Table 8.1). The fecal coliform counts were similar to the previous year (Fig. 8.3).

Table 8.1. Water quality summary statistics for Howe Creek, 2012, as mean (st. dev.) / range. Fecal coliform bacteria as geometric mean / range.

Parameter	HW-FP	HW-GP	HW-DT
Salinity (ppt)	34.0(3.8) 26.3-36.5	26.2(4.3) 21.5-33.7	10.8(9.5) 2.9-25.3
Dissolved oxygen (mg/L)	6.8(1.8) 4.4-8.9	5.7(2.0) 3.9-8.4	6.0(2.1) 3.4-9.1
Turbidity (NTU)	3(3) 0-8	7(5) 0-15	7(5) 0-11
TSS (mg/L)	12.7(6.8) 5.2-21.6	16.4(5.7) 9.4-22.2	11.0(5.3) 4.2-18.2
Chlor *a* (μg/L)	2(1) 1-4	7(3) 1-10	20(11) 8-37
Fecal coliforms (CFU/100 mL)	7 5-28	121 64-637	564 91-3,400

Figure 8.1. Howe Creek watershed and sampling sites used in various years.

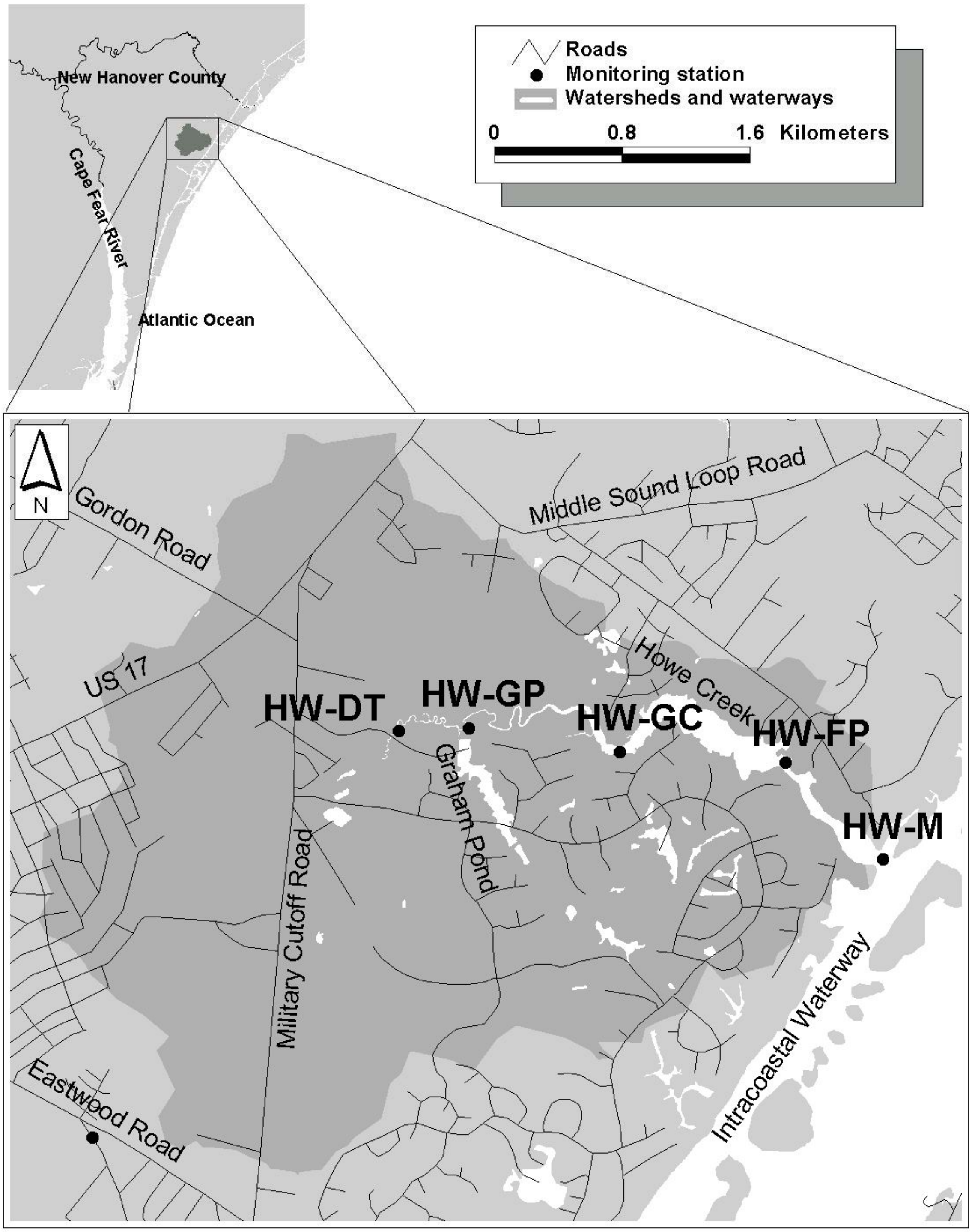


Figure 8.2. Chlorophyll *a* concentrations (algal blooms) in Howe Creek below Graham Pond before and after 1998 wetland enhancement in upper Pond, 1993-2012.

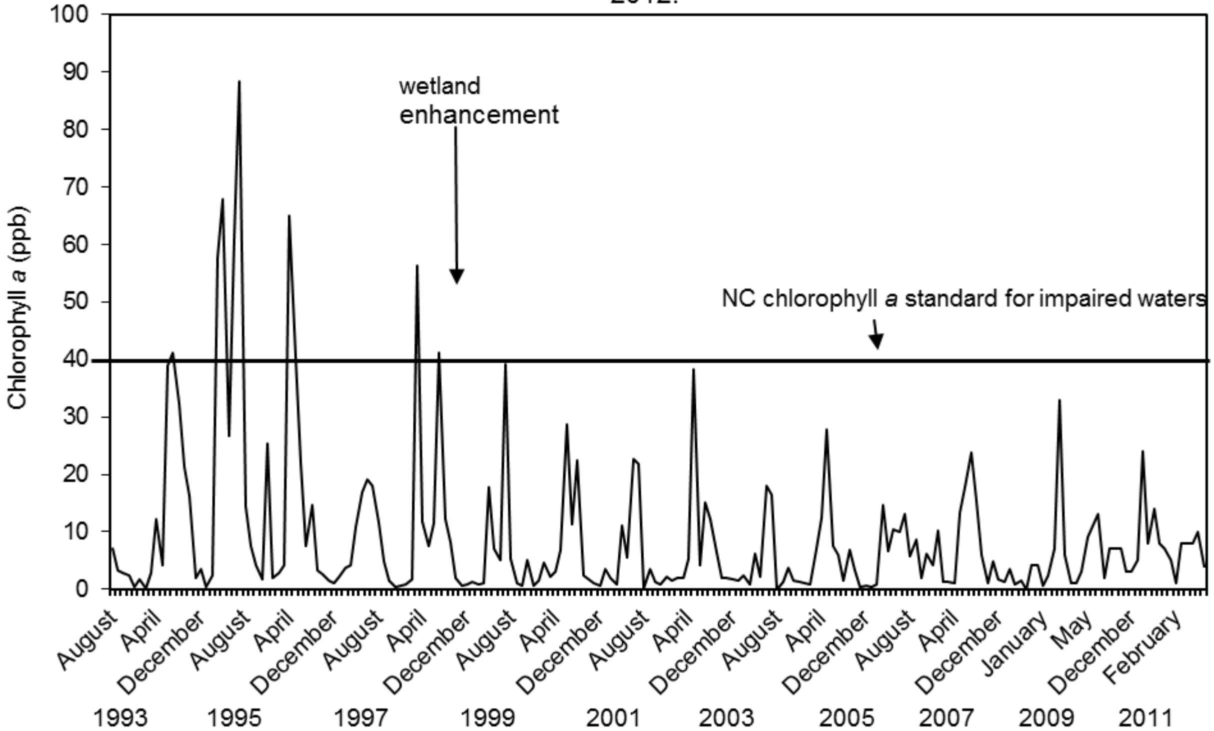
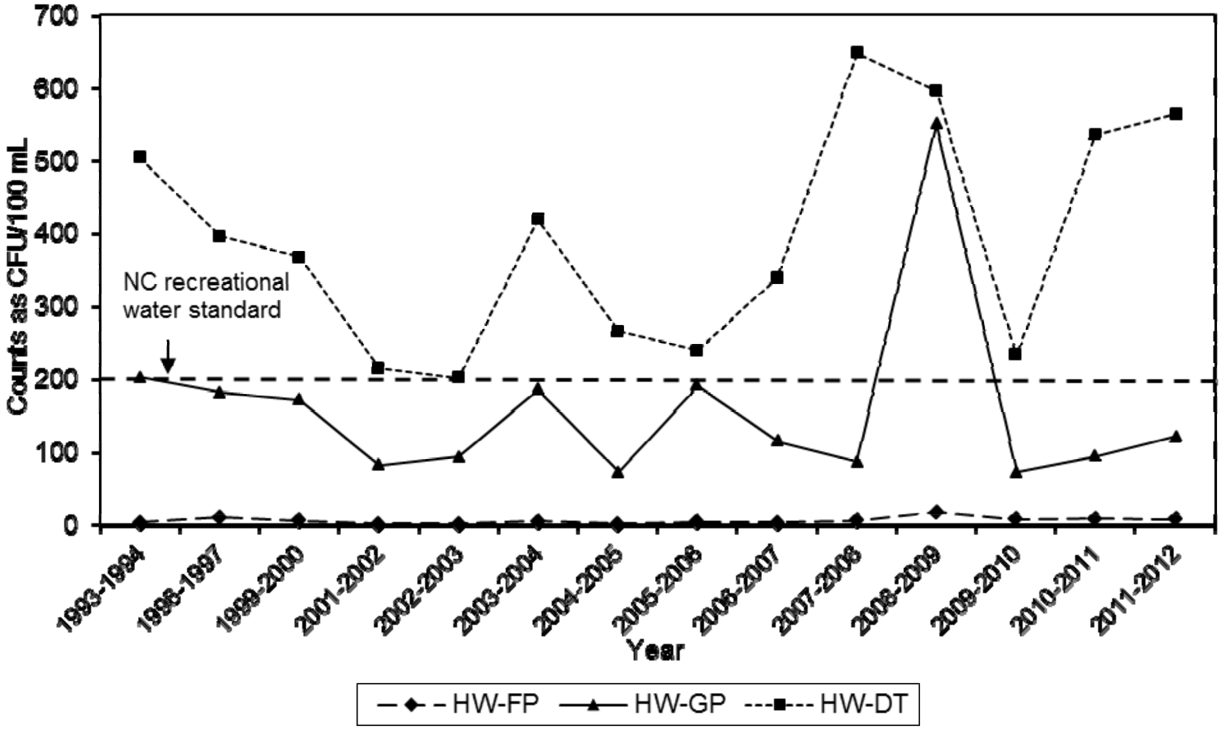


Table 8.2. Inorganic nutrient concentration summary statistics for Howe Creek, 2012, as mean (standard deviation) / range, N/P ratio as mean / median.

