ENVIRONMENTAL QUALITY OF WILMINGTON AND NEW HANOVER COUNTY WATERSHEDS, 2020

by

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Executive Summary

This report represents results of Year 23 of the Wilmington Watersheds Project. Water quality data are presented from a watershed perspective, regardless of political boundaries. The 2020 program involved 5 watersheds and 20 sampling stations. In this summary we first present brief water quality overviews for each watershed from data collected between January and December 2020. As part of a change in priorities, sampling at Barnards, Howe, Motts and Whiskey Creek were suspended for the time being to emphasize upper Bradley Creek and the Greenfield Lake watershed, both of which are scheduled for restoration measures.

Barnards Creek – Barnards Creek drains into the Cape Fear River Estuary. It drains a 4,173 acre watershed that consists of 22.3% impervious surface coverage, and a human population of approximately 12,200. Due to Covid-19 and resource re-allocation, sampling was suspended here in 2020.

Bradley Creek – Bradley Creek drains a watershed of 4,583 acres, including much of the UNCW campus, into the Atlantic Intracoastal Waterway (AICW – Plate 1). The watershed contains about 27.8% impervious surface coverage, with a population of about 16,470. A new site, BC-RD, on upper Clear Run at Racine Dr. was added to the three previous sites (BC-CA, Clear Run at College Acres; BC-NB, Bradley Creek north branch at Wrightsville Ave., and BC-SB, Bradley Creek south branch at Wrightsville Ave.). The new site was sampled three times and the old sites six times in 2020.

There were a few incidents of high turbidity and suspended solids in 2020. Dissolved oxygen was stressed (< 5.0 mg/L) on several occasions at the two upper sites BC-RD and BC-CA. Ammonium and nitrate concentrations were low to moderate while nitrate and orthophosphate concentrations were low on almost all sampling occasions. Our Bradley Creek stations did not host significant algal blooms during the 2020 sampling trips. Fecal coliform bacteria counts were excessive at all four sites but particularly so at BC-RD and BC-CA, which had geometric mean counts of 4,061 and 1,242 CFU/100 mL, compared with the NC standard for safe waters of 200 CFU/100 mL.

Burnt Mill Creek – Burnt Mill Creek drains a 4,207 acre watershed with a population of about 23,700. Its watershed is extensively urbanized (39.8% impervious surface coverage) and drains into Smith Creek. Three locations were sampled during 2020, on seven occasions. Dissolved oxygen concentrations were Good in the two upper stations and Fair in the remaining lower creek site. High fecal coliform counts occurred at two sites in 2020, especially at the uppermost site BMC-AP1 above Anne McCrary Pond, the regional wet detention pond on Randall Parkway, and at the lowermost station BMC-PP at Princess Place. We note that fecal coliform counts and nitrate-N concentrations significantly declined during passage through the detention pond. Major algal blooms were not seen in 2020, though a few minor ones occurred. Several water quality parameters showed an increase in pollutant levels along the creek from the exit from the detention pond to the downstream Princess Place sampling station, including fecal coliform bacteria, nitrogen and phosphorus, indicating non-point pollution sources continue to pollute the lower creek.

Futch Creek – Futch Creek is situated on the New Hanover-Pender County line and drains a 3,813 acre watershed (12.3% impervious coverage) into the ICW. UNC Wilmington was not funded to sample this creek in 2020. New Hanover County employed a consulting firm to sample this creek and data may be requested from the County.

Greenfield Lake – This lake drains a watershed of 2,465 acres, covered by about 37% impervious surface area with a population of about 10,630. This urban lake has suffered from low dissolved oxygen, algal blooms, periodic fish kills and high fecal bacteria counts over the years. The lake was sampled at four tributary sites and three in-lake sites on 11 occasions. Of the tributaries of Greenfield Lake, Squash Branch (near Lake Branch Drive), Jumping Run Branch at 17th Street, Jumping Run Branch at Lakeshore Dr., and Clay Bottom Branch (near Lakeshore Commons Apartments), three suffered from low dissolved oxygen problems, although main lake stations maintained good oxygen concentrations.

Algal blooms are chronically problematic in Greenfield Lake, and have occurred during all seasons, but are primarily a problem in spring and summer. In 2020 a massive spring-summer blue-green algal bloom of *Anabaena* occurred. Previously-published studies found a statistically significant relationship within the lake between chlorophyll *a* and five-day biochemical oxygen demand (BOD5) meaning that the algal blooms are an important cause of low dissolved oxygen, and high BOD occurred congruent with the blooms in 2020. In 2020 all four tributary stations exceeded the fecal coliform State standard on >35% of occasions sampled and rated Poor, but the in-lake stations were in Good to Fair condition for fecal bacteria.

Greenfield Lake is currently on the NC 303(d) list for impaired waters due to excessive algal blooms. The thesis work of UNCW graduate student Nick Iraola assessed the five main inflowing tributaries to the lake to demonstrate that the largest inorganic nutrient loads came in from Jumping Run Branch and Squash Branch. We are pleased to say that a coalition of stakeholders (the City, Cape Fear River Watch, UNCW, NCSU and the engineering firm Moffat & Nichol) have been awarded funds for 2020-2022 and UNCW has begun sampling in support of future nutrient reduction efforts on Jumping Run Branch. Early data show the Willard Street Wetland, between Willard St., 15th St. and 16th St. receives high nutrient and very high fecal coliform loads from inflowing drains, and elevated concentrations of those pollutants make it out of the wetland into Jumping Run Branch. Thus, the engineering team is currently devising strategies to restore the wetland to reduce the pollutant load. An analysis of sediment phosphorus loads found elevated concentrations in Jumping Run Branch, suggesting upstream sources.

Hewletts Creek – Hewletts Creek drains a large (7,478 acre) watershed into the Atlantic Intracoastal Waterway. This watershed has about 25.1% impervious surface coverage with a population of about 20,210. In 2020 the creek was sampled at four tidal sites on six occasions and one non-tidal freshwater site (PV-GC-9) on three occasions.

Incidents of low dissolved oxygen did not occur at Hewletts Creek in 2020. Turbidity was low and did not exceed the state standard, and no algal blooms occurred. Fecal coliform bacteria counts were elevated sufficiently at all sites for a Poor rating, but only the geometric mean at NB-GLR exceeded 200 CFU/100 mL; and the geometric mean of fecal bacteria counts at HC-3 was over the state shellfishing standard.

Howe Creek – Howe Creek drains a 3,516 acre watershed into the ICW. This watershed hosts a population of approximately 6,460 with about 21.4% impervious surface coverage. Due to Covid-19 and resource re-allocation, sampling was suspended here in 2020.

Motts Creek – Motts Creek drains a watershed of 3,342 acres into the Cape Fear River Estuary with a population of about 9,530; impervious surface coverage 23.4%. Due to Covid-19 and resource re-allocation, sampling was suspended here in 2020.

Pages Creek – Pages Creek drains a 5,025 acre watershed with 17.8% impervious surface coverage into the ICW. UNC Wilmington was not funded to sample this creek from 2008-2020. New Hanover County employed a private firm to sample this creek and data may be requested from the County.

Smith Creek – Smith Creek drains into the lower Northeast Cape Fear River just upstream of where it merges with the Cape Fear River (Plate 1). It has a watershed of 16,650 acres that has about 21.3% 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).

The dissolved oxygen standard for Smith Creek, which is rated as C Sw waters, is 4.0 mg/L, which was violated on only one of 12 occasions in our 2020 samples for a Good rating. The North Carolina turbidity standard for estuarine waters (25 NTU) was not exceeded. There were no major algal blooms present in our 2020 sampling. Fecal coliform bacterial concentrations exceeded 200 CFU/100 mL on only one of 12 sampling occasions in 2020 for a Good rating.

Whiskey Creek – Whiskey Creek is the southernmost large tidal creek in New Hanover County that drains into the AICW (Plate 1). It has a watershed of 2,078 acres, a population of about 8,000, and is covered by approximately 25.1% impervious surface area. Due to Covid-19 and resource re-allocation, sampling was suspended here in 2020.

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 (see Appendix A) 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 2020 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 (20 sites sampled for fecal coliforms) showed 15% to be in Good condition, 10% in Fair condition but 75**%** in Poor condition, a deterioration over the previous year. Dissolved oxygen conditions (measured at the surface) system-wide (20 sites) showed 60% of the sites were in Good condition, 15% were in Fair condition, and 25% were in Poor condition. For algal bloom presence, measured as chlorophyll *a*, 80% of the 20 stations sampled were rated as Good, 10% as Fair and 10% as Poor. For turbidity, 85% of sites were Good, 10% Fair, and only 5% Poor. It is important to note that the 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 – 39% impervious coverage; Greenfield Lake – 37% impervious coverage; Bradley Creek – 28% impervious coverage.

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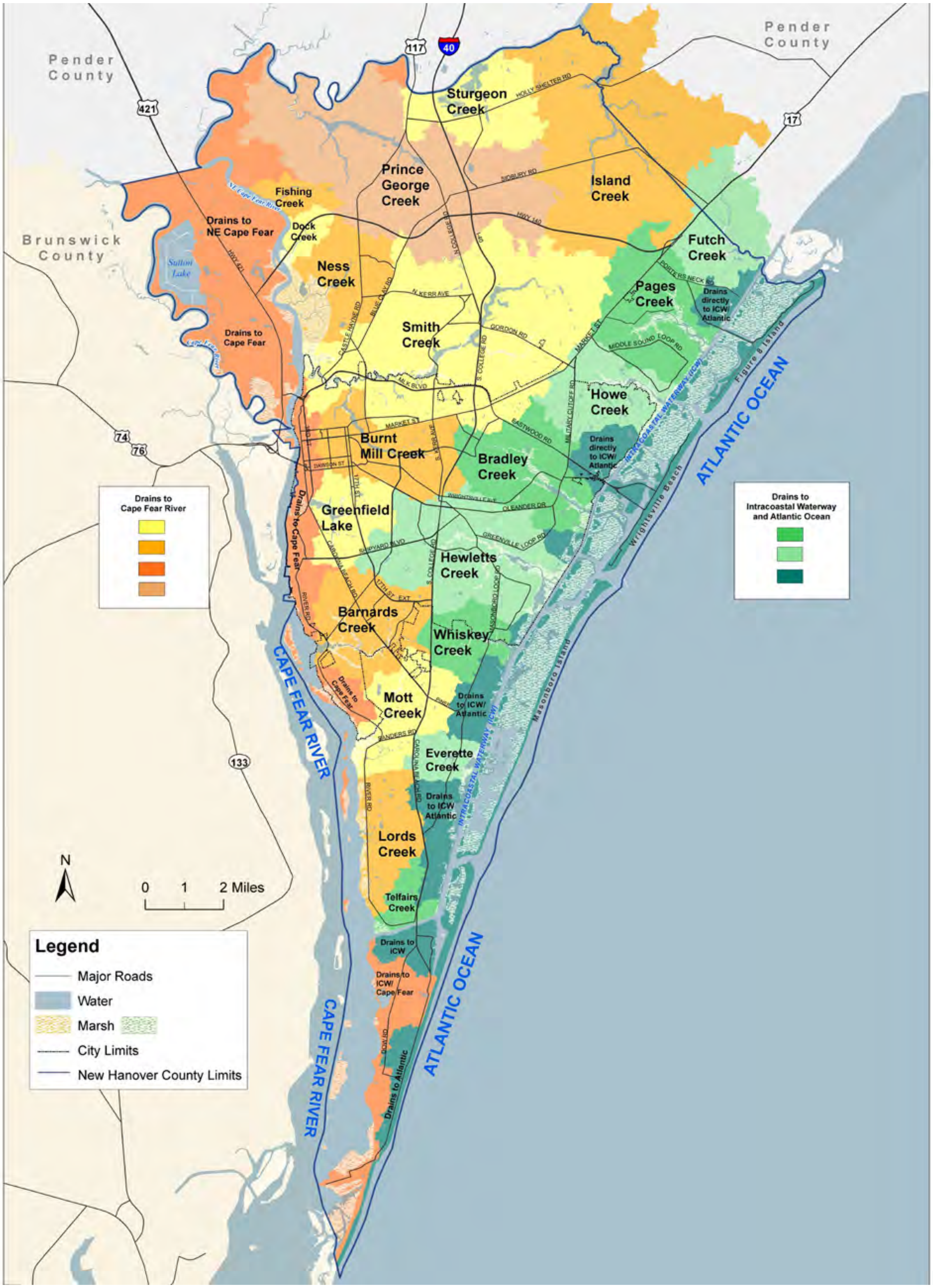


Plate 1. Wilmington and New Hanover County watersheds 2014 map by Wilmington Stormwater Services. Station coordinates are in Appendix C.