Parameter	HW-FP	HW-GP	HW-DT
Nitrate (mg/L)	0.012(0.004) 0.010-0.200	0.033(0.029) 0.010-0.080	0.058(0.075) 0.010-0.200
Ammonium (mg/L)	0.018(0.013) 0.005-0.070	0.020(0.021) 0.005-0.060	0.026(0.028) 0.005-0.070
Orthophosphate (mg/L)	0.013(0.008) 0.010-0.050	0.012(0.004) 0.010-0.020	0.017(0.016) 0.010-0.030
Molar N/P ratio	5.8 6.1	10.7 5.5	14.2 5.0

Figure 8.3. Fecal coliform counts over time for three Howe Creek stations, 1993-2012.

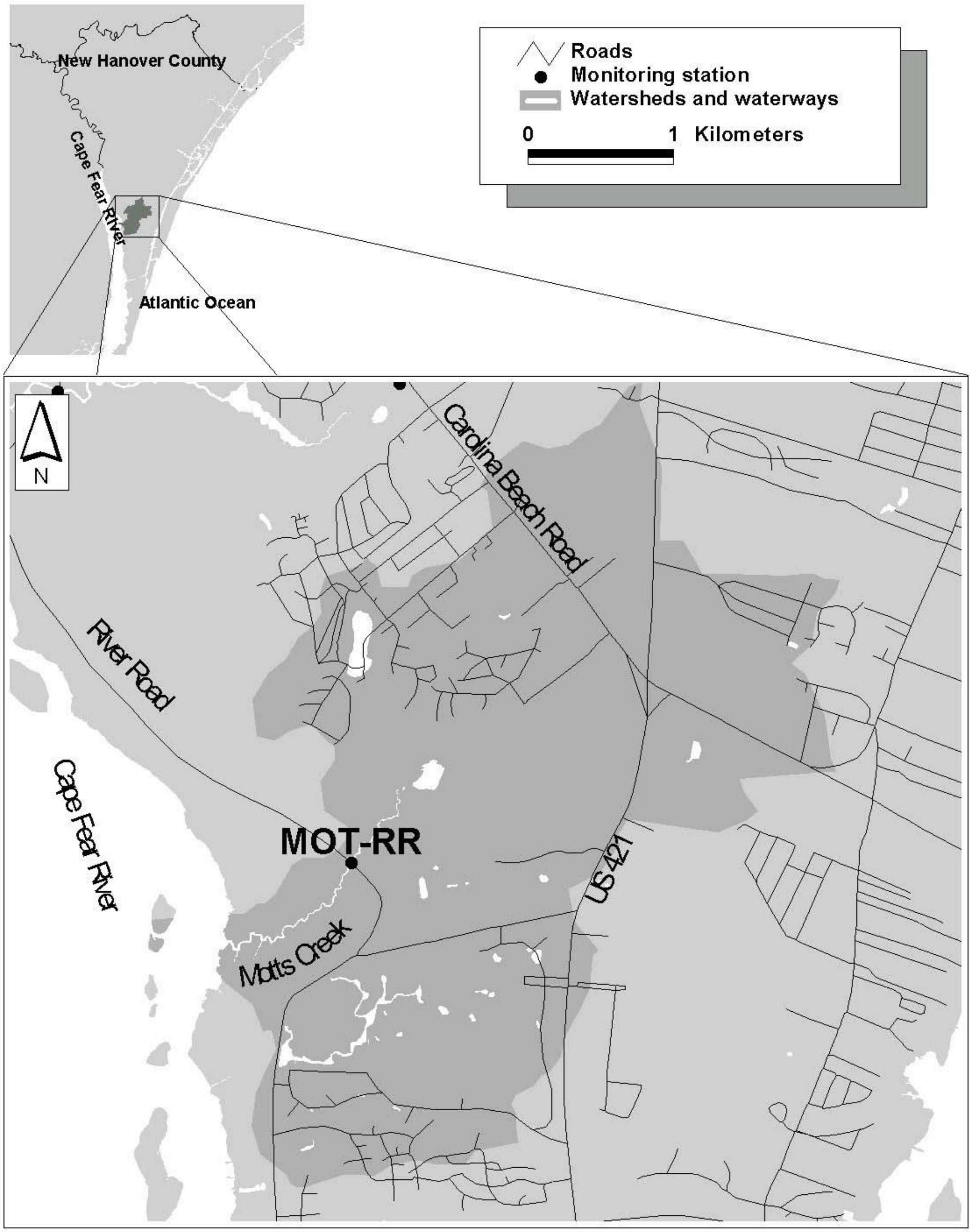


9.0 Motts Creek

Snapshot
Watershed area: 3,328 acres (1,347 ha)
Impervious surface coverage: 14%
Watershed population: 9,530
Overall water quality: poor
Problematic pollutants: Periodic algal blooms; high fecal coliform bacteria

Motts Creek drains into the Cape Fear River Estuary (Fig. 9.1), and the creek area near River Road has been classified by the State of North Carolina as a Natural Heritage Site because of the area's biological attributes. These include the pure stand wetland communities, including a well-developed sawgrass community and unusually large flats dominated by *Lilaeopsis chinensis* and spider lily, with large cypress in the swamp forest. During 2012 UNCW was not funded to sample water quality in lower Motts Creek. New Hanover County sponsors some water quality sampling in areas of upper Motts Creek, collected by Coastal Planning & Engineering of North Carolina, Inc.

Figure 9.1 Motts Creeks watershed

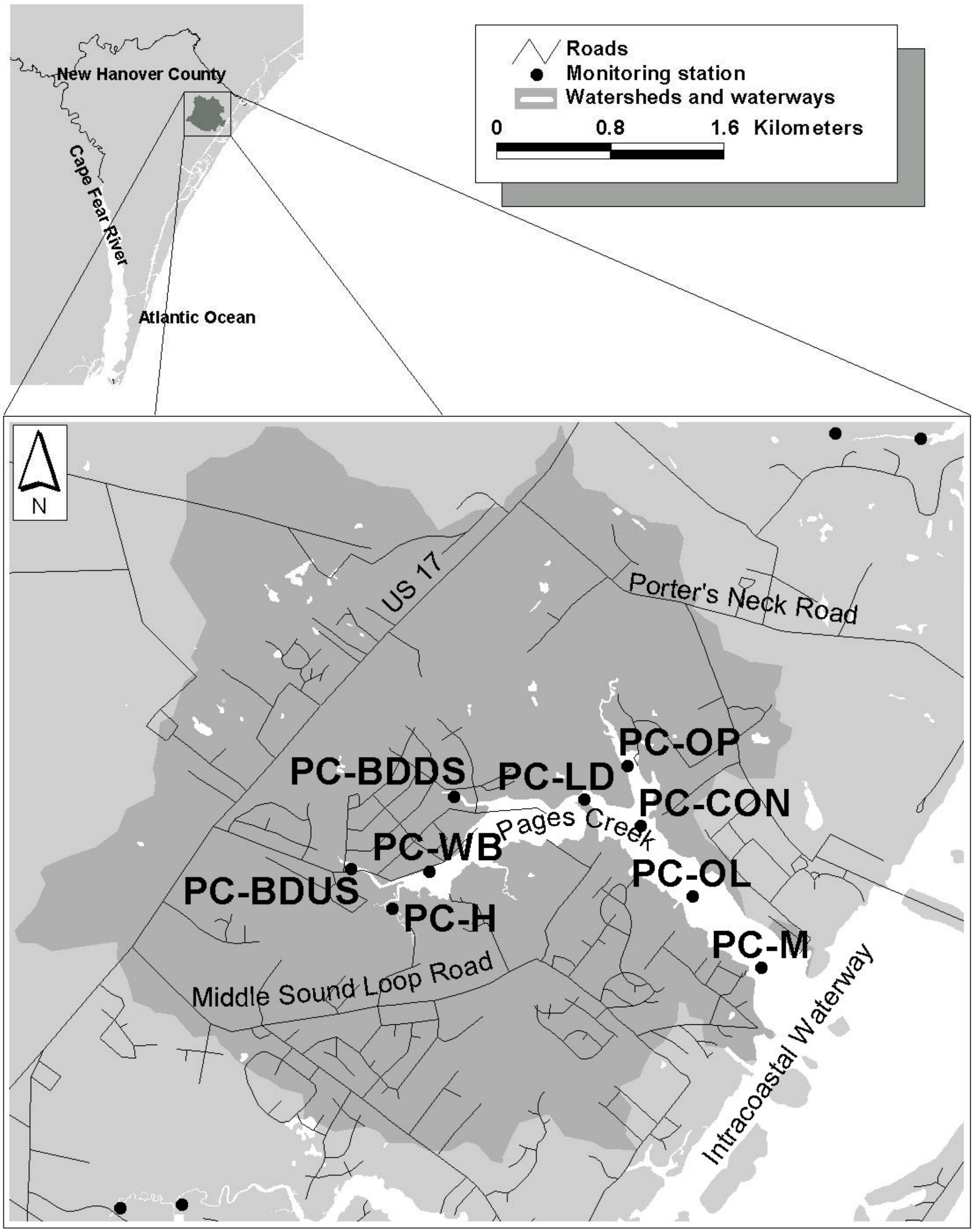


10.0 Pages Creek

Snapshot
Watershed area: 4,100 acres (1,659 ha)
Impervious surface coverage: >13%
Watershed population: Approximately 8,390

The University of North Carolina Wilmington was not funded by the County in 2012 to sample Pages Creek. Subsequent County-sponsored sampling of this creek was performed by Coastal Planning & Engineering of North Carolina, Inc., with data and information for this creek available on the County Planning Department website: http://www.nhcgov.com/AgnAndDpt/PLNG/Pages/WaterQualityMonitoring.aspx.