1.0 Introduction

In 1993 scientists from the Aquatic Ecology Laboratory 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. 1998). Data from that report were later published in the peer-reviewed literature (Mallin et al. 2000; Mallin et al. 2001) and were used in 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 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. Also, certain sites were analyzed for sediment heavy metals concentrations (EPA Priority Pollutants). In the past 23 years we produced several combined Tidal Creeks – Wilmington City Watersheds reports (see Appendix E). 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 (see Appendix E). In the present report we present results of sampling conducted during 2020, with current funding by the City of Wilmington, the U.S. fish & Wildlife Service and the NCDEQ 319 Program. In early 2020 the advent of Covid-19 suppressed sampling, and as part of a change in priorities, sampling at Barnards, Howe, Motts and Whiskey Creek were suspended to emphasize upper Bradley Creek and the Greenfield Lake watershed, both of which are scheduled for restoration measures.

Water quality parameters analyzed in the 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. From 2010-2013 a suite of metals, PAHs and PCBs were assessed in the sediments of the creeks and Greenfield Lake. The 2014 report presented summary material regarding that study.

From 2010-2014 Wilmington Stormwater Services collaborated with UNCW to investigate potential sewage spills and leaks and illicit sanitary connections potentially polluting city waterways; the results of those sample collections have been provided in various reports.

1.1 Water Quality Methods

Samples were collected on five to eleven occasions at 19 locations within the Wilmington City watersheds between January and December 2020. In addition, one station on Smith Creek was also sampled during 12 months as part of the Lower Cape Fear River Program and reported here as well. Field parameters were measured at each site using a YSI EXO 3 Multiparameter Water Quality sonde linked to a YSI EXO display unit. Individual probes within the instrument measured water temperature, pH, dissolved oxygen, turbidity, salinity, and conductivity. The YSI EXO 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). Samples were collected on-site for State-certified 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* is based on Welschmeyer (1994) and Method 445.0 from US EPA (1997). 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, orthophosphate, total phosphorus) and total suspended solids (TSS) were analyzed by a state-certified 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).

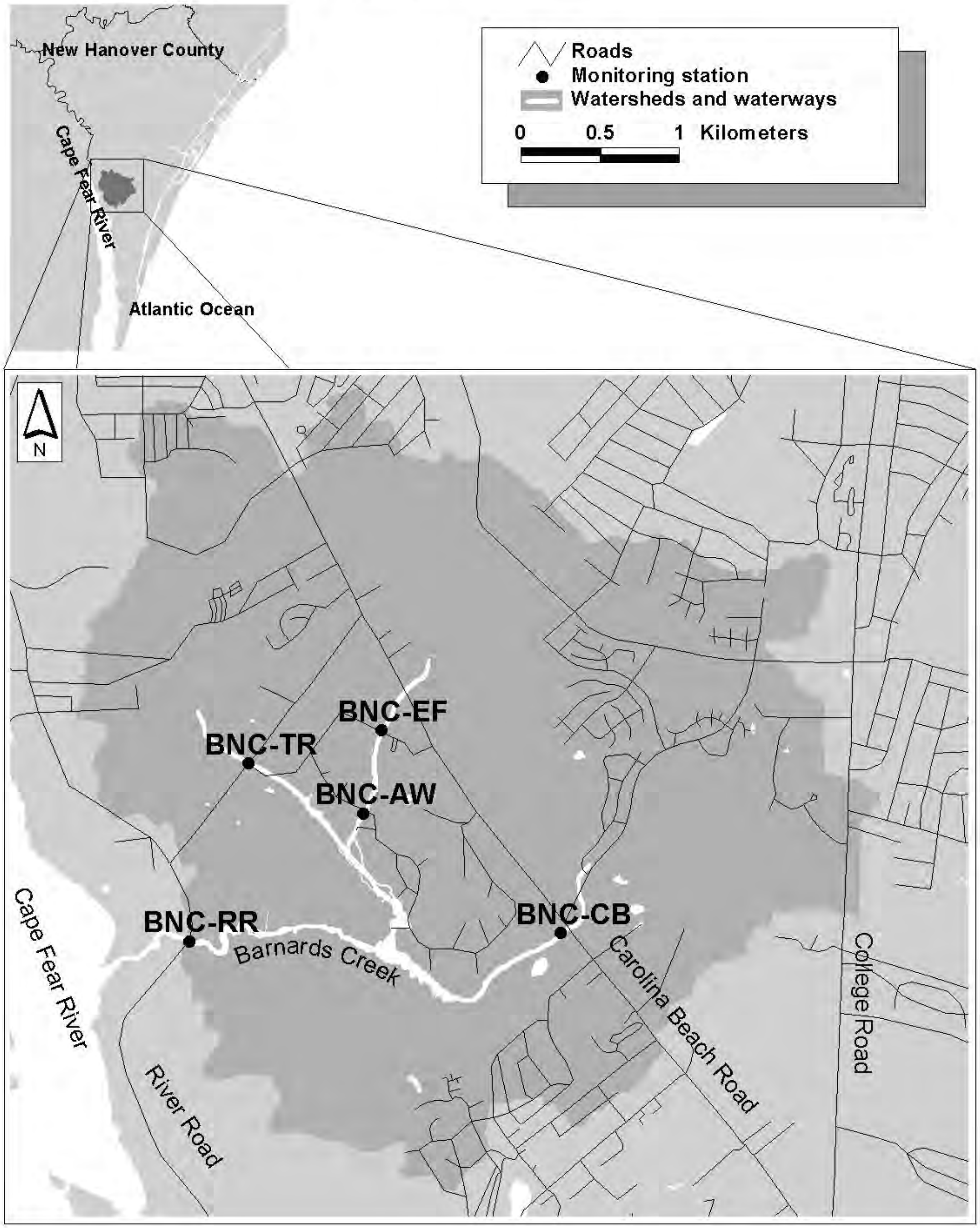
For a large wet detention pond (Ann McCrary Pond on Burnt Mill Creek) we collected data from input and outfall stations. We used these data to test for statistically significant differences in pollutant concentrations between pond input and output stations. The data were first tested for normality using 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).

2.0 Barnards Creek

Snapshot
Watershed area: 4,161 acres (1,690 ha)
Impervious surface coverage: 22.3%
Watershed population: Approximately 12,200
Overall water quality: Algal blooms, and minor fecal coliform problems

Lower Barnard's Creek drains single family and multifamily housing 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 well under construction between Barnards and Motts Creeks. This site was not sampled for several years due to lack of funding. However, renewed funding allowed UNCW to re-initiate sampling of Barnards Creek at River Road (BNC-RR) in 2018-2019. In 2020 sampling of this creek was suspended due to Covid-19 and resource re-allotment.

Figure 2.1 Barnards Creek watershed



3.0 Bradley Creek

Snapshot
Watershed area: 4,583 acres (1,856 ha)
Impervious surface coverage: 27.8% (2014 data)
Watershed population: Approximately 16,470
Overall water quality: fair-poor
Problematic pollutants: high fecal bacteria, occasional low dissolved oxygen

The Bradley Creek watershed was previously a principal location for Clean Water Trust Fund mitigation activities, including the purchase and renovation of Airlie Gardens by the County. There has been redevelopment of the former Duck Haven property bordering Eastwood Road and development across Eastwood Road; which drains to the creek. This creek has been one of the most polluted in New Hanover County, particularly by fecal coliform bacteria (Mallin et al. 2000) and has suffered from sewage leaks (Tavares et al. 2008) and stormwater runoff. Three upstream stations (BC-SB, BC-NB and BC-CA) have been sampled in previous years, both fresh and brackish (Fig. 3.1), and a new site, BC-RD on Racine Drive (see cover photo) was added in July as stream restoration activities are planned for this upper branch (also called Clear Run) and more background data are needed. Thus, there were six samples collected at most sites, and three collected at BC-RD. BC-RD is approximately 90% impervious surface coverage.

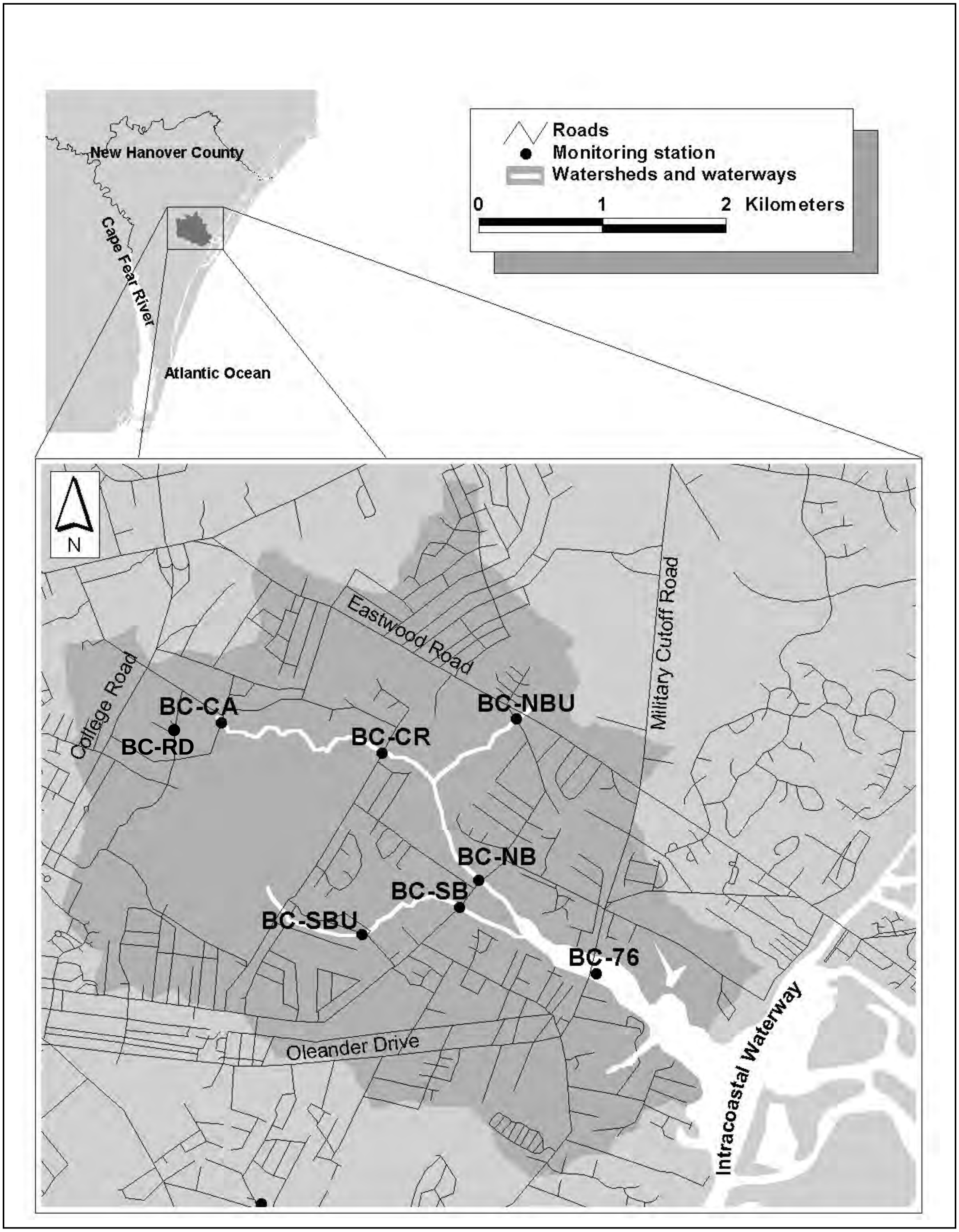
Turbidity was not a problem during 2020; the standard of 25 NTU was exceeded on one occasion each at BC-RD, BC-CA and BC-SB (Table 3.1). There are no NC ambient standards for total suspended solids (TSS), but UNCW considers 25 mg/L high for the Coastal Plain. As such, TSS exceeded that number twice at BC-SB and once each at the other three stations. Dissolved oxygen was below standard (< 5.0 mg/L) on 67% of the time at BC-RD and 50% of the time at BC-CA, and once each at the other two sites.

Ammonium and nitrate concentrations were low to moderate at all sites (Table 3.1). Nitrate and orthophosphate concentrations were low in general at all the sites. Our Bradley Creek stations did not host algal blooms during the sampling trips in 2020. Median nitrogen to phosphorus ratios at BC-NB and BC-SB were low to moderate (9-19) indicating that inputs of inorganic nitrogen are likely to stimulate algal blooms in the lower creek. Fecal coliform bacteria counts were excessive at all four sites (Table 3.1). However, counts were especially high at BC-RD and BC-CA, with geometric means of 4,061 and 1,242 CFU/100 mL, respectively, and maxima of 30,000 CFU/100 mL at both sites (Table 3.1) compared with the NC standard of 200 CFU/100 mL for freshwater safety. Note that upper Clear Run receives considerable drainage from across College Road (Fig. 3.1) where there are large parking lots and high impervious surface coverage. There is also a considerable amount of dog feces lying on the ground near BC-RD between the nearest apartment parking lot and the creek.