Figure 10.1. Pages Creek watershed and sampling sites.



11.0 Smith Creek

Snapshot
Watershed area: 13,895 acres (5,623 ha)
Impervious surface coverage: 33%
Watershed population: 31,780
Overall water quality: Fair-Poor
Problematic pollutants: some turbidity and low dissolved oxygen, fecal coliform pollution

Smith Creek drains into the lower Northeast Cape Fear River just before it joins with the mainstem Cape Fear River at Wilmington (Fig. 11.1). One location on Smith Creek, SC-CH at Castle Hayne Road (Fig. 11.1) is sampled monthly by UNCW under the auspices of the Lower Cape Fear River Program for selected parameters (field physical parameters and fecal coliform bacteria) and these data are shown below (Table 11.1).

The dissolved oxygen standard for Smith Creek, which is rated as C Sw waters is 4.0 mg/L, which was violated three times in our 2012 samples. The North Carolina turbidity standard for estuarine waters (25 NTU) was exceeded two of 12 sampling occasions.

Fecal coliform bacterial pollution increased over 2011. Concentrations exceeded 200 CFU/100 mL on five sampling occasions at SC-CH in 2012, for a Poor rating; one exceedence was very high 60,000 CFU/100 mL (Table 11.1).

Table 11.1. Selected water quality parameters in Smith Creek watershed as mean (standard deviation) / range, 2012, n = 12 months.

Parameter	SC-CH	
	Mean (SD)	Range
Salinity (ppt)	4.0 (3.8)	0.1-10.2
Dissolved oxygen (mg/L)	6.3 (2.3)	3.7-9.4
Turbidity (NTU)	14.5 (9.8)	4-34
Fecal col. /100 mL (geomean / range)	257	46-60,000

Sediment Metals and Chemical Toxins

We collected sediment samples at three stations in Smith Creek in 2012 for analysis of sediment metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) as well some basic chemical parameters including total nitrogen, total phosphorus and total organic carbon. Discussion of the importance of these parameters and what their concentrations mean is in the Greenfield Lake chapter of this report.

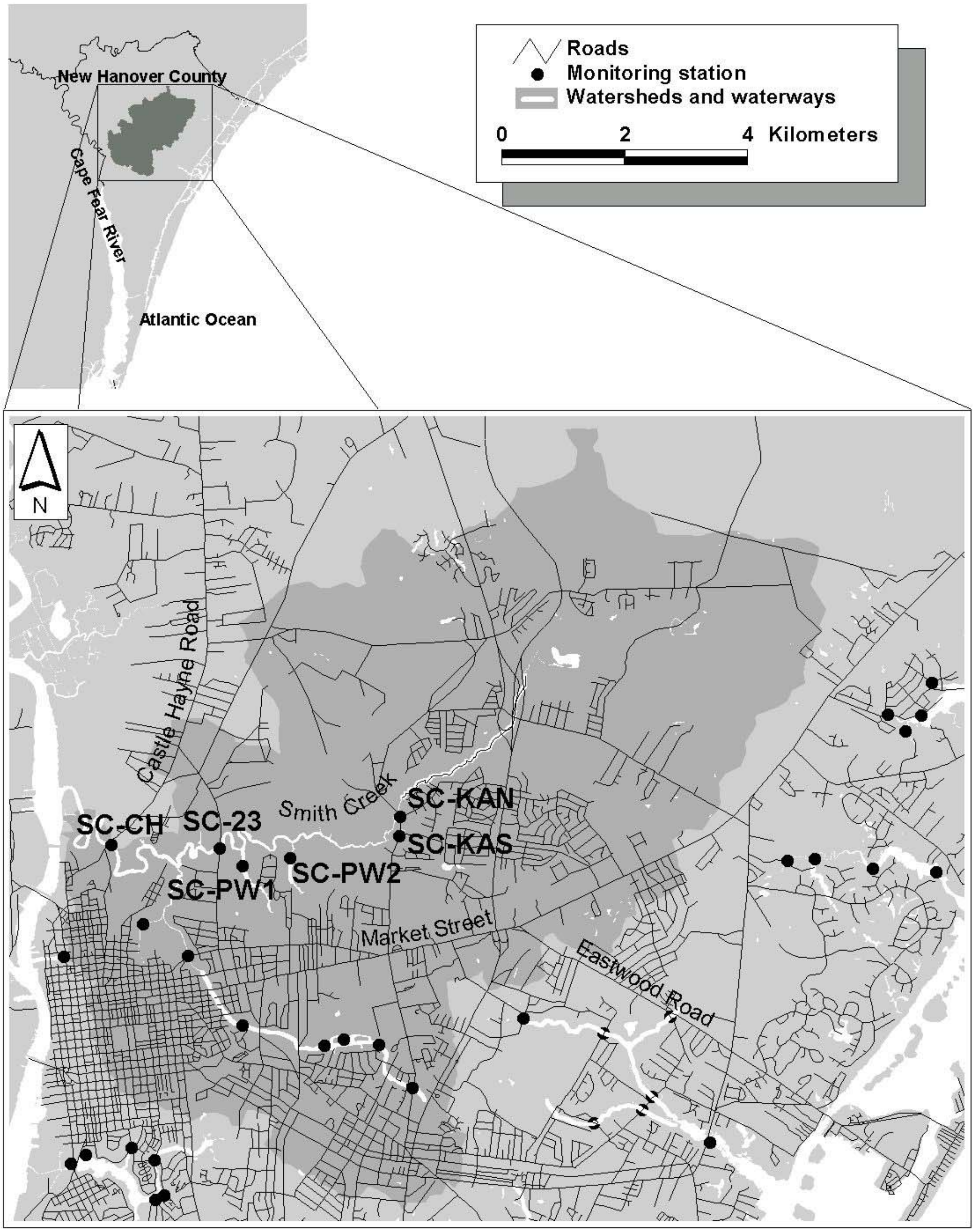
Results (Table 11.3) showed that there were no problematic metals or toxin concentrations in either the north or south branches of Smith Creek as sampled at Kerr Avenue (SC-KAN and SC-KAS). However, the lower station at Castle Hayne Road (SC-CH) had elevated concentrations of two PAHs, Fluoranthene and Chrysene; both were both at problematic levels, exceeding the Effects Range Low (Long 1995).

Table 11.3. Concentrations of sediment metals and polycyclic aromatic hydrocarbons (PAHs) in Smith Creek, 2012. Concentrations in bold type exceed the level at which harmful effects to benthic organisms may occur according to Long et al. (1995).

Parameter	SC-KAS	SC-KAN	SC-CH
	Dry wt., ppm = µg/g = mg/kg		
Antimony	<0.187	<0.165	<0.195
Arsenic	<0.187	<0.165	<0.195
Beryllium	<0.187	<0.165	0.230
Cadmium	<0.187	<0.165	<0.195
Chromium	8.62	8.75	13.5
Copper	7.35	4.26	10.1
Lead	29.7	11.5	28.4
Mercury	<0.0220	0.2100	0.0320
Nickel	3.05	2.51	4.19
Selenium	<0.187	<0.165	<0.195
Silver	<0.187	<0.165	<0.195
Thallium	<0.187	<0.165	<0.195
Zinc	69.2	34.0	48.2
	Dry wt., ppb = ng/g = µg/kg		
Total PAH	BDL	BDL	2265
Phenanthrene	BDL	BDL	BDL
Fluoranthene	BDL	BDL	**749**
Pyrene	BDL	BDL	584
B(a)anthracene	BDL	BDL	BDL
Chrysene	BDL	BDL	**463**
Benzo(b)fluoranthene	BDL	BDL	496
Benzo(a)pyrene	BDL	BDL	BDL
Total PCBs	BDL	BDL	BDL
TN (mg/kg)	176.0	103.0	34.6
TP	55.0	55.8	98.3
TOC	1140.0	1050.0	1090.0

BDL = below detection limit

Figure 11.1 Smith Creek watershed



12.0 Whiskey Creek

Snapshot
Watershed area: 2,095 acres (848 ha)
Impervious surface coverage: 19%
Watershed population: 7,980
Overall Water Quality: Fair
Problematic pollutants: Low dissolved oxygen

Whiskey Creek drains into the ICW. Sampling of this creek began in August 1999, at five stations. One station was dropped due to access issues in 2005; four stations were sampled until and including 2007; in 2008 this was reduced to one station, WC-MLR (from the bridge at Masonboro Loop Road – Fig. 12.1). In 2012 salinity at this station was relatively high, what scientists consider euhaline, ranging from 27 – 33 ppt and averaging about 31 ppt (Table 12.1).