Table 3.1. Water quality parameter concentrations at Bradley Creek sampling stations, 2020. Data as mean (SD) / range, N/P ratio as mean/median, fecal coliform bacteria as geometric mean / range, n = 6 samples collected (except for 3 at BC-RD).

Station	BC-RD	BC-CA	BC-NB	BC-SB
Salinity (ppt)	0.1 (0.0) 0.1-0.1	0.1 (0.0) 0.1-0.1	11.9 (14.5) 0.0-32.9	10.3 (12.2) 0.1-30.0
DO (mg/L)	7.8 (2.3) 3.4-7.4	5.2 (2.2) 2.8-8.3	8.1 (2.7) 3.7-11.4	6.8 (1.7) 3.9-8.4
Turbidity (NTU)	41 (54) 2-79	17 (37) 2-92	8 (6) 3-20	17 (27) 2-71
TSS (mg/L)	31.1 (48.9) 1.3-87.5	14.5 (31.4) 1.3-78.5	16.0 (12.8) 7.7-41.5	19.0 (14.9) 7.0-46.5
Nitrate (mg/L)	0.06 (0.06) 0.1-0.13	0.08 (0.07) 0.01-0.19	0.04 (0.04) 0.01-0.10	0.03 (0.02) 0.01-0.07
Ammonium (mg/L)	0.21 (0.16) 0.10-0.39	0.12 (0.09) 0.04-0.27	0.12 (0.10) 0.01-0.22	0.14 (0.19) 0.01-0.45
TN (mg/L)	0.72 (0.18) 0.51-0.83	0.82 (0.18) 0.53-1.01	0.63 (0.27) 0.36-1.10	0.67 (0.27) 0.51-0.83
Orthophosphate (mg/L)	0.02 (0.01) 0.01-0.02	0.02 (0.01) 0.01-0.02	0.02 (0.01) 0.01-0.02	0.05 (0.07) 0.01-0.18
TP (mg/L)	0.13 (0.15) 0.04-0.30	0.12 (0.16) 0.02-0.43	0.09 (0.14) 0.01-0.37	0.16 (0.20) 0.02-0.54
N/P	26.6 29.9	24.0 23.3	27.9 18.8	24.3 8.9
Chlorophyll *a* (µg/L)	4 (3) 2-8	3 (2) 1-6	6 (6) 1-13	3 (2) 2-6
Fecal coliforms (CFU/100 mL)	4,061 235-30,000	1,242 228-30,000	152 10-1,300	206 28-1,950

Figure 3.1. Bradley Creek watershed and sampling sites.



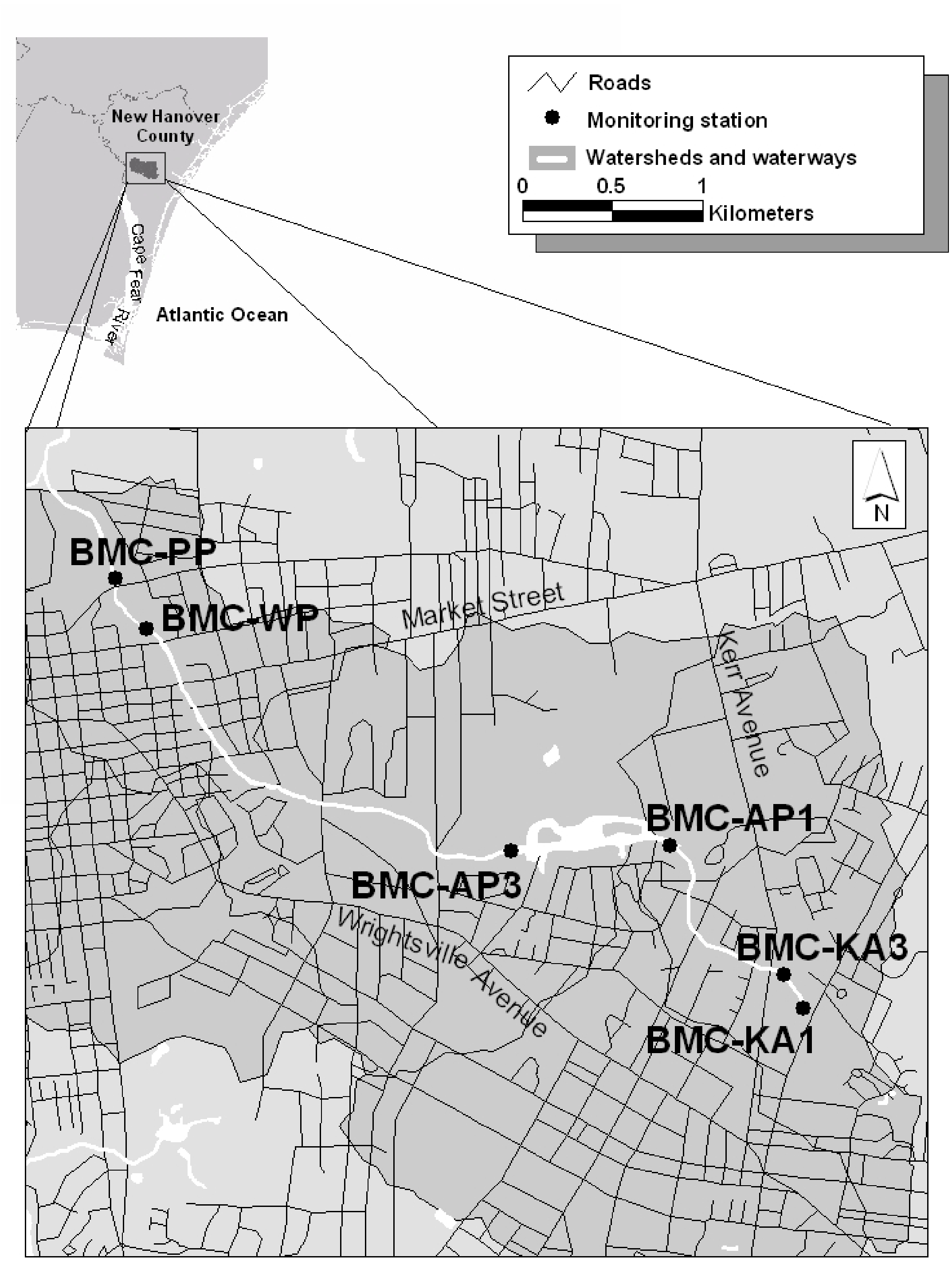
4.0 Burnt Mill Creek

Snapshot
Watershed area: 4,207 acres (1,703 ha)
Impervious surface coverage: 39.3%
Watershed population: Approximately 23,700
Overall water quality: poor
Problematic pollutants: Fecal bacteria, periodic algal blooms, some low dissolved oxygen issues, contaminated sediments (PAHs, Hg, Pb, Zn, TN, and TP)

Burnt Mill Creek is an urban creek flowing entirely through the City of Wilmington. Its high impervious surface coverage (about 39%) puts it at risk for excessive pollutant loads. A prominent feature in the Burnt Mill Creek watershed (Fig. 4.1) is the Ann McCrary Pond on Randall Parkway, 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 growths of submersed aquatic vegetation, with *Hydrilla verticillata, Egeria densa, Alternanthera philoxeroides, Ceratophyllum demersum* and *Valliseneria americana* having been common at times (some of these taxa are invasive). 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. 2002). Numerous waterfowl utilize this pond as well. Burnt Mill Creek has been studied by a number of researchers, and 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. 2010; 2011). This creek is currently on the NC 303(d) list for impaired waters, for an impaired benthic community. Sediment toxicant analysis (summarized in Mallin et al. 2015) found elevated concentrations of polycyclic aromatic hydrocarbons (PAHs), mercury, lead and zinc at several locations in this creek.

<u>Sampling Sites</u>: During 2020 samples were collected on seven occasions from three stations on the creek (Fig. 4.1). The upper creek was sampled just upstream (BMC-AP1) and about 40 m downstream (BMC-AP3) of Ann McCrary 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.



<u>The Upper Creek</u>

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 seven occasions in 2020. Dissolved oxygen concentrations were within standard on all sampling occasions at BMC-AP1 and BMC-AP3. Both DO and pH showed a significant ($p < 0.01$) increase between the pond inflow and the outflow (Table 4.1). The NC standard for turbidity in freshwater is 50 NTU; there were no exceedences of this value during our 2020 sampling, and on average there was no significant change through the pond. Total suspended solids concentrations were relatively low on all sampling occasions in 2020, and there was no significant change through the pond on average (Table 4.1). Fecal coliform concentrations entering Ann McCrary Pond at BMC-AP1 were moderate, exceeding the state standard 43% of the time sampled (Table 4.1). The three high counts were 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). There was a significant ($p < 0.05$) reduction in fecal coliform counts during passage through the regional detention pond (Table 4.1). There were three minor algal blooms at BMC-AP3, ranging from 20-22 µg/L, and chlorophyll *a* exiting the pond was significantly higher than entering the pond ($p < 0.05$). There were no statistically-significant changes in most nutrient concentrations between entering and exiting the pond, although nitrate-N did show a significant decrease through the pond (Table 4.1).

<u>Lower Burnt Mill Creek</u>: The Princess Place location (BMC-PP) was the only lower creek station sampled in 2020. One parameter that is key to aquatic life health is dissolved oxygen. Dissolved oxygen at BMC-PP was substandard (< 4.0 mg/L) on two of seven sampling occasions. Turbidity concentrations at BMC-PP did not exceed the State standard on any of our sampling occasions and total suspended solids (TSS) were low.

In 2020 there were no major algal blooms at our Burnt Mill Creek stations, just the minor ones at AP-3, mentioned above. The North Carolina water quality standard for chlorophyll *a* is 40 µg/L. Algal blooms can cause disruptions in the food web, depending upon the species present (Burkholder 2001), and decomposing blooms can contribute to low dissolved oxygen (Mallin et al. 2006).

It is important to determine what drives algal bloom formation in Burnt Mill Creek. Nitrate and orthophosphate concentrations were somewhat elevated at BMC-PP, relative to BMC-AP-3. Examination of inorganic nitrogen to phosphorus ratios (Table 4.1) shows that mean and median N/P ratios at AP-3, just below the pond outfall was <13. However, both AP-1 and BMP-PP had ratios considerably higher. 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, inputs of either N or P could drive an algal bloom.

Important from a public health perspective are fecal coliform bacteria counts. None of the three stations had geometric means exceeding the State standard for human contact waters (200 CFU/100 mL) in our 2020 samples. Fecal coliform counts were greater than the State standard on 43% of sampling occasions at BMC-PP, and 43% at BMC-AP1. Whereas geometric mean fecal coliform counts at BMC-AP3 were 20 CFU/100 mL, counts then increased along the passage to the Princess Place location (geometric mean 123 CFU/100 mL; Fig. 4.2), as in previous years. It is likewise notable that nitrate and total phosphorus concentrations increased from the outflow from Ann McCrary Pond downstream to the lower main stem station (Table 4.1; Fig. 4.3). Clearly, there are inputs of pollutants to this creek as it passes from the large detention pond to its lower reaches.

Figure 4.2. Fecal coliform bacteria geometric means for Burnt Mill Creek, 2020

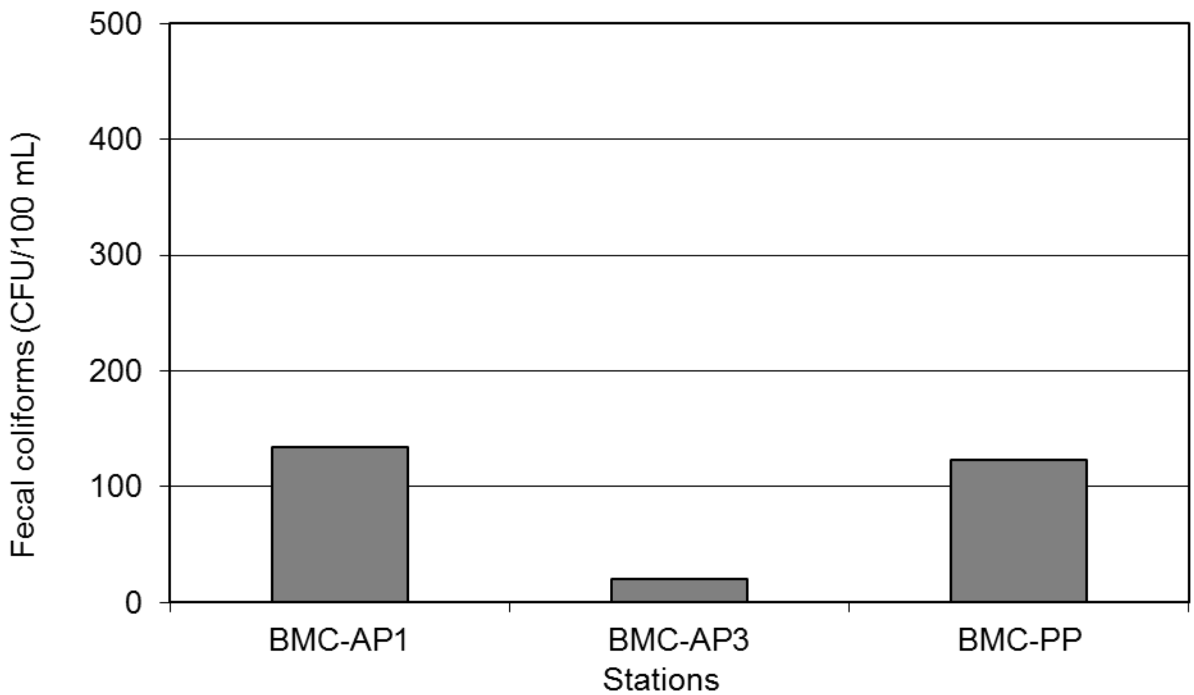


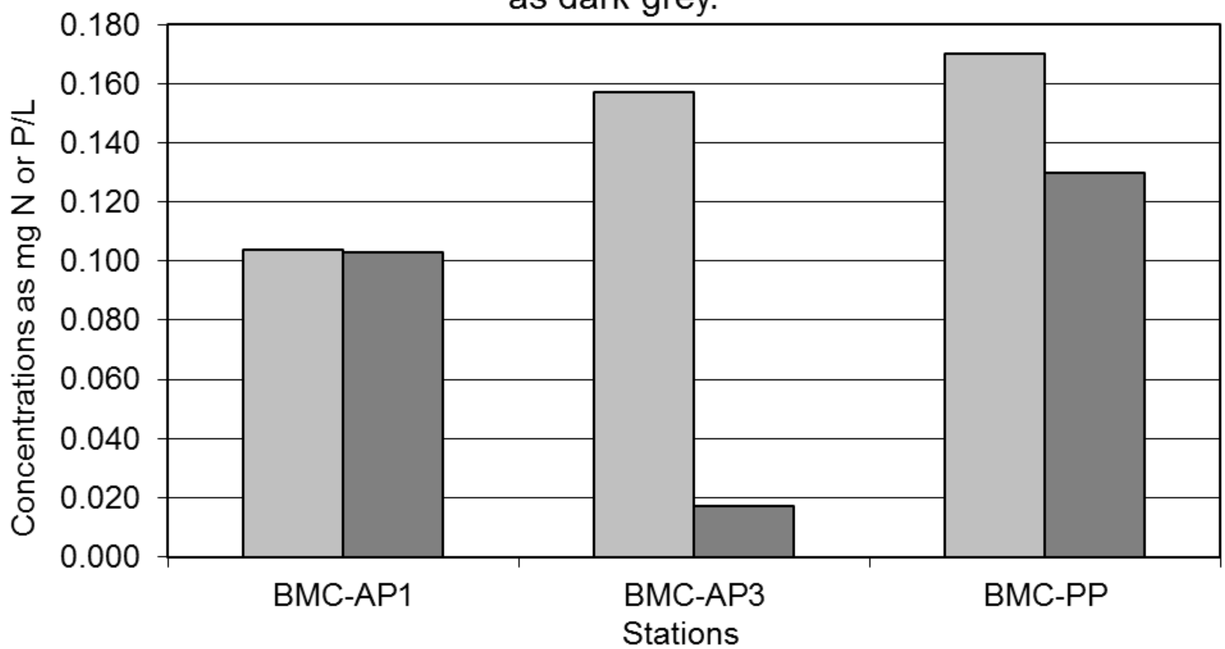
Table 4.1. Water quality data in Burnt Mill Creek, 2020, as mean (standard deviation)/range. Fecal coliforms as geometric mean; N/P as mean/median, n = 7 samples collected.

Parameter	BMC-AP1	BMC-AP3	BMC-PP
DO (mg/L)	7.2 (1.1) 5.7-9.1	9.9 (1.3)** 8.5-12.0	5.7 (1.9) 3.3-7.9
Cond. (µS/cm)	254 (28) 196-227	223 (26) 191-255	316 (32) 254-358
pH	6.9 (0.2) 6.7-7.2	7.7 (0.2)** 7.4-8.0	7.4 (0.3) 7.2-8.0
Turbidity (NTU)	2 (1) 2-4	4 (1) 2-6	2 (1) 2-3
TSS (mg/L)	4.4 (4.5) 1.3-11.9	6.2 (2.3) 4.0-10.8	3.1 (0.8) 1.3-3.9
Nitrate (mg/L)	0.103 (0.087) 0.010-0.220	0.017 (0.013)* 0.010-0.040	0.130 (0.093) 0.010-0.250
Ammonium (mg/L)	0.124 (0.137) 0.040-0.430	0.059 (0.051) 0.010-0.140	0.074 (0.073) 0.010-0.230
TN (mg/L)	0.539 (0.198) 0.210-0.760	0.559 (0.238) 0.200-0.930	1.060 (1.267) 0.120-3.860
OrthoPhos. (mg/L)	0.016 (0.005) 0.010-0.020	0.020 (0.017) 0.010-0.050	0.019 (0.009) 0.010-0.030
TP (mg/L)	0.104 (0.070) 0.010-0.210	0.157 (0124) 0.030-0.340	0.170 (0.144) 0.030-0.430
N/P molar ratio	36.1 37.6	12.7 8.3	28.9 22.1
Chlor. *a* (µg/L)	3 (2) 1-7	15 (8)* 1-22	5 (4) 1-10
FC (CFU/100 mL)	134 19-455	20* 10-82	123 10-300

* Statistically significant difference between inflow (AP1) and outflow (AP3) at $p<0.05$; ** $p < 0.01$.

To summarize, in some years including 2020, Burnt Mill Creek has had problems with low dissolved oxygen (hypoxia) at the Princess Place station BMC-PP. Algal blooms did not occur in 2020 at BMC-PP, contrary to previous years. The N/P ratios in the lower creek indicate that inputs of phosphorus were likely to stimulate algal bloom formation in 2020, but such ratios have differed in previous years. It is notable that nutrient concentrations increased from the outfall of the regional Ann McCrary wet detention pond as one moves downstream toward the lower creek (Fig. 4.3). An important human health issue is the periodic high fecal bacteria counts found at two of the three sampling stations. BMC-AP3, below the detention pond was the exception. 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 previously demonstrated for this creek (Mallin et al. 2009b), indicating as stormwater runoff pollution problem. As this is one of the most heavily developed creeks in the Wilmington area, it also remains one of the most polluted.

Figure 4.3. Average TP and nitrate concentrations by station for Burnt Mill Creek, 2020; TP as light grey, nitrate as dark grey.

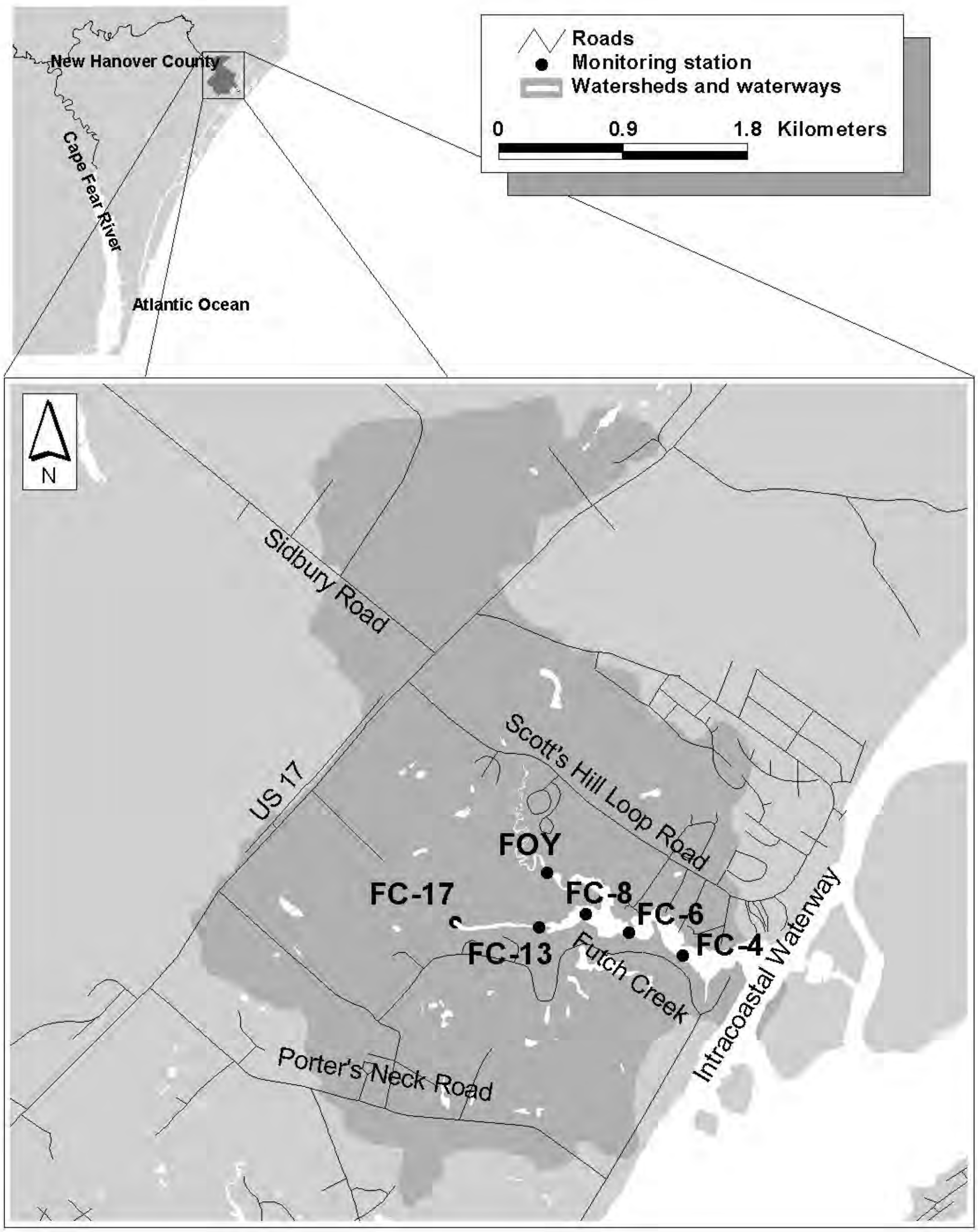


5.0 Futch Creek

Snapshot
Watershed area: 3,813 acres (1,544 ha)
Impervious surface coverage: 12.3%
Watershed population: 4,620

Six stations were sampled by the University of North Carolina Wilmington's Aquatic Ecology Laboratory in Futch Creek from 1993 through 2007. UNCW was not funded by the County to sample Futch Creek following 2007. We present the above information and map below purely for informational purposes. Water quality information for the creek can be obtained from the County.

Figure 5.1. Futch Creek watershed and sampling sites.



6.0 Greenfield Lake Water Quality

Snapshot
Watershed area: 2,551 acres (1,033 ha)
Impervious surface coverage: 37% (2013 data)
Watershed population: 10,630
Overall water quality: Poor
Problematic pollutants: High fecal bacteria and low dissolved oxygen in tributaries, high BOD and algal blooms in main lake, sediments contaminated with metals and PAHs

Four stations on tributaries to Greenfield Lake were sampled for a full suite of physical, chemical and biological parameters on 11 occasions in 2020 (Table 6.1, Fig. 6.1). Some tributary stream sites suffered from low dissolved oxygen (DO), as GL-LB (creek at Lake Branch Drive, called Squash Branch, Station GL-SQB) showed DO concentrations below the state standard (DO < 5.0 mg/L) on 73% of sampling occasions and GL-LC was below standard 50% of the time (Table 6.1; Appendix B). Station GL-JRB (Jumping Run Branch) had substandard DO on two sampling occasions. Turbidity concentrations were generally low in the tributary stations, with no violations of the freshwater standard of 50 NTU (Table 6.1). Suspended solids were elevated in JRB-17 in August (Table 6.1).