Dissolved oxygen concentrations were below the State standard on three of six sampling occasions at WC-MLR (Table 12.1). Turbidity was within state standards for tidal waters on all sampling occasions (Table 12.1; Appendix B). High suspended solids (28.4 mg/L) were found on the June 20 sample trip. Algal blooms are relatively rare in this creek and there were no blooms detected in our 2012 sampling (Table 12.1). Nutrient concentrations were generally low at this station, particularly inorganic nitrogen (ammonium and nitrate). Total nitrogen and total phosphorus were similar to 2011.

Fecal coliform bacteria were acceptable for human contact at this site and below the North Carolina standard of 200 CFU/100 mL on all six occasions sampled whiskey Creek is presently closed to shellfishing by the N.C. Division of Marine Fisheries.

We note that our previous sampling showed that most water quality problems occurred near the headwaters of the creek rather than the middle section we currently sample.

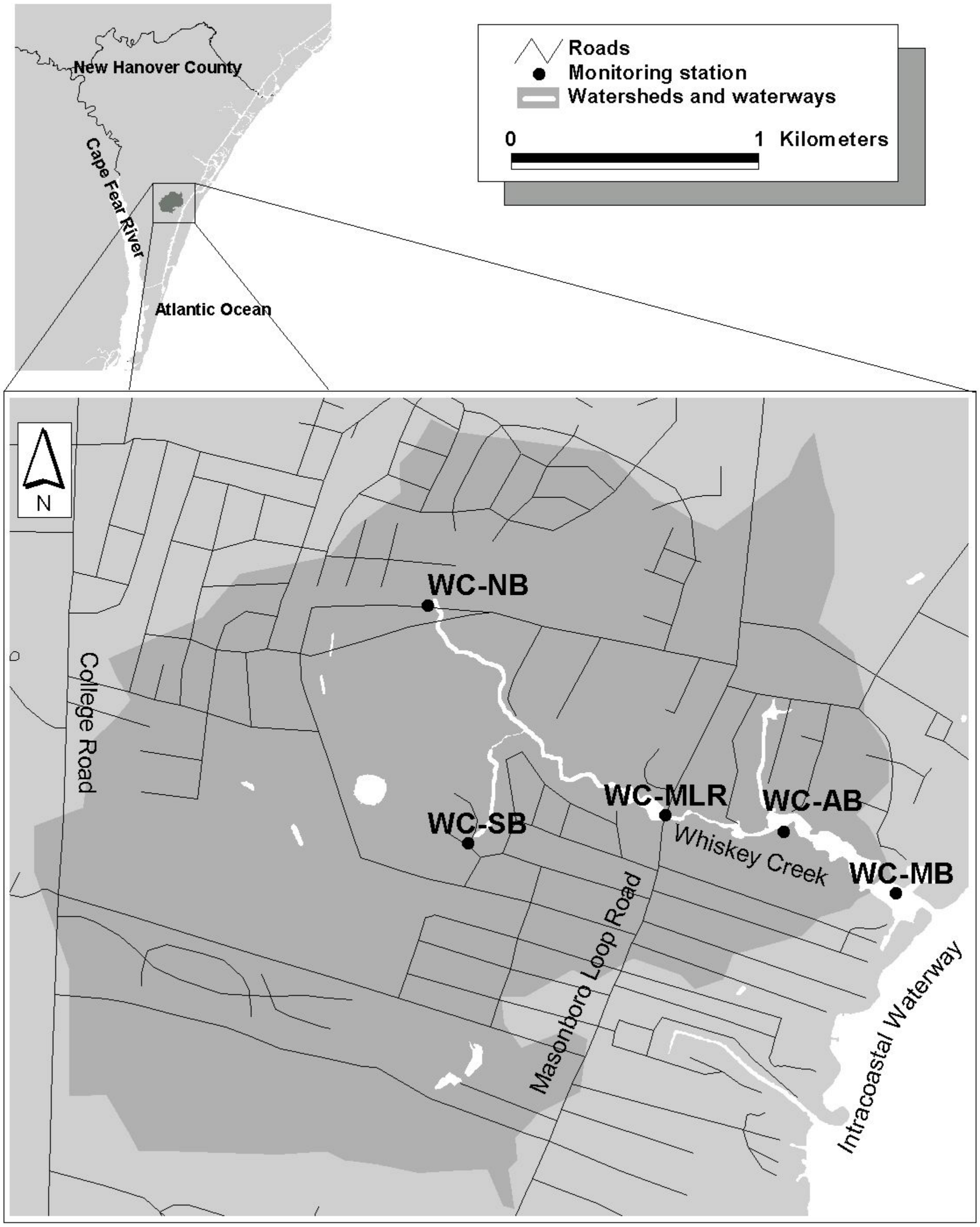
Table 12.1. Water quality summary statistics for Whiskey Creek, 2012, presented as mean (standard deviation) / range, fecal coliforms as geometric mean / range.

	Salinity (ppt)	DO (mg/L)	Turbidity (NTU)	TSS (mg/L)	Chlor *a* (μg/L)	FC CFU/100 mL
WC-MLR	31.0 (2.2)	5.5 (2.3)	8 (4)	16.6 (6.2)	4 (3)	41
	27.2-33.2	3.4-8.1	4-13	12.0-28.4	1-9	10-163

Table 12.2. Nutrient concentration summary statistics for Whiskey Creek, 2012, as mean (standard deviation) / range, N/P ratio as mean / median.

	Nitrate (mg/L)	Ammonium (mg/L)	TN (mg/L)	Phosphate (mg/L)	TP (mg/L)	N/P ratio
WC-MLR	0.02 (0.02)	0.01 (0.02)	0.46 (0.59)	0.02 (0.01)	0.04 (0.02)	6.0
	0.01-0.05	0.01-0.50	0.07-1.63	0.01-0.02	0.01-0.06	3.7

Figure 12.1. Whiskey Creek. Watershed and sampling sites.



13.0 Special Pollution Investigations

Periodically the City Stormwater Services and UNCW collaborate on special investigations to further assess deliberate or accidental sewage discharges, stormwater problems, or other pollution incidents.

On April 17, 2012, Dr. Mallin and Matthew McIver accompanied City stormwater staff to several locations in the Burnt Mill Creek watershed to search for possible sewage leaks. Here are the data for that investigation:

250 PP (Princess Place storm drain) ammonia = 61.8 mg/L, BOD5 = 138 mg/L, fecal coliforms = 600,000 CFU/100 mL, optical brighteners = 38 (definite strong sewage signal).

UMBC (ditch behind church) ammonia 1.0 mg/L, BOD5 = 1.5 mg/L, fecal coliforms = 780 CFU/100 mL, optical brighteners = 5 (chance of sewage none to minor, possible old signal).

W CHIME (Windchime storm drain ditch) ammonia = 0.5 mg/L, BOD5 = 1.5 mg/L, fecal coliforms 138 CFU/100 mL, optical brighteners = 35 (possibly older minor sewage leak, weak)

On September 11, 2012, Dr. Mallin and Matthew McIver accompanied Ms. Beth Nunnally to the dock at Parsely Woods development on Bradley Creek; foam on the surface had been reported to City staff at that location. Sampling results found a fecal coliform count of 64 CFU/100 mL, and a BOD5 of 2.0 mg/L; neither parameter was remarkable and no sewage leak was implicated. Observations from the dock by the sample team saw plumes of turbidity actively being caused by bioturbation of benthic invertebrates (burrowing); thus the surface scum was likely due to natural causes.

On October 1, 2012, Dr. Mallin and Matthew McIver (at request of Ms. Beth Nunnally) collected a sample at Station AP-1, draining Mill Creek Apartments and just upstream of Ann McCrary pond on Burnt Mill Creek. Fecal coliforms were very high (31,000 CFU/100 mL) though optical brightener concentrations were relatively low at 10. Thus, sewage did not appear to be the problem, potentially stormwater runoff moving fecal waste from the excessive pet waste piles in the apartment complex was the problem. Note that this location has had excessive fecal coliform counts on several occasions in 2011 as well as 2012.

We have intensified sample collection in Burnt Mill Creek based on the data above. Dr. Mallin had an intern (Stephanie Protopappas) conduct a project sampling the area several times in fall 2012, with the cooperation of Beth Nunnally of the City of Wilmington Stormwater Services. Those data are presented in Chapter 14 in this annual report.

14.0 Potential Sewage Discharge Locations in Lower Burnt Mill Creek

Stephanie Protopappas, Michael A. Mallin and Matthew R. McIver

Abstract

Burnt Mill Creek has been afflicted by elevated fecal bacterial counts, as well as low dissolved oxygen and algal blooms for many years. The City of Wilmington Stormwater Services has reason to believe there could be sewage leaks contaminating one or more stormwater drains entering the creek. As such, eight sites were chosen by Wilmington Stormwater services in order to identify potential sewage inputs entering Burnt Mill Creek. Each sample site was at or near a stormwater outfall point, which narrows the scope of potential sewer contamination. The UNCW Aquatic Ecology Laboratory at The Center for Marine Science conducted sampling at or near these chosen sites for fecal coliform bacteria and optical brightener concentrations. This project was conducted from June 4th through the month of August 2012, with emphasis toward rain events. Of the seven sites that UNCW collected significant data on, three showed possible sewage influence. These were: BMC-MDW and BMC-MDE, located on Rankin St. between 12th and 13th - these are stormwater pipes flowing into McCumbers Ditch, a tributary to Burnt Mill Creek; and Station 21-NB, located in close proximity to the mouth of Burnt Mill Creek where it meets up with the Northeast Cape Fear River. This site is a small bridge directly underneath a street storm drain located off of 21st St. between Noble and Brandon.

Introduction

Historically and presently Burnt Mill Creek is categorized as polluted. This is indicative of its location, flowing through downtown Wilmington. Any major body of water that flows through a developed area is subject to pollution for many reasons; impervious surfaces, high traffic volumes and aging and leaking underground pipes. This project was conducted in conjunction with The City of Wilmington Stormwater Services to assess whether there is reason to believe one or more potential sewage leaks are occurring in the lower Burnt Mill Creek Watershed.