Nitrate, ammonium and TN concentrations were highest at GL-JRB and JRB-17, with GL-SQB nearly as high (Table 6.1). Highest phosphorus concentrations occurred at GL-SQB, followed by GL-JRB. We note that both JRB-17 and GL-JRB are downstream of a golf course, which covers 22% of the Jumping Run Branch watershed surface area. Chlorophyll *a* concentrations were high in June at GL-LC, with a bloom exceeding 65 µg/L in June from a large spring-summer algal bloom of the nitrogen-fixing cyanobacterium (blue-green alga) *Anabaena*; chlorophyll *a* concentrations were also very high at GL-SQB in August with a concentration of 170 µg/L. The geometric mean fecal coliform bacteria counts exceeded the state standard at three of the four tributary stations (Table 6.1). The fecal coliform standard was exceeded on eight dates at GL-SQB, four dates at JRB-17, three sampling dates at GL-JRB, and on three dates at GL-LC. August was a particularly bad month for fecal coliforms as Hurricane Isaias occurred the week before sampling, but many of the other non-hurricane months showed high fecal bacteria counts too.

Table 6.1. Mean and (standard deviation) / range of selected field water quality parameters in tributary stations of Greenfield Lake, 2020. Fecal coliforms (FC) given as geometric mean, N/P ratio as mean / median; n = 11 samples collected except for GL-LC (6 samples collected).

Parameter	JRB-17	GL-JRB	GL-LB (SQB)	GL-LC (CBB)
DO (mg/L)	7.1 (1.4) 5.3-10.2	6.2 (1.8) 2.6-9.5	4.1 (1.6) 1.9-6.8	5.1 (1.4) 3.4-6.9
Turbidity (NTU)	4 (3) 2-11	3 (2) 1-9	3 (2) 1.8	2 (1) 1-3
TSS (mg/L)	5.3 (5.1) 1.3-20.0	2.7 (2.5) 1.3-9.3	2.9 (3.4) 1.3-12.9	4.7 (3.4) 1.3-9.5
Nitrate (mg/L)	0.13 (0.10) 0.01-0.26	0.14 (0.12) 0.01-0.32	0.18 (0.18) 0.01-0.44	0.10 (0.07) 0.01-0.19
Ammon. (mg/L)	0.10 (0.05) 0.03-0.16	0.06 (0.04) 0.01-0.13	0.11 (0.06) 0.01-0.20	0.04 (0.02) 0.01-0.07
TN (mg/L)	0.81 (0.28) 0.46-1.47	0.78 (0.36) 0.27-1.34	0.84 (0.40) 0.30-1.64	0.75 (0.70) 0.20-1.95
Ortho-P. (mg/L)	0.04 (0.02) 0.02-0.09	0.03 (0.03) 0.01-0.10	0.04 (0.02) 0.02-0.08	0.02 (0.01) 0.01-0.04
TP (mg/L)	0.17 (0.17) 0.03-0.63	0.17 (0.13) 0.01-0.38	0.18 (0.16) 0.01-0.59	0.12 (0.09) 0.03-0.24
Inorganic N/P ratio	16.7 15.5	21.4 13.3	16.6 15.5	15.6 10.0
Chlor. *a* (μg/L)	8 (9) 1-24	6 (5) 1-18	17 (51) 0-170	14 (25) 2-65
FC (CFU/100 mL)	218 28-4,500	164 23-1,050	420 125-1,650	254 73-1,300

Three in-lake stations were sampled (Figure 6.1). Station GL-2340 represents an area receiving an influx of urban/suburban runoff (but buffered by wetlands), GL-YD is downstream and receives some outside impacts, and GL-P is at the Greenfield Lake Park boathouse, away from inflowing streams but in a high-use waterfowl area (Fig. 6.1). Low dissolved oxygen was not a problem in-lake in 2020 (see also Section 6.1). Turbidity was at or below the state standard on all sampling occasions. There was a peak in suspended solids in September of 70 mg/L, concurrent with the onset of a blue-green algae (i.e. cyanobacterial) bloom of *Anabaena* (see below). In-lake fecal coliform concentrations exceeded the standard twice each at GL2340 and GL-YD, one of those months was August, following the Hurricane Isaias passage.

Concentrations of all inorganic nutrients in-lake were generally low but highest at the upstream station GL-2340 (Table 6.2). Total N was highest at GL-2340, likely reflecting biomass from the spring-summer cyanobacterial bloom. Total phosphorus (TP) and orthophosphate concentrations were highest at GL-2340, concurrent with summer algal blooms (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 mean and median N/P ratios in the lake (Table 6.2), phytoplankton growth in Greenfield Lake can be readily stimulated by nitrogen (i.e. inputs of nitrogen can cause algal blooms. Our previous bioassay experiments indicated that nitrogen was usually the stimulatory nutrient in this lake (Mallin et al. 1999; 2016).

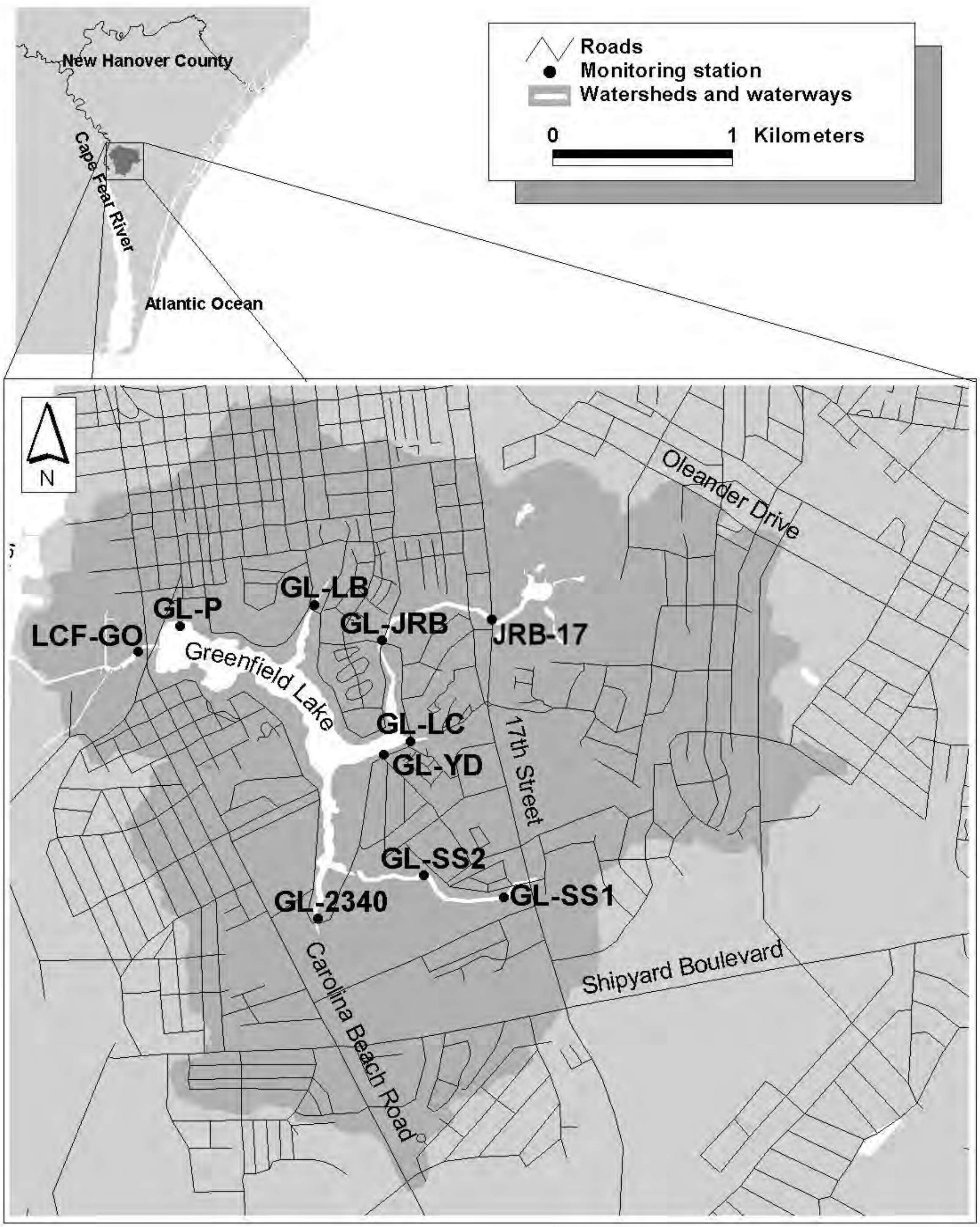
Phytoplankton blooms are problematic in Greenfield Lake (Table 6.2), and usually consist of green or blue-green algal species, or both together. These blooms have occurred during all seasons, but are primarily a problem in spring and summer. In 2020 an extensive bloom of the blue-green *Anabaena spiroides* began in May and lasted until October. As such, four blooms exceeding the North Carolina water quality standard of 40 µg/L of chlorophyll *a* occurred at GL-YD, three blooms at GL-2340, and two blooms at GL-P with the largest bloom (616 µg/L) occurring at GL-2340 in September. For the past several years chlorophyll *a* has exceeded the state standard >30% of occasions sampled. Based on these data, the North Carolina Division of Environmental Quality placed this lake on the 303(d) list in 2014. Average biochemical oxygen demand (BOD5) for 2020 was elevated, especially at GL-2340 (average = 5.9 mg/L; Table 6.1) with maxima of 24 mg.L in September and 22 mg/L in July. Because phytoplankton (floating microalgae) are easily-decomposed sources of BOD, the blooms in this lake are a periodic driver of low dissolved oxygen; chlorophyll *a* is strongly correlated with BOD in this lake (Mallin et al. 2016).

Based on summary literature values (summarized in Wetzel 2001) the average chlorophyll *a* concentrations within this lake put it in the eutrophic (highly enriched) category for 2020. We also note that previous research (summarized in Mallin et al. 2015) found excessive concentrations of polycyclic aromatic hydrocarbons (PAHs), lead and zinc in the sediments of this lake.

Table 6.2. Mean and (standard deviation) / range of selected field water quality parameters in lacustrine stations of Greenfield Lake, 2020. Fecal coliforms (FC) given as geometric mean, N/P ratio as mean / median; n = 11 samples collected.

Parameter	GL-2340	GL-YD	GL-P
DO (mg/L)	7.0 (3.9) 4.3-17.5	8.3 (1.6) 5.7-10.4	9.3 (2.1) 6.1-12.8
Turbidity (NTU)	4 (7) 0-28	3 (1) 1-5	3 (3) 0-9
TSS (mg/L)	10.5 (20.1) 1.3-70.0	5.1 (4.5) 1.3-13.0	4.7 (3.0) 1.4-9.8
Nitrate (mg/L)	0.07 (0.08) 0.01-0.22	0.01 (0.01) 0.01-0.04	0.01 (0.01) 0.01-0.05
Ammonium (mg/L)	0.04 (0.03) 0.01-0.08	0.04 (0.07) 0.01-0.23	0.05 (0.10) 0.01-0.31
TN (mg/L)	1.32 (1.73) 0.31-5.17	0.65 (0.34) 0.20-1.14	0.70 (0.42) 0.10-1.35
Orthophosphate (mg/L)	0.02 (0.01) 0.01-0.04	0.01 (0.01) 0.01-0.03	0.02 (0.01) 0.01-0.04
TP (mg/L)	0.24 (0.21) 0.01-0.62	0.16 (0.15) 0.01-0.56	0.18 (0.15) 0.01-0.54
N/P molar ratio	12.5 10.0	10.3 4.4	10.1 4.4
Fec. col. (CFU/100 mL)	89 5-2,150	27 5-273	30 5-864
Chlor. *a* (μg/L)	85 (185) 0-616	45 (53) 1-168	25 (27) 2-76
BOD5	5.9 (8.5) 1.0-24.0	3.9 (2.7) 1.0-9.0	4.2 (2.5) 2.0-9.0

Figure 6.1. Greenfield Lake watershed.