Utilizing fecal coliform bacteria counts and a potential relationship it can have with an optical brightener signature we were able to assess whether or not there were sewer leaks in any of the sites located in the Burnt Mill Creek Watershed. Typically, fecal coliform counts are highest when there are high stormwater flow rates, due to runoff. Simultaneously, optical brightener, an additive in laundry detergents and a characteristic of human sewage, has a lower signature during high flow rate due to dilution. Thus, if there is an inverse relationship between fecal coliform and optical brightener than one can expect the fecal counts generated by stormwater runoff rather than a sewage leak. However, if both fecal counts and optical brightener measurements are high, it is likely due to a sewage leak. This would be most evident during dry periods.

Site Description

The site selection was determined in conjunction with The City of Wilmington Stormwater Services. There was reason to believe that one or more of the sites chosen is connected or situated near a leaking sewage pipe (Map 1).

- BMC-FHS (1) is a storm drain that opens up to Burnt Mill Creek under the bridge at Forest Hill Rd. This area is predominantly residential and contains a nearby school.
- The second site, MSB-GS (2), is downstream about a quarter mile, where Mineral Spring Branch passes under Gibson Street and then enters Burnt Mill Creek. This site is not a storm drain; instead it is a designated tributary specifically draining excess stormwater from the surrounding residential property (mainly a dense apartment complex).
- The third site, BMC-MA (3) tested was a storm drain which flows out underneath the bridge located on Metts Ave., a predominantly residential area, close to the outskirts of the downtown district.
- The next two sites are close together, MDW (4) and MDE (5). Stormwater Services chose these sites because they are the unique stormwater pipes that travel underneath the city, approximately 2-3 miles long opening up and flowing into McCumbers Ditch, a tributary to Burnt Mill Creek. This site is located on Rankin St. between 12th and 13th.
- The next two sites are similar because they are closely located, but differ because they are West and East storm drains that flow directly into Burnt Mill Creek, along Chestnut St., (BMC-WCS and BMC-ESC). The latter is designated as a "rain only" site, due to the natural flow which only occurs during a rain storm; *thus data collections were too limited to make quantifiable analyses*.
- The last site tested (21-NB) was chosen because of its close proximity to the mouth of Burnt Mill Creek where it meets up with the Northeast Cape Fear River. This site is a small bridge directly underneath a street storm drain located off of 21st St. between Noble and Brandon.

Methods

This study took place in the Lower Burnt Mill Creek Watershed, downstream of Ann McCrary wet detention pond. Eight sites were chosen for fecal coliform and optical brightener testing. The eight sites were chosen specifically so that water could be collected inside the stormwater drainage pipe or ditch. At each site 500mL of water was collected in sterile glass jars for fecal coliform bacteria, along with 125mL of water in opaque plastic bottles for optical brightener assessment. Once collected each sample was stored on ice. For fecal bacteria we used Standard Methods 2.12 M-FC, Fecal Coliform Bacteria by Membrane Filtration, with initiation within 3 hours of sampling. Collection volumes changed during the course of the sampling effort. At first, 100mL samples were filtered in conjunction with 10mL samples. This became problematic due to the high counts of fecal coliform bacteria. An additional issue occurred because another bacterium was present and appeared on the plates. This bacterium is pink and is commonly found in stormwater. In large sample volumes this bacteria either consumes the media too fast, not allowing the fecal to grow or thrives off of the fecal that have grown and eventually takes over. In either case it was difficult to accurately count the amount of fecal coliform present. Eventually, the sample volumes were decreased to 1mL and 0.1mL. This allowed for an accurate count.

The optical brightener samples were stored in the refrigerator at approx. 40 ° F and tested at a later time. Optical Brighteners are a common constituent found in laundry detergent. Testing for this signature allows us to distinguish between human waste water (sewer), or nearby animal waste being transported into the creek. Optical Brightener samples are collected in opaque plastic bottles, so as to avoid UV light exposure which enables the compound to break down. Testing for optical brighteners is performed by utilizing a hand held fluorometer (Turner AquaFluor 10AU). As such, one can measure the amount of optical brightener present on a calibrated scale of 1 mg of Tide detergent to 100mL of DI water. Duplicate samples were measured at each site and an average was recorded. Four sites, MSB-GS, MDW, MDE and 21-NB, breached the mark of concern, being >20. This allowed us to narrow our scope of investigation.

Results and Analyses

Water temperatures at the sites ranged from 21.8-26.0 ºC, with nothing unusual found. pH ranged from neutral (6.9) to somewhat alkaline (8.2); specific conductance ranged from low (33) to moderate (516) and salinities were all 0.2 ppt or below. Turbidity was not consistently high at any one site, but on one of the rain event days (June 12 – 0.52 in) turbidity was elevated at most sites (18 to 52 NTU).

If a sewage input is occurring into a given stormwater system (under dry conditions), it should leave a signature of both elevated fecal coliforms (from the human waste) and elevated optical brighteners (from detergents entering sewage systems from homes or businesses). Thus, if fecal coliforms and optical brighteners are positively correlated, sewage is likely present. However, if there is significant rain, than the optical brighteners may be diluted from stormwater, but the stormwater itself leads to high fecal coliforms. This was evident on August 28, when there was 2.38 in of rain, yielding high fecal coliforms (Table 1) but low optical brighteners (Table 2) at all sampling sites.

Since sampling was conducted in both wet and dry periods, there were no significant correlations between fecal coliforms and optical brighteners. If there is no sewage present but fecal coliforms are correlated with rainfall, then stormwater runoff is a problem but sewage leaks are not. As such, there were several significant ($p < 0.05$) or nearly-significant correlations between rainfall and fecal coliforms (MSB-GS, BMC-MA, BMC-MDE, BMC-WCS) showing clear stormwater pollution. Concentrating on dry periods, when stormwater should not be a problem, there were a number of sampling dates and sites when both fecal coliforms and optical brighteners were elevated, these sites are likely candidates for potential sewage inputs. Below we assess each site for its sewage influence potential.

<u>Station BMC-FHS</u>: This location had a number of high fecal coliform counts (Table 1); these occurred primarily in wet periods but some periods of low rainfall showed elevated counts as well. However, all the optical brightener tests proved to be low (Table 2). There were no statistical correlations between fecal coliforms and optical brighteners, or with precipitation. Thus, sewage influence at this site was not detected in these samples.

Station MSB-GS: this tributary stream draining a large apartment complex showed several high fecal coliform counts (Table 1), and the counts were positively correlated with area precipitation ($r = 0.75$; $p = 0.05$). There were a couple of high optical brightener concentrations but not enough of a signal to demonstrate a sewage input.

Station BMC-MA: there were a few high fecal coliform counts (Table 1), and these showed a strong and near-significant ($r = 0.73$; $p = 0.06$) correlation with rainfall demonstrating a runoff signal. There were low optical brightener concentrations (Table 2), and no detectable sewage input here.

Station BMC-MDW: There were several high fecal coliform counts at this site (Table 1) and no correlation with rainfall. On at least two occasions (June 26 and August 13) there were high fecal coliform counts as well as high optical brightener counts (Table 2) corresponding with only trace precipitation, **indicating likely sewage input**.

Station BMC-MDE: this site had consistently high fecal coliform counts (Table 1) and yielded a positive correlation with rainfall ($r = 0.78$; $p = 0.036$). Thus, there was a strong stormwater signal. However, there were also several high optical brightener counts, including during fairly dry periods (June 26 and August 13) corresponding to high fecal counts. Thus, **this station likely has periodic sewage input**.

Station BMC-WCS: this site had some elevated fecal coliform counts (Table 1) which were correlated with rainfall ($r = 0.79$; $p = 0.035$). Optical brightener concentrations were low, with no sewage input likely.

Station 21-NB: this site had the highest geometric mean fecal counts of the whole series (3,123 CFU/100 mL) but no correlation with rainfall. There were several high optical brightener concentrations (Table 2). Although not correlated with fecal coliform counts, on at least two periods of very low rainfall (June 26 and August 13) there were high fecal coliform counts and correspondingly high optical brightener concentrations, **indicating a likely sewage input signal**.

At the three sites indicating potential sewage contamination, further action is recommended to assess for leaks. If more sampling is desired, dry period sampling for fecal coliforms, optical brighteners, and ammonium would be helpful, in addition to physical detection methods.