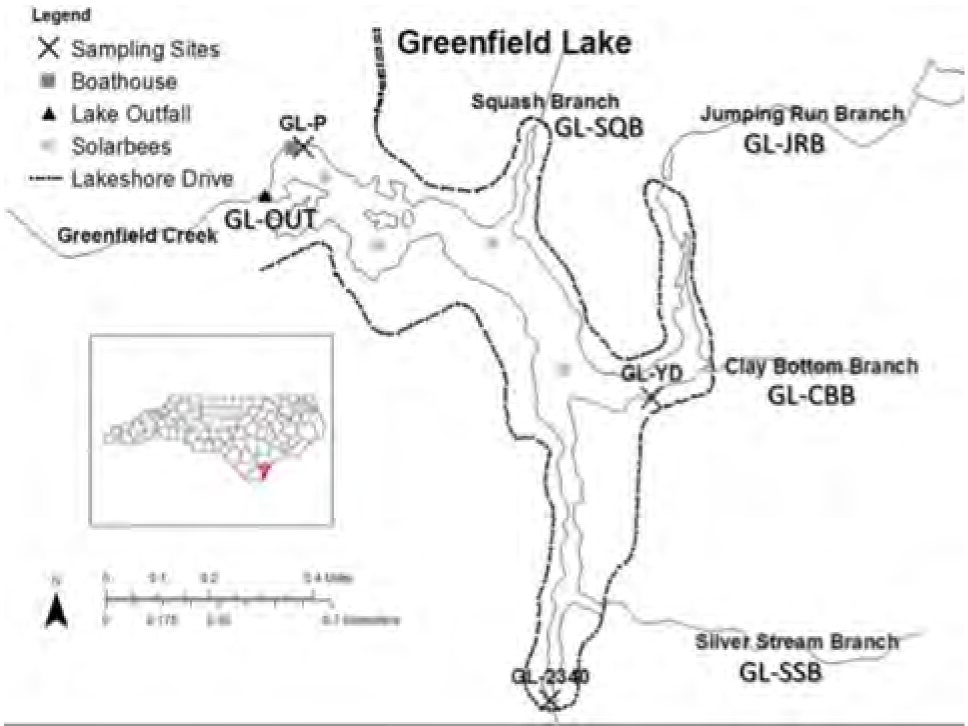


Continuing Efforts to Restore Water Quality in Greenfield Lake

Greenfield Lake has long suffered from eutrophication, and beginning in 2005 several steps were taken by the City of Wilmington to restore viability to the lake. These steps included additions of grass carp to control (by grazing) the overabundant aquatic macrophytes, and installation of four SolarBee water circulation systems (SB10000v12 units) with the general objectives of providing algae control, improving water quality and the fishery, reducing and/or compacting soft organics in the littoral zone and enhance nuisance macrophyte control. Cape Fear River Watch does monthly shoreline inspections of the lake, and city crews and contract firms have spot treated areas of the lake to control macrophyte and nuisance phytoplankton blooms with herbicide annually since 2007. Since the various treatments (artificial circulation, grass carp additions, herbicide use) the lake's water quality has changed, in some ways improving and, in some ways deteriorating. The results of a multi-year study were reported in a previous report (Mallin et al. 2015) and in a subsequent peer-reviewed professional paper (Mallin et al. 2016). Rehabilitation measures performed to-date on Greenfield Lake have improved the appearance of the lake to the public and have improved dissolved oxygen (DO) concentrations by eliminating near-anoxia incidents and reducing DO standard violations by 26%. However, they have significantly increased chlorophyll *a* concentrations in the lake and led to a tripling of chlorophyll *a* violations that have gotten this lake placed on the NC 303(d) list. Chlorophyll *a* is strongly correlated with BOD5 in this lake; thus, the algal blooms can result in lowered DO. None of the above efforts were designed to reduce nutrient loading, however.

UNCW graduate student Nick Iraola performed a year-long study (July 2016 – June 2017) to quantify the amount of nutrients that are added by the five perennial streams (Fig. 6.2) that feed Greenfield Lake (Iraola 2018). Lake eutrophication (algal blooms and elevated BOD), is driven by excessive nutrient inputs such as nitrogen and phosphorus. Therefore, the five perennial streams that drain the highly impervious and developed Greenfield Lake watershed were evaluated for their nutrient contributions to the lake during rainy and dry periods.

Figure 6.2. Greenfield Lake feeder stream stations sampled in 2016-2017. Note that GL-SQB is also known as GL-LB, and GL-CBB is also known as GL-LC.



The results were detailed in the 2017 report and showed that nutrient concentrations were consistently higher in Jumping Run Branch (GL-JRB) and Squash Branch (GL-SQB; also known as GL-LB). Nutrient load to Greenfield Lake is computed by multiplying nutrient concentration and stream discharge for each inflowing stream. As such, GL-JRB was the highest nutrient loader of nitrate-N, orthophosphate-P, total nitrogen, and total phosphorus. GL-SQB was the highest ammonium-N loader and second highest in nitrate-N and orthophosphate-P. GL-JRB and GL-SQB were the two highest loaders of dissolved inorganic nitrogen and phosphorus, which accounted for a higher percentage of their overall total nitrogen and total phosphorus compared to other streams. Inorganic forms of N and P are most critical because these are the nutrient forms most readily taken up by algae and bacteria. We are pleased to note here that a coalition including the City of Wilmington, Cape Fear River Watch, UNC Wilmington, NCSU and a private consulting firm (Moffat & Nichol) has received funds from 2020-2022 through the NC Division of Environmental Quality via the EPA-sponsored 319 Program to begin nutrient reduction measures on Jumping Run Branch. The specific areas to be targeted for restoration work were the Willard Street Wetland, between Willard St., 15th St., and 16th St. (Fig. 6.3) and the SurgiCare Pond along 17th St., with cooperation from the owners (Fig. 6.4).

Willard Street Wet Pond/Wetland is bordered by 15th Street, 16th Street, and Willard St. and flows into the Jumping Run Branch Tributary of Greenfield Lake

Figure 6.3. Willard St. Wetland and sampling sites, along Jumping Run Branch tributary of Greenfield Lake.

Figure 6.4. SurgiCare Pond on Rt. 17, drains to Jumping Run Branch, sampled by UNCW in forebay and outfall.

Willard Street Wetland and SurgiCare Pond Sampling Efforts

Seven water quality sampling efforts were completed for Willard Street Wetland and SurgiCare Pond spring and summer 2020; sampling was not permitted earlier by UNCW administration due to strict Covid-19 university shut-down procedures. Field parameters were measured at each site using a YSI EXO 3 Multiparameter Water Quality sonde linked to a YSI EXO display unit. Individual probes within the instrument measured water temperature, pH, dissolved oxygen, turbidity, salinity, and conductivity. The YSI EXO 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). Water samples were collected for ammonium, nitrate, total nitrogen, orthophosphate, total phosphorus, total suspended solids (TSS) and fecal coliform bacteria. Samples were placed on ice and transported back to the laboratory at the Center for Marine Sciences for processing and analysis. TSS samples were analyzed using Method SM 2540D. Fecal coliform bacteria were analyzed using Method 9222D MF (APHA 2005).

Sediment phosphorus samples were collected at SCP-IN, and near the outfall structure at SCP-OUT (Fig. 6.4; also cover photo), at WSW-15 (cover photo), WSW-16, and three locations in the WSW pond proper between the inflows and the outfall (Fig. 6.3). Three sediment samples were also collected in Jumping Run Branch downstream of the outfall at WSW-OUT. On-site, duplicate 5-cm cores were taken at each site with a 2.5 cm diam clear PVC corer, placed into 50-mL centrifuge tubes and kept on ice until delivery at the laboratory, where they were dried at 50 °C until analysis. Dried sediment samples were mixed thoroughly, a subsample was weighed (to 0.0001 g), and the subsample was extracted using 10 mL of the Mehlich III reagent (to quantify ‘bioavailable’ P, Mehlich, 1984), then reacted with 1 additional mL of the P mixed reagent (Parsons et al., 1984, ‘the molybdenum blue’ mixed reagent, prepared fresh) for 24 hrs. Samples were then centrifuged to create clear supernatant and we measured absorbance of the supernatant vs. duplicate true blank samples (everything except the sediment) at 885 nm on a Fisherbrand accuSkan GO model spectrophotometer (Thermo Fisher Scientific, MA). Dried sediment subsamples were then ashed at 450 ^{o}C for 24 hours, then a weighed amount (to 0.0001 g) was extracted and reacted as above. The sediments generally had a high organic content (~43% on average, as weight loss on ignition, WLOI). Samples were then centrifuged to create clear supernatants and we measured absorbance of the supernatant vs. duplicate true blank samples (everything except the sediment) at 885 nm on a Fisherbrand accuSkan GO model spectrophotometer (Thermo Fisher Scientific, MA). Absorbance values were converted to µM, multiplied by 31 to convert to µg P, then expressed as µg P per gram ashed sediment, then converted to µg P per gram of dried sediment using WLOI values for each sample. The average of the duplicate samples was used for site sediment P concentrations. Total P values are reported in Table 3; the difference between total P and ‘bioavailable’ P corresponds to organic P.

Data Highlights

Water Quality

Samples were collected during both wet and dry periods. Dry periods were defined as no noticeable rain the previous five days, and wet periods were defined as having at least one half inch of rain fallen within the previous 24 hours. The rainfall data used were that collected at the Port of Wilmington by the NC State Port Authority (available from the Weather Underground and State Climate Office of North Carolina).

Water quality data are presented here as average data for dry periods (n = 2) and wet periods (n = 5) for several key parameters: turbidity, TSS, fecal coliform bacteria, ammonium, nitrate, TN and TP (Table 6.3). We caution that the data, especially dry period samples, are limited, and should be assessed with that in mind.

Turbidity was generally low at all sites (Table 6.3). This is likely because the coastal soils in the Wilmington area have generally low concentrations of clays (the lightest portions of the soil compositions); clays tend to stay suspended in the water longest and contribute to turbidity. There was no difference in wet v dry periods for turbidity; the SurgiCare forebay maintained higher turbidity than the outfall area.

Total suspended solids (TSS) were likewise low in most samples (Table 6.3). However, a major exception to this was Station WSW-15, the inflow area to the Willard Street Wetland for the 15^{th} Street area. Average TSS during wet periods was 486 mg/L and the median was 133 mg/L; both far higher than any other station. The highest sample was 1,667 mg/l in the June 8 rainy period. Again, the SurgiCare forebay maintained considerably higher TSS than the outfall, and wet periods in general were mostly higher than dry periods.

Fecal coliform bacteria showed sharply higher concentrations in wet periods compared to the two dry period samples. This was true at each location sampled except the outflow from the Willard St. Wetland (Table 6.3). Notably, Station WSW-15 had extremely high fecal coliform counts in wet periods flowing out of the WSW-15 inflow pipe; dry period samples were elevated too (Table 6.3). It is possible that some of the high counts that occurred there (91,000 CFU/100 mL on June 8 and 52,000 CFU/100 mL on June 12 may be reflective of a sewer leak upstream and should be investigated as such. Fecal coliform counts were reduced in passage through the Willard Street Wetland, but were still at unacceptably high levels in the outflow during wet and dry periods (Table 6.3). The SurgiCare pond showed considerable reduction of fecal coliforms between entry and outfall (Table 6.3).

Ammonium in the SurgiCare Pond was low in the upper pond, and actually increased somewhat exiting the pond (Table 6.3). In the Willard St. Wetland, ammonium was by far the highest at WSW-16, and decreased through the wetland. Nitrate was generally low in SurgiCare Pond and increased at the exit relative to the inflow (Table 6.3). Nitrate was high at WSW-16, decreased somewhat through the wetland but was still rather high in the wetland outfall to Jumping Run Branch, higher than average levels in the creek proper (Tables 6.1, 6.3). There was no real difference between wet and dry samples for nitrate anywhere. Likewise, TN during wet periods was not higher than TN in dry periods. TN did decrease in SurgiCare Pond from entry to exit. TN was quite high at WSW-16, and was still quite high in the wetland outfall (Table 6.3), and similar to creek TN levels (Table 6.1). TP concentrations were not lower in dry periods than wet periods. In Surgicare Pond TP was considerably reduced as it passed from the inflow to the outflow area (Table 6.3). There was no decrease in TP during passage through the Willard St. Wetland, although outfall concentrations were much lower that levels in the creek proper (Table 6.1).

Table 6.3. Water quality data for selected parameters, pre-construction sampling in the Jumping Run Branch watershed, 2020, wet periods v dry periods (as averages/medians, geometric means for fecal coliforms, 5 wet samples, and 2 dry samples).