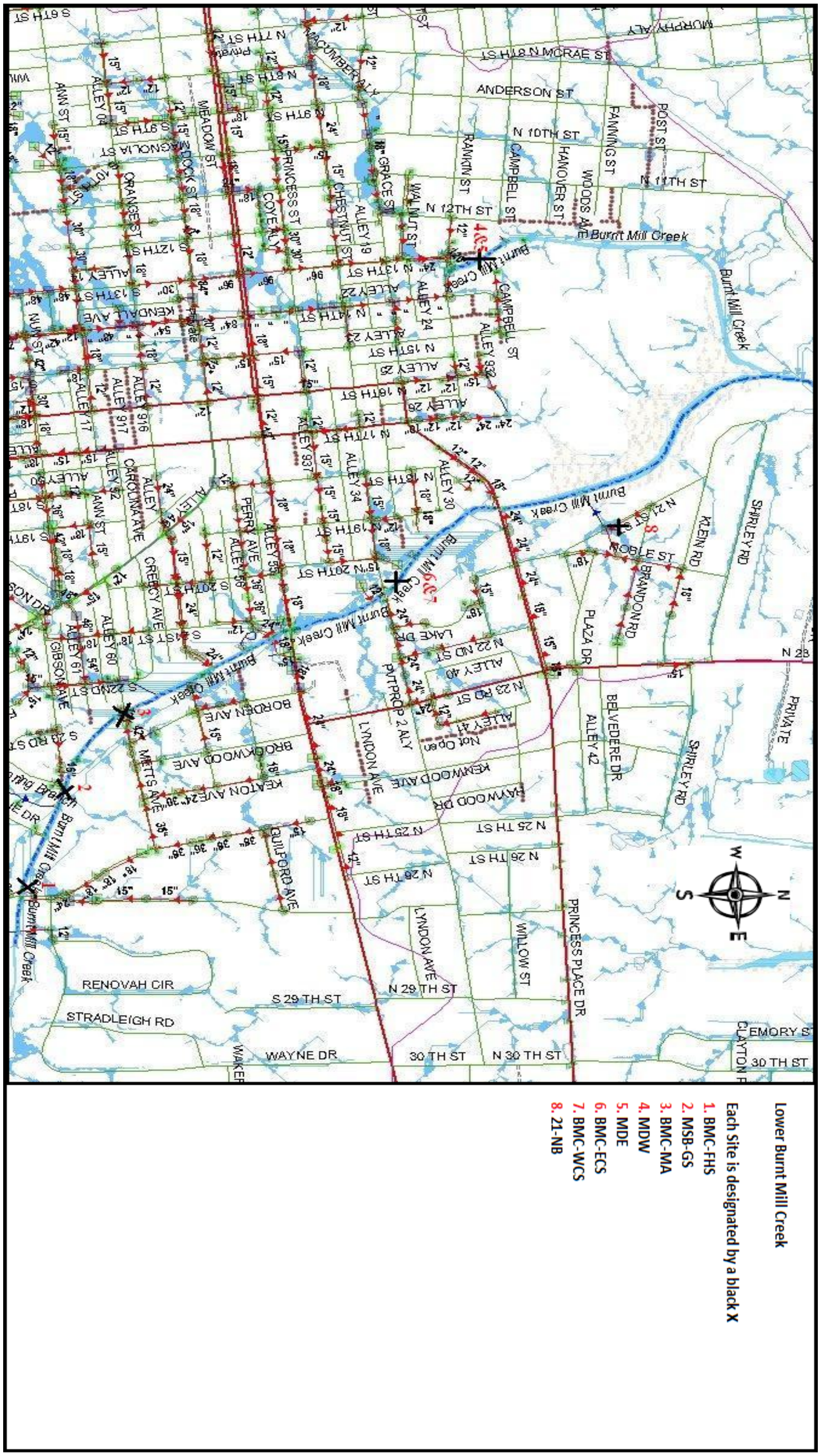
Table 1. Fecal coliform bacteria counts at the sampling sites.

Fecal Coliform Bacteria Counts (CFU/100 mL)									
Sites	BMC-FHS	MSB-GS	BMC-MA	BMC-WCS	BMC-ECS	MDW	MDE	21-NB	PPT (inches)
Date									
6/4	600	233	70	320		500	950	189	0.01
6/12	8,000	8,850	3,500	9,500	9,850	10,450	6,250	3,150	**0.52**
6/20	350	235	75	175		210	1,615	420	0
6/26	1,850	1,350	1,950	1,350		11,200	3,700	10,000	0.09
7/2	1,000	1,600	150	2,200		850	2,500	10,000	**0.51**
7/11	1,250	1,850	2,050	1,800		1,600	7,250	37,100	**0.39**
8/13	2,950	1,400	700	1,725	600	6,700	6,700	9,000	0.03
8/28	32,900	13,500	26,500	25,400	25,266	12,400	23,500	7,600	**2.38**
mean	6,113	3,627	4,374	5,309	11,905	5,489	6,558	9,682	0.49
St. dev.	11,101	4,858	9,023	8,643		5,290	7,252	11,804	0.80
minimum	350	233	70	175	600	210	950	189	0.00
max	32,900	13,500	26,500	25,400	25,266	12,400	23,500	37,100	2.38
median	1,125	1,475	1,050	1,575	9,850	1,225	3,100	6,575	0.24
geomean	1,254	1,116	472	1,190	5,305	1,599	2,938	3,123	

Table 2. Optical brightener concentrations at the sample sites (high values **bolded**).

Optical Brightener Concentrations									
Sites	BMC-FHS	MSB-GS	BMC-MA	BMC-WCS	BMC-ECS	MDW	MDE	21-NB	PPT (inches)
Date									
6/4									0.01
6/12	11.2	10.7	11.6	8.5	7.0	11.6	9.9	3.9	**0.52**
6/20	7.5	12.0	2.9	6.8		**19.0**	14.6	12.0	0
6/26	11.5	**28.1**	8.5	**18.2**		**20.1**	**27.7**	**25.6**	0.09
7/2	7.2	**22.6**	6.1	10.2		**19.3**	**21.8**	**27.5**	**0.51**
7/11	9.5	16.2	3.6	10.0		18.5	**21.0**	**20.1**	**0.39**
8/13	11.5	12.8	8.9	13.4	10.9	**21.3**	**19.5**	18.8	0.03
8/28	8.1	7.5	7.7	8.6	8.8	10.7	14.9	7.4	**2.38**
mean	9.5	15.7	7.0	10.8	8.9	17.2	18.5	16.5	0.49
St. dev.	1.9	7.2	3.1	3.8	2.0	4.2	5.8	9.0	0.80
minimum	7.2	7.5	2.9	6.8	7.0	10.7	9.9	3.9	0.00
max	11.5	28.1	11.6	18.2	10.9	21.3	27.7	27.5	2.38
median	9.5	12.8	7.7	10.0	8.8	19.0	19.5	18.8	0.24

Map 1. Location of the sampling sites along Burnt Mill Creek



15.0 Report References Cited

APHA. 1995. Standard Methods for the Examination of Water and Wastewater, 19th ed. American Public Health Association, Washington, D.C.

Burkholder, J.M. 2001. Eutrophication and Oligotrophication. *In* "Encyclopedia of Biodiversity", Vol. 2, pp 649-670. Academic Press.

Duernberger, K.A. 2009. Tracing nitrogen through the food chain in an urbanized tidal creek. M.S. Thesis, University of North Carolina Wilmington, Center for Marine Science. 70 pp.

Hecky, R.E. and P. Kilham. 1988. Nutrient limitation of phytoplankton in freshwater and marine environments: A review of recent evidence on the effects of enrichment. *Limnology and Oceanography* 33:796-822.

Long, E.R., D.D. McDonald, S.L. Smith and F.D. Calder. 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental Management* 19:81-97.

Mallin, M.A., L.B. Cahoon, J.J. Manock, J.F. Merritt, M.H. Posey, R.K. Sizemore, W.D. Webster and T.D. Alphin. 1998a. *A Four-Year Environmental Analysis of New Hanover County Tidal Creeks, 1993-1997.* CMSR Report No. 98-01, Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, J.J. Manock, J.F. Merritt, M.H. Posey, T.D. Alphin, D.C. Parsons and T.L. Wheeler. 1998b. *Environmental Quality of Wilmington and New Hanover County Watersheds, 1997-1998*. CMSR Report 98-03. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., S.H. Ensign, D.C. Parsons and J.F. Merritt. 1999. *Environmental Quality of Wilmington and New Hanover County Watersheds, 1998-1999.* CMSR Report No. 99-02. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A. and T.L. Wheeler. 2000. Nutrient and fecal coliform discharge from coastal North Carolina golf courses. *Journal of Environmental Quality* 29:979-986.

Mallin, M.A., K.E. Williams, E.C. Esham and R.P. Lowe. 2000a. Effect of human development on bacteriological water quality in coastal watersheds. *Ecological Applications* 10:1047-1056.

Mallin, M.A., S.H. Ensign, D.C. Parsons, V.L. Johnson and J.F. Merritt. 2000b. *Environmental Quality of Wilmington and New Hanover County Watersheds, 1999-2000.* CMSR Report No. 00-02. Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., S.H. Ensign, M.R. McIver, G.C. Shank and P.K. Fowler. 2001. Demographic, landscape, and meteorological factors controlling the microbial pollution of coastal waters. *Hydrobiologia* 460:185-193.

Mallin, M.A., L.B. Cahoon, M.H. Posey, L.A. Leonard, D.C. Parsons, V.L. Johnson, E.J. Wambach, T.D. Alphin, K.A. Nelson and J.F. Merritt. 2002a. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2000-2001*. CMS Report 02-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., S.H. Ensign, T.L. Wheeler and D.B. Mayes. 2002b. Pollutant removal efficacy of three wet detention ponds. *Journal of Environmental Quality* 31:654-660.

Mallin, M.A., L.B. Cahoon, M.H. Posey, D.C. Parsons, V.L. Johnson, T.D. Alphin and J.F. Merritt. 2003. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2001-2002*. CMS Report 03-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, M.H. Posey, V.L. Johnson, T.D. Alphin, D.C. Parsons and J.F. Merritt. 2004. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2002-2003*. CMS Report 04-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, M.H. Posey, V.L. Johnson, D.C. Parsons, T.D. Alphin, B.R. Toothman, M.L. Ortwine and J.F. Merritt. 2006a. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2004-2005*. CMS Report 06-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., V.L. Johnson, S.H. Ensign and T.A. MacPherson. 2006b. Factors contributing to hypoxia in rivers, lakes and streams. *Limnology and Oceanography* 51:690-701.

Mallin, M.A., L.B. Cahoon, T.D. Alphin, M.H. Posey, B.A. Rosov, D.C. Parsons, R.M. Harrington and J.F. Merritt. 2007. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2005-2006*. CMS Report 07-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, M.I.H. Spivey, M.E. Tavares, T.D. Alphin and M.H. Posey. 2008. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2006-2007*. CMS Report 08-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, M.I.H. Spivey and B. Song. 2009a. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2008*. CMS Report 09-03, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., V.L. Johnson and S.H. Ensign. 2009b. Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. *Environmental Monitoring and Assessment* 159:475-491.

Mallin, M.A., M.R. McIver, M.I. Haltom, E.A. Steffy and B. Song. 2010a. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2009*. CMS Report 10-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., J. McAuliffe, M.R. McIver, D. Mayes and M.R. Hanson. 2012. High pollutant removal efficacy of a large constructed wetland leads to receiving stream improvements. *Journal of Environmental Quality* 41:2046-2055.

Mallin, M.A., E.A. Steffy, M.R. McIver and M.I. Haltom. 2011. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2010*. CMS Report 11-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

NCDEHNR. 1996. Water Quality Progress in North Carolina, 1994-1995 305(b) Report. Report No. 96-03. North Carolina Department of Environment, Health, and Natural Resources, Division of Water Quality. Raleigh, N.C.

NCDENR. 2005. Cape Fear River Basinwide Water Quality Plan. North Carolina Department of Environment and Natural Resources, Division of Water Quality, Raleigh, N.C.

Perrin, C., J. Wright, W.F. Hunt, P. Beggs, M.A. Mallin and M. Burchell. 2008. *Restoring the Burnt Mill Creek Watershed through Stormwater Management and Community Development*. FY04 EPA 319 Grant Final Report.

Schlotzhauer, S.D. and R.C. Littell. 1997. SAS system for elementary statistical analysis, 2nd Edition. SAS Institute, Inc., SAS Campus Dr., Cary, N.C.

Tavares, M.E., M.I.H. Spivey, M.R. McIver and M.A. Mallin. 2008. Testing for optical brighteners and fecal bacteria to detect sewage leaks in tidal creeks. *Journal of the North Carolina Academy of Science* 124:91-97.

U.S. EPA. 1997. Methods for the Determination of Chemical Substances in Marine and Estuarine Environmental Matrices, 2nd Ed. EPA/600/R-97/072. National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

US EPA 2000. Guidance for assessing chemical contaminant data for use In fish advisories, Volume 2: Risk assessment and fish consumption limits. EPA-823-B-00-008. United States Environmental Protection Agency, Office of Research and Development, Office of Water, Washington, D.C.

US EPA. 2004. National Coastal Condition Report II. EPA-620/R-03/002. United States Environmental Protection Agency, Office of Research and Development, Office of Water, Washington, D.C.

Welschmeyer, N.A. 1994. Fluorometric analysis of chlorophyll *a* in the presence of chlorophyll *b* and phaeopigments. *Limnology and Oceanography* 39:1985-1993.

16.0 Acknowledgments

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17.0 Appendix A. North Carolina Water Quality standards for selected parameters (NCDEHNR 1996). We note that these standards are general, and differ with designated water body use. Details can be found at within the N.C. Division of Water quality website at: http://h2o.enr.state.nc.us/csu/documents/ncactable290807.pdf

Parameter	Standard
Dissolved oxygen	5.0 ppm (mg/L)
Turbidity	25 NTU (tidal saltwater) 50 NTU (freshwater)
Fecal coliform counts	14 CFU/100 mL (shellfishing waters), and more than 10% of the samples cannot exceed 43 CFU/100 mL. 200 CFU/100 mL (human contact waters)
Chlorophyll *a*	40 ppb (μg/L)

CFU = colony-forming units
mg/L = milligrams per liter = parts per million
μg/L = micrograms per liter = parts per billion

18.0 Appendix B. UNCW ratings of sampling stations in Wilmington watersheds based on 2012, where available, for chlorophyll *a*, dissolved oxygen, turbidity, and fecal coliform bacteria (human contact standard) based on North Carolina state chemical standards for freshwater or tidal saltwater, *fecal coliform based on contact standard.

G (good quality) – state standard exceeded in ≤ 10% of the measurements
F (fair quality) – state standard exceeded in 11-25% of the measurements
P (poor quality) – state standard exceeded in >25% of the measurements

Watershed	Station	Chlor *a*	DO	Turbidity	Fecal coliforms*
Bradley Creek	BC-CA	G	F	G	P
	BC-SB	F	P	G	P
	BC-NB	G	F	G	P
Burnt Mill Creek	BMC-AP1	F	P	G	P
	BMC-AP3	F	G	G	P
	BMC-PP	F	P	G	P
Greenfield Lake	GL-LC	-	F	G	-
	GL-JRB	-	P	G	-
	GL-LB	-	P	G	-
	GL-2340	F	P	G	P
	GL-YD	P	G	G	P
	GL-P	P	G	G	P
Hewletts Creek	HC-3	G	P	G	G
	NB-GLR	G	P	G	P
	MB-PGR	G	G	G	P
	SB-PGR	G	P	G	G
	PVGC-9	G	F	G	P
Howe Creek	HW-FP	G	F	G	G
	HW-GP	G	P	G	F
	HW-DT	G	P	G	P
Smith Creek	SC-CH	-	F	F	P
Whiskey Creek	WC-MLR	G	P	G	G

19.0 Appendix C. GPS coordinates for the Wilmington Watersheds Project sampling stations used during various years.

Watershed	Station	GPS coordinates	
Barnard's Creek	BNC-RR	N 34.15867	W 77.93784
Bradley Creek	BC-CA	N 34.23260	W 77.86659
	BC-CR	N 34.23070	W 77.85251
	BC-SB	N 34.21963	W 77.84593
	BC-SBU	N 34.21724	W 77.85435
	BC-NB	N 34.22138	W 77.84424
	BC-NBU	N 34.23287	W 77.84036
	BC-76	N 34.21484	W 77.83368
Burnt Mill Creek	BMC-KA1	N 34.22215	W 77.88522
	BMC-KA3	N 34.22279	W 77.88592
	BMC-AP1	N 34.22917	W 77.89173
	BMC-AP2	N 34.23016	W 77.89805
	BMC-AP3	N 34.22901	W 77.90125
	BMC-WP	N 34.24083	W 77.92415
	BMC-PP	N 34.24252	W 77.92515
	BMC-ODC	N 34.24719	W 77.93304
Futch Creek	FC-4	N 34.30150	W 77.74660
	FC-6	N 34.30290	W 77.75050
	FC-8	N 34.30450	W 77.75414
	FC-13	N 34.30352	W 77.75760
	FC-17	N 34.30374	W 77.76370
	FOY	N 34.30704	W 77.75707
Greenfield Lake	GL-SS1	N 34.19963	W 77.92460
	GL-SS2	N 34.20051	W 77.92947
	GL-LC	N 34.20752	W 77.92976
	GL-JRB	N 34.21266	W 77.93157
	GL-LB	N 34.21439	W 77.93559
	GL-2340	N 34.19853	W 77.93556
	GL-YD	N 34.20684	W 77.93193
	GL-P	N 34.21370	W 77.94362
Hewletts Creek	HC-M	N 34.18230	W 77.83888
	HC-2	N 34.18723	W 77.84307
	HC-3	N 34.19011	W 77.85062
	HC-NWB	N 34.19512	W 77.86155
	NB-GLR	N 34.19783	W 77.86317
	MB-PGR	N 34.19800	W 77.87088
	SB-PGR	N 34.19019	W 77.86474

	PVGC-9	N 34.19161	W 77.89177
Howe Creek	HW-M	N 34.24765	W 77.78718
	HW-FP	N 34.25468	W 77.79510
	HW-GC	N 34.25448	W 77.80512
	HW-GP	N 34.25545	W 77.81530
	HW-DT	N 34.25562	W 77.81952
Motts Creek	MOT-RR	N 34.12924	W 77.91611
Pages Creek	PC-M	N 34.27020	W 77.77123
	PC-OL	N 34.27450	W 77.77567
	PC-CON	N 34.27743	W 77.77763
	PC-OP	N 34.28292	W 77.78032
	PC-LD	N 34.28090	W 77.78485
	PC-BDDS	N 34.28143	W 77.79447
	PC-WB	N 34.27635	W 77.79582
	PC-BDUS	N 34.27702	W 77.80163
	PC-H	N 34.27440	W 77.79890
Smith Creek	SC-23	N 34.25794	W 77.91956
	SC-CH	N 34.25897	W 77.93872
	SC-KAN	N 34.26249	W 77.88759
	SC-KAS	N 34.25964	W 77.88778
Whiskey Creek	WC-NB	N 34.16803	W 77.87648
	WC-SB	N 34.15939	W 77.87481
	WC-MLR	N 34.16015	W 77.86629
	WC-AB	N 34.15967	W 77.86177
	WC-MB	N 34.15748	W 77.85640

20.0 Appendix D. University of North Carolina at Wilmington reports and papers concerning water quality in New Hanover County's tidal creeks.

Reports

Merritt, J.F., L.B. Cahoon, J.J. Manock, M.H. Posey, R.K. Sizemore, J. Willey and W.D. Webster. 1993. *Futch Creek Environmental Analysis Report*. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, E.C. Esham, J.J. Manock, J.F. Merritt, M.H. Posey and R.K. Sizemore. 1994. *Water Quality in New Hanover County Tidal Creeks, 1993-1994*. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C. 62 pp.

Mallin, M.A., L.B. Cahoon, J.J. Manock, J.F. Merritt, M.H. Posey, T.D. Alphin and R.K. Sizemore. 1995. *Water Quality in New Hanover County Tidal Creeks, 1994-1995*. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C. 67 pp.

Mallin. M.A., L.B. Cahoon, J.J. Manock, J.F. Merritt, M.H., Posey, R.K. Sizemore, T.D. Alphin, K.E. Williams and E.D. Hubertz. 1996. *Water Quality in New Hanover County Tidal Creeks, 1995-1996*. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C. 67 pp.