Site	SCP-IN	SCP-OUT	WSW-15	WSW-16	WSW-MID	WSW-OUT
Turbidity (NTU)						
Wet	2.8/2.0	0.9/1.0	5.9/5.0	6.8/4.0	3.9/3.0	4.1/2.0
Dry	5.5/5.5	0.0/0.0	3.3/3.3	7.0/7.0	2.4/2.4	0.5/0.5
TSS (mg/L)						
Wet	4.8/3.5	1.9/1.5	485.6/133.4	4.4/2.7	4.2/3.3	3.8/2.2
Dry	7.7/7.7	0.6/0.6	24.3/24.3	7.1/7.1	1.1/1.1	0.0/0.0
Fecal coliform bacteria (CFU/100 mL)						
Wet	1,050	147	16,911	554	2,304	1,696
Dry	610	6	1,625	91	1,142	1,599
Ammonium (µg/L)						
Wet	28/34	19/10	25/24	140/150	75/70	68/80
Dry	6/6	96/96	27/27	158/158	54/54	29/29
Nitrate (µg/L)						
Wet	30/20	84/20	329/430	738/710	492/490	383/360
Dry	9/9	35/35	444/444	785/785	594/594	407/407
TN (µg/L)						
Wet	430/310	248/210	586/580	1,168/1,210	936/960	754/830
Dry	458/458	376/376	692/692	1,253/1,253	1,013/1,013	719/719
TP (µg/L)						
Wet	59/50	23/20	50/40	62/50	67/50	68/60
Dry	74/74	23/23	146/146	42/42	83/83	72/72

<u>Sediment Phosphorus Concentrations</u>

Sediment phosphorus concentrations were elevated in the forebay of SurgiCare Pond, but considerably reduced near the outfall (Table 6.4). Data from SurgiCare pond sediments show that the presence of the forebay helped to reduce stormwater-driven sediment P during its passage through the pond (Table 6.4). However, the situation in the Willard Street Wetland differed; Sediment P concentrations were similar in most of the wetland, and were actually elevated in the downstream area of the wetland (Table 6.4). Another concerning issue that the sampling demonstrated is that sediment P concentrations in Jumping Run Branch are quite high, higher than those of either the wetland or SurgiCare Pond. Thus, the sediment P data indicate the Willard Street Wetland is currently ineffective in reducing P loading through the wetland, and other important sources of P to Jumping Run Branch appear to be located upstream of 17^{th} Street in watershed areas currently not sampled by UNCW.

Table 6.4. Sediment phosphorus concentrations in the Jumping Run Branch watershed, June 2020

Station replicates except	Sediment P concentrations (µg/g sediment); mean of two JRB samples (individual data)
SCP-IN	42.2
SCP-OUT (near)	22.7
WSW-15	44.9
WSW-16	39.6
WSW upper	41.0
WSW middle	43.6
WSW lower	60.1
JRB-1	87.5
JRB-2	81.2
JRB-3	80.7

7.0 Hewletts Creek

Snapshot
Watershed area: 7,478 acres (3,028 ha)
Impervious surface coverage: 25.1% (2013 data)
Watershed population: Approximately 20,200
Overall water quality: Fair
Problematic pollutants: high fecal bacteria, minor algal bloom issues

Hewletts Creek was sampled six times at four tidally-influenced areas (HC-3, NB-GLR, MB-PGR and SB-PGR) and three times at a freshwater stream station draining Pine Valley Country Club (PVGC-9 - Fig. 7.1). Based on these data, at all sites the physical data indicated that turbidity was well within State standards during this sampling period during all sampling events. TSS levels were below 25 mg/L at all times sampled except for February at SB-PGR when TSS rose to 32.2 mg/L, and NB-GLR in June when TSS was 31.2 mg/L (Table 7.2). Dissolved oxygen was within standard on all sampling occasions. 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 Course (Fig. 7.1; Mallin and Wheeler 2000). Nitrate was slightly elevated at MB-PGR, and even more so at NB-GLR. Ammonium concentrations were generally low to moderate in most locations but rather high at HC-3 in the estuary; several oyster reefs are present there and the ammonium may be a waste product from oyster excretion. Total nitrogen was highest at PVGC-9, with the other stations all somewhat lower. Orthophosphate concentrations were low to moderate, as were total phosphorus concentrations. The N/P ratios were high in most sites but low at NB-GLR, indicating that inputs of inorganic nitrogen could cause algal blooms at that location. Ratios were high at HC-3, due to elevated ammonium, indicating that at times P can stimulate algal growth at this lower site. The chlorophyll *a* data (Tables 7.1 and 7.2) showed that no major blooms occurred during the spring sampling runs; SB-PGR had one minor bloom of 36 µg/l chlorophyll *a* in February 2020. Fewer blooms have occurred in the past few years than had previously occurred in upper Hewletts Creek (Mallin et al. 1998; 2004; Duernberger 2009). We note that water quality in the south branch of Hewletts Creek improved significantly following construction of a large stormwater treatment wetland in 2007 (Mallin et al. 2012).

Fecal coliform bacteria counts exceeded State standards over 25% of the times sampled at all sites, and 50% of the times at NB-GLR and SB-PGR. The geometric mean at NB-GLR exceeded 200 CFU/100 mL (356 CFU/100 mL). A Poor rating for this pollutant parameter was given to all sites. The geometric mean of fecal bacteria counts at HC-3 was 42 CFU/100 mL, over the shellfishing standard of 14 CFU/100 mL. 2020 was a particularly rainy year, which likely contributed to the high counts, as well as the high impervious surface coverage of this watershed (> 25% impervious).

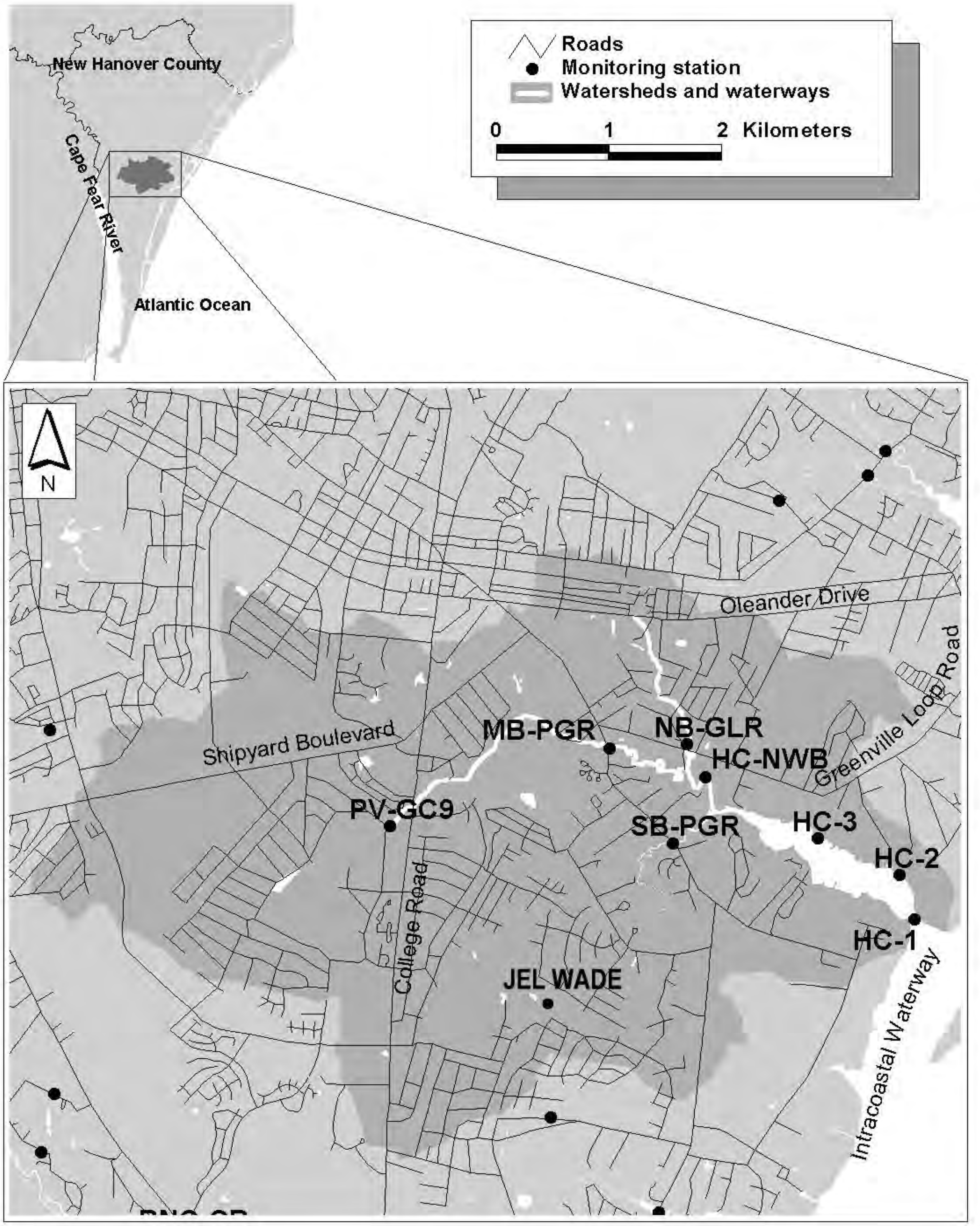


Figure 7.1. Hewletts Creek watershed.

Table 7.1. Selected water quality parameters at upper and middle creek stations in Hewletts Creek watershed 2020 as mean (standard deviation) / range, inorganic N/P ratios as mean / median, fecal coliform bacteria presented as geometric mean / range, n = 6 samples collected except for PVGC-((3 samples).

Parameter	PVGC-9	MB-PGR
Salinity (ppt)	0.1 (0) 0.1-0.1	6.6 (11.1) 0.1- 27.2
Turbidity (NTU)	4 (3) 2-8	4 (3) 0-8
TSS (mg/L)	3.6 (4.0) 1.3-8.2	6.2 (5.6) 1.3-16.5
DO (mg/L)	7.6 (1.3) 6.3-8.9	6.9 (1.6) 4.1-8.2
Nitrate (mg/L)	0.233 (0.230) 0.010-0.470	0.110 (0.119) 0.010-0.250
Ammonium (mg/L)	0.030 (0.035) 0.010-0.070	0.102 (0.149) 0.010-0.400
TN (mg/L)	0.963 (0.189) 0.800-1.170	0.705 (0.195) 0.440-1.000
Orthophosphate (mg/L)	0.033 (0.015) 0.020-0.050	0.030 (0.015) 0.010-0.050
TP (mg/L)	0.077 (0.074) 0.020-0.160	0.090 (0.089) 0.020-0.240
N/P inorganic	25,1 21.4	28.7 18.5
Chlorophyll *a* (µg/L)	3 (2) 2-5	5 (6) 1-17
Fecal col. (CFU/100 mL)	163 41-864	174 59-955

Table 7.2. Selected water quality parameters at stations in Hewletts Creek watershed, 2020, as mean (standard deviation) / range, fecal coliforms as geometric mean / range, n = 6 samples collected.