Mallin, M.A., L.B. Cahoon, J.J. Manock, J.F. Merritt, M.H. Posey, R.K. Sizemore, W.D. Webster and T.D. Alphin. 1998. *A Four-Year Environmental Analysis of New Hanover County Tidal Creeks, 1993-1997.* CMSR Report No. 98-01, Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, J.J. Manock, J.F. Merritt, M.H. Posey, T.D. Alphin, D.C. Parsons and T.L. Wheeler. 1998. *Environmental Quality of Wilmington and New Hanover County Watersheds, 1997-1998*. CMSR Report 98-03. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., S.H. Ensign, D.C. Parsons and J.F. Merritt. 1999. *Environmental Quality of Wilmington and New Hanover County Watersheds, 1998-1999*. CMSR Report No. 99-02. Center for Marine Science Research, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, S.H. Ensign, D.C. Parsons, V.L. Johnson and J.F. Merritt. 2000. *Environmental Quality of Wilmington and New Hanover County Watersheds, 1999-2000*. CMS Report No. 00-02. Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, M.H. Posey, L.A. Leonard, D.C. Parsons, V.L. Johnson, E.J. Wambach, T.D. Alphin, K.A. Nelson and J.F. Merritt. 2002. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2000-2001*. CMS Report 02-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., H.A. CoVan and D.H. Wells. 2003. *Water Quality Analysis of the Mason inlet Relocation Project*. CMS Report 03-02. Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, M.H. Posey, D.C. Parsons, V.L. Johnson, T.D. Alphin and J.F. Merritt. 2003. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2001-2002*. CMS Report 03-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, M.H. Posey, V.L. Johnson, T.D. Alphin, D.C. Parsons and J.F. Merritt. 2004. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2002-2003*. CMS Report 04-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., H.A. Wells and M.R. McIver. 2004. *Baseline Report on Bald Head Creek Water Quality*. CMS Report No. 04-03, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., H.A. Wells, T.A. MacPherson, T.D. Alphin, M.H. Posey and R.T. Barbour. 2004. *Environmental Assessment of Surface Waters in the Town of Carolina Beach*. CMS Report No. 04-02, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, M.H. Posey, V.L. Johnson, D.C. Parsons, T.D. Alphin, B.R. Toothman and J.F. Merritt. 2005. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2003-2004*. CMS Report 05-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A. 2006. Wading in waste. *Scientific American* 294:52-59.

Mallin, M.A., L.B. Cahoon, M.H. Posey, V.L. Johnson, D.C. Parsons, T.D. Alphin, B.R. Toothman, M.L. Ortwine and J.F. Merritt. 2006. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2004-2005*. CMS Report 06-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., B.R. Toothman, M.R. McIver and M.S. Hayes. 2007. *Bald Head Creek Water Quality: Before and After Dredging*. Final Report to the Village of Bald Head Island. CMS report 07-02. Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., L.B. Cahoon, T.D. Alphin, M.H. Posey, B.A. Rosov, D.C. Parsons, R.M. Harrington and J.F. Merritt. 2007. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2005-2006*. CMS Report 07-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, M.I.H. Spivey, M.E. Tavares, T.D. Alphin and M.H. Posey. 2008. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2006-2007*. CMS Report 08-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, M.I.H. Spivey and B. Song. 2009. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2008*. CMS Report 09-03, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.I.H. Spivey and B. Song. 2009. *Sources of Fecal Bacterial Pollution to Upper Pages Creek, N.C*. Report to Coastal Planning & Engineering of North Carolina, Inc. UNCW-CMS Report 09-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., J.A. McAuliffe, Y. Shirazi and M.R. McIver. 2010. Pollutant Removal Efficacy of a Constructed Wetland: The Clean Water Management Trust Fund 2004B-707 Wilmington Bethel Road Wetlands Project, UNCW CMS Report 10-03, University of North Carolina Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, M.I. Haltom, E.A. Steffy and B. Song. 2010. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2009*. CMS Report 10-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., E.A. Steffy, M.R. McIver and M.I. Haltom. 2011. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2010*. CMS Report 11-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., E.A. Steffy, M.R. McIver and E. Clay. 2012. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2011*. UNCW-CMS Report 12-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Peer-Reviewed Journal Papers

Mallin, M.A., E.C. Esham, K.E. Williams and J.E. Nearhoof. 1999. Tidal stage variability of fecal coliform and chlorophyll *a* concentrations in coastal creeks*. Marine Pollution Bulletin* 38:414-422.

Mallin, M.A. and T.L. Wheeler. 2000. Nutrient and fecal coliform discharge from coastal North Carolina golf courses. *Journal of Environmental Quality* 29:979-986.

Mallin, M.A., K.E. Williams, E.C. Esham and R.P. Lowe. 2000. Effect of human development on bacteriological water quality in coastal watersheds. *Ecological Applications* 10:1047-1056.

Mallin, M.A., L.B. Cahoon, R.P. Lowe, J.F. Merritt, R.K. Sizemore and K.E. Williams. 2000. Restoration of shellfishing waters in a tidal creek following limited dredging. *Journal of Coastal Research* 16:40-47.

Mallin, M.A., J.M. Burkholder, L.B. Cahoon and M.H. Posey. 2000. The North and South Carolina coasts. *Marine Pollution Bulletin* 41:56-75.

Mallin, M.A., S.H. Ensign, M.R. McIver, G.C. Shank and P.K. Fowler. 2001. Demographic, landscape, and meteorological factors controlling the microbial pollution of coastal waters. *Hydrobiologia* 460:185-193.

Mallin, M.A., S.H. Ensign, T.L. Wheeler and D.B. Mayes. 2002. Pollutant removal efficacy of three wet detention ponds. *Journal of Environmental Quality* 31:654-660.

Posey, M.H., T.D. Alphin, L.B. Cahoon, D.G. Lindquist, M.A. Mallin and M.E. Nevers. 2002, Resource availability versus predator control: questions of scale in benthic infaunal communities. *Estuaries* 25:999-1014.

Cressman, K.A., M.H. Posey, M.A. Mallin, L.A. Leonard and T.D. Alphin. 2003. Effects of oyster reefs on water quality in a tidal creek estuary. *Journal of Shellfish Research* 22:753-762.

Mallin, M.A. and A.J. Lewitus. 2004. The importance of tidal creek ecosystems. *Journal of Experimental Marine Biology and Ecology* 298:145-149.

Mallin, M.A., D.C. Parsons, V.L. Johnson, M.R. McIver and H.A. CoVan. 2004. Nutrient limitation and algal blooms in urbanizing tidal creeks. *Journal of Experimental Marine Biology and Ecology* 298:211-231.

Nelson, K.A., L.A. Leonard, M.H. Posey, T.D. Alphin and M.A. Mallin. 2004. Transplanted oyster (*Crassostrea virginica*) beds as self-sustaining mechanisms for water quality improvement in small tidal creeks. *Journal of Experimental Marine Biology and Ecology* 298:347-368.

Mallin, M.A., S.H. Ensign, D.C. Parsons, V.L. Johnson, J.M. Burkholder and P.A. Rublee. 2005. Relationship of *Pfiesteria* spp. and *Pfiesteria*-like organisms to environmental factors in tidal creeks draining urban watersheds. pp 68-70 in Steidinger, K.A., J.H. Landsberg, C.R. Tomas and G.A. Vargo, (Eds.) *XHAB*, *Proceedings of the Tenth Conference on Harmful Algal Blooms, 2002*, Florida Fish and Wildlife Conservation Commission, Florida Institute of Oceanography, and Intergovernmental Commission of UNESCO.

Mallin, M.A., L.B. Cahoon, B.R. Toothman, D.C. Parsons, M.R. McIver, M.L. Ortwine and R.N. Harrington. 2006. Impacts of a raw sewage spill on water and sediment quality in an urbanized estuary. *Marine Pollution Bulletin* 54:81-88.

Mallin, M.A., V.L. Johnson, S.H. Ensign and T.A. MacPherson. 2006. Factors contributing to hypoxia in rivers, lakes and streams. *Limnology and Oceanography* 51:690-701.

Mallin, M.A., L.B. Cahoon, B.R. Toothman, D.C. Parsons, M.R. McIver, M.L. Ortwine and R.N. Harrington. 2007. Impacts of a raw sewage spill on water and sediment quality in an urbanized estuary. *Marine Pollution Bulletin* 54:81-88.

Cahoon, L.B., M.A. Mallin, B. Toothman, M. Ortwine, R. Harrington, R. Gerhart, S. Gill and J. Knowles. 2007. Is there a relationship between phosphorus and fecal microbes in aquatic sediments? Report No. 366, Water Resources Research Institute of the University of North Carolina.

Dafner, E.V., M.A. Mallin, J.J. Souza, H.A. Wells and D.C. Parsons. 2007. Nitrogen and phosphorus species in the coastal and shelf waters of southeastern North Carolina, Mid-Atlantic U.S. coast. *Marine Chemistry*. 103:289-303.

MacPherson, T.A., M.A. Mallin and L.B. Cahoon. 2007. Biochemical and sediment oxygen demand: patterns of oxygen depletion in tidal creeks. *Hydrobiologia* 586: 235-248.

Tavares, M.E., M.I.H. Spivey, M.R. McIver and M.A. Mallin. 2008. Testing for optical brighteners and fecal bacteria to detect sewage leaks in tidal creeks. *Journal of the North Carolina Academy of Science* 124:91-97.

Mallin, M.A., V.L. Johnson and S.H. Ensign. 2009. Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. *Environmental Monitoring and Assessment* 159:475-491.

Toothman, B.R., L.B. Cahoon and M.A. Mallin. 2009. Phosphorus and carbohydrate limitation of fecal coliform and fecal enterococcus within tidal creek sediments. *Hydrobiologia* 636:401-412.

Duernberger, K., C. Tobias and M.A. Mallin. 2012. Tracing nitrogen transformations through the food chain in an urbanized tidal creek. Report No. 405. Water Resources Research Institute of the University of North Carolina, Raleigh, N.C.

Mallin, M.A., J. McAuliffe, M.R. McIver, D. Mayes and M.R. Hanson. 2012. High pollutant removal efficacy of a large constructed wetland leads to receiving stream improvements. *Journal of Environmental Quality* 41:2046-2055.