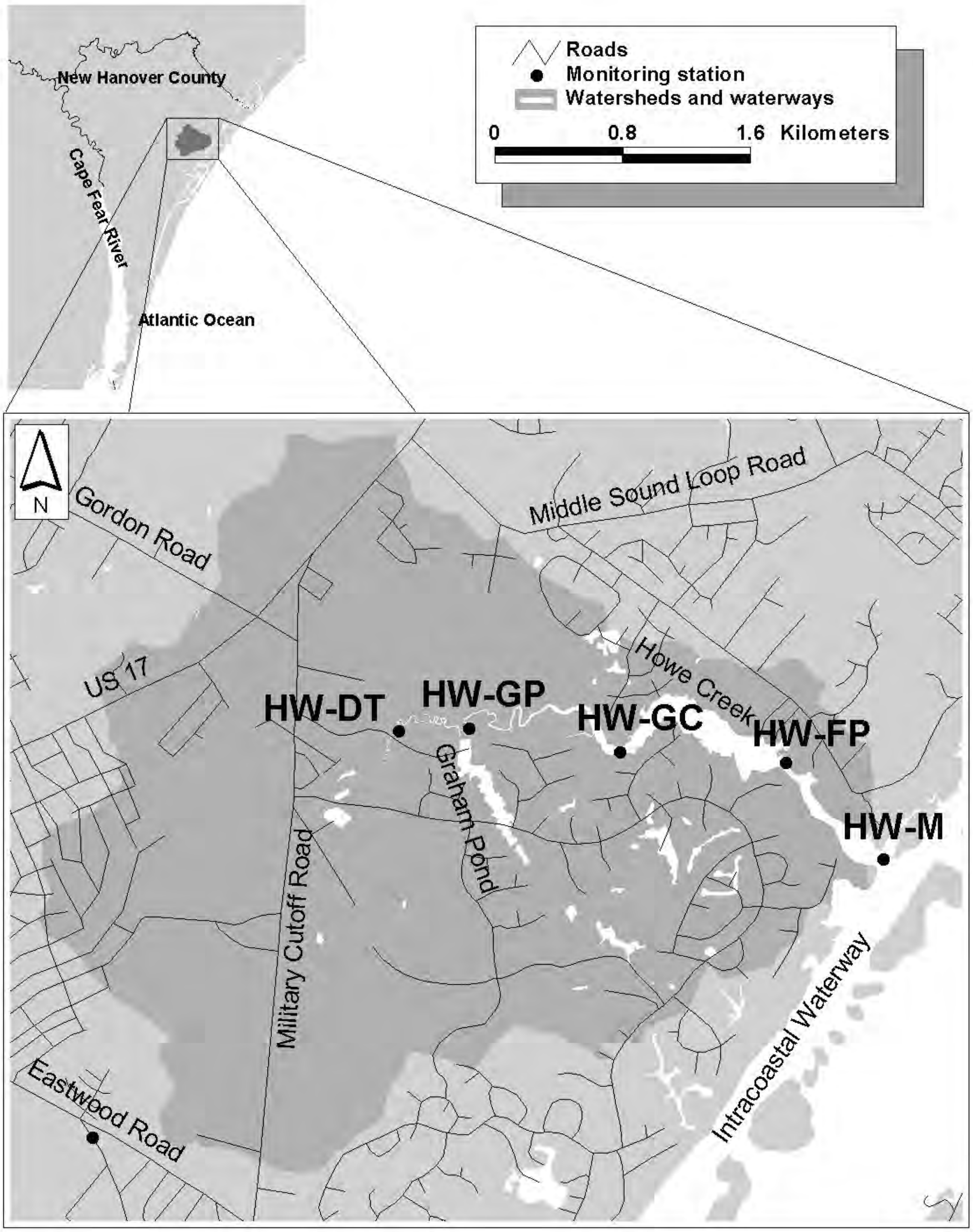
Parameter	NB-GLR	SB-PGR	HC-3
Salinity (ppt)	6.6 (11.5) 0.1-29.1	16.9 (13.4) 0.5-34.0	26.2 (10.2) 9.3-34.9
Turbidity (NTU)	6 (5) 0-8	7 (5) 1-17	5 (3) 1-10
TSS (mg/L)	13.9 (1.9) 2.8-31.2	18.2 (9.2) 8.2-32.3	16.8 (2.9) 13.7-21.2
DO (mg/L)	7.3 (1.1) 5.8-8.4	6.5 (1.7) 3.6-8.2	6.9 (1.5) 4.6-8.3
Nitrate (mg/L)	0.107 (0.088) 0.010-0.240	0.032 (0.037) 0.010-0.100	0.030 (0.035) 0.010-0.100
Ammonium (mg/L)	0.097 (0.120) 0.010-0.330	0.235 (0.207) 0.010-0.550	0.270 (0.208) 0.010-0.580
TN (mg/L)	0.808 (0.290) 0.440-1.300	0.828 (0.254) 0.590-1.300	0.547 (0.141) 0.310-0.710
Orthophosphate (mg/L)	0.037 (0.027) 0.020-0.090	0.020 (0.011) 0.010-0.040	0.027 (0.012) 0.010-0.040
TP (mg/L)	0.143 (0.198) 0.010-0.540	0.177 (0.280) 0.020-0.740	0.125 (0.204) 0.020-0.540
Mean N/P ratio Median	13.2 13.5	46.1 20.5	29.8 20.5
Chlor *a* (µg/L)	4 (5) 2-14	9 (13) 2-36	2 (1) 1-4
Fecal coliforms (CFU/100 mL)	356 125-1,950	185 17-1,700	42 5-364

8.0 Howe Creek Water Quality

Snapshot
Watershed area: 3,516 acres (1,424 ha)
Impervious surface coverage: 21.4%
Watershed population: Approximately 6,460
Overall water quality: Fair-Poor
Problematic pollutants: Fecal coliform bacteria, algal blooms

Howe Creek drains a 3,516 acre watershed into the ICW (Fig. 8.1). Two to five stations have been sampled in this creek in various years. Due to Covid-19 and resource re-allocation, sampling was suspended for the time being in 2020.

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

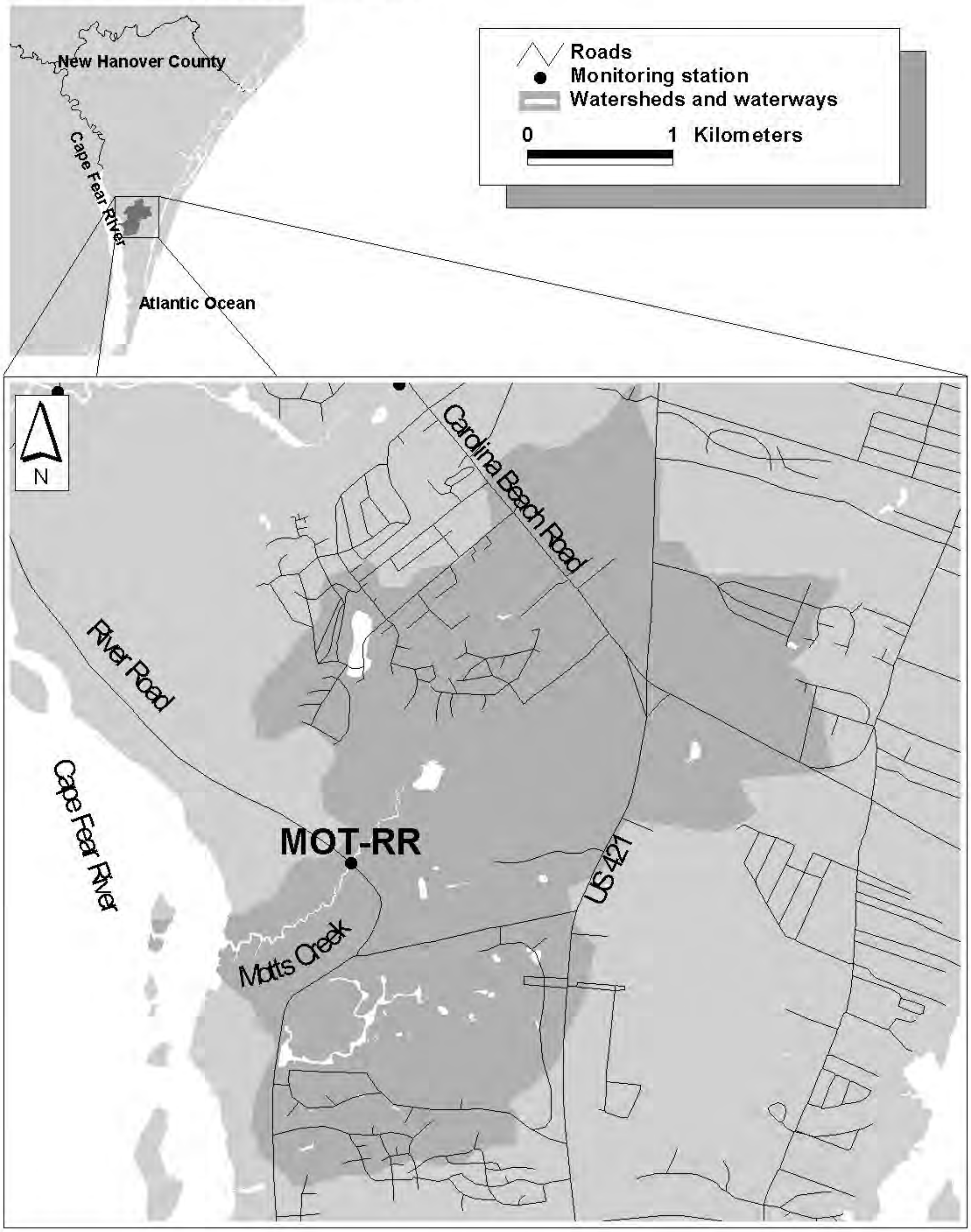


9.0 Motts Creek

Snapshot
Watershed area: 3,328 acres (1,354 ha)
Impervious surface coverage: 23.4%
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 with large cypress in the swamp forest. City funding received by UNCW in late 2017 allowed us to re-initiate sampling of Motts Creek at River Road (MOT-RR) 2018-2019. Due to Covid-19 and resource re-assignment, sampling is currently suspended on this creek.

Figure 9.1 Motts Creeks watershed

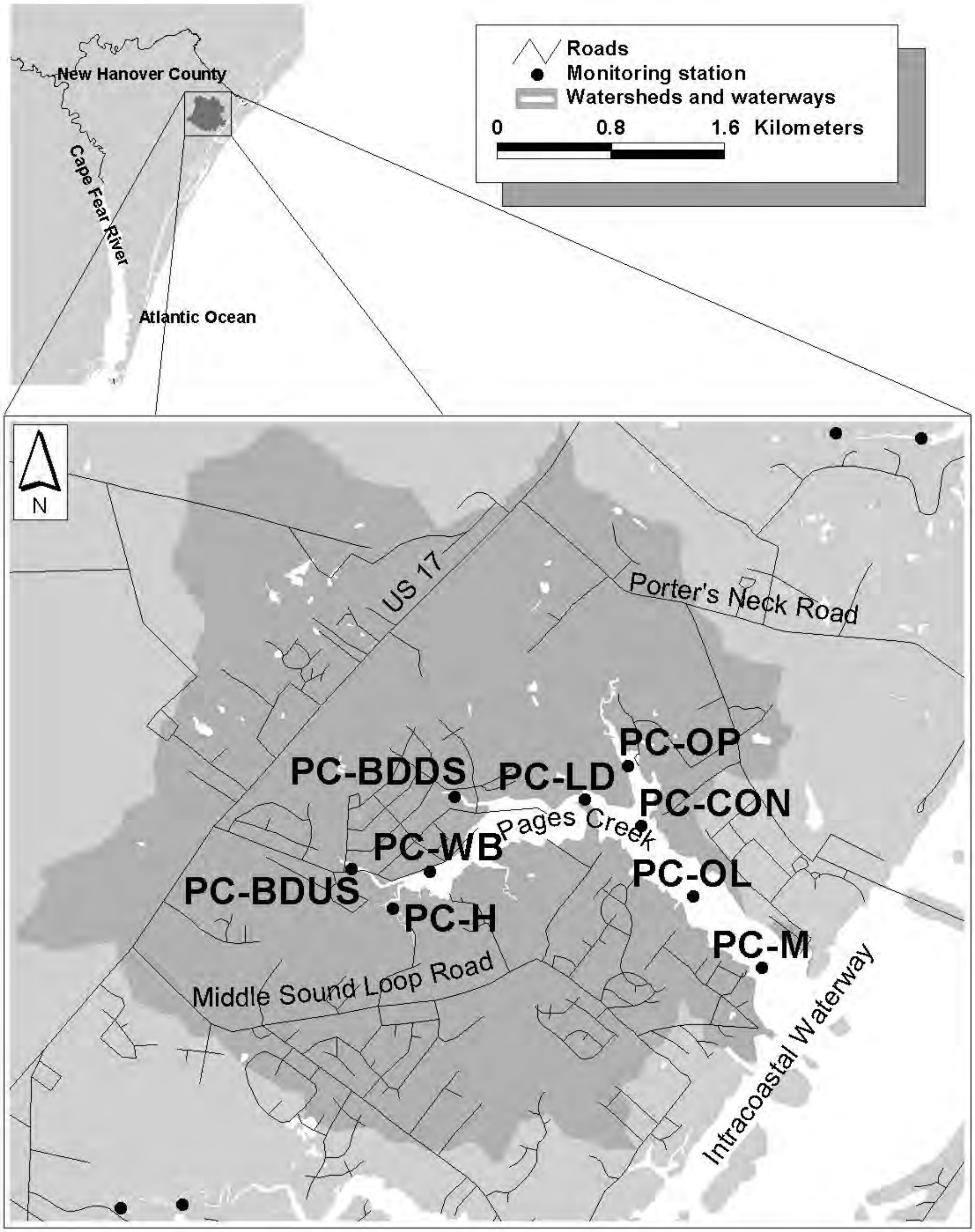


10.0 Pages Creek

Snapshot
Watershed area: 5,025 acres (2,035 ha)
Impervious surface coverage: 17.8% (2014 data)
Watershed population: Approximately 8,390

The University of North Carolina Wilmington was not funded by the County since 2007 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 from the County.

Figure 10.1. Pages Creek watershed and sampling sites.



11.0 Smith Creek

Snapshot
Watershed area: 16,650 acres (6,743 ha)
Impervious surface coverage: 21.3% (2014 data)
Watershed population: 31,780
Overall water quality: Good to Fair
Problematic pollutants: occasional turbidity, low dissolved oxygen and 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, nutrients, chlorophyll and fecal coliform bacteria) and these data are summarized below (Table 11.1).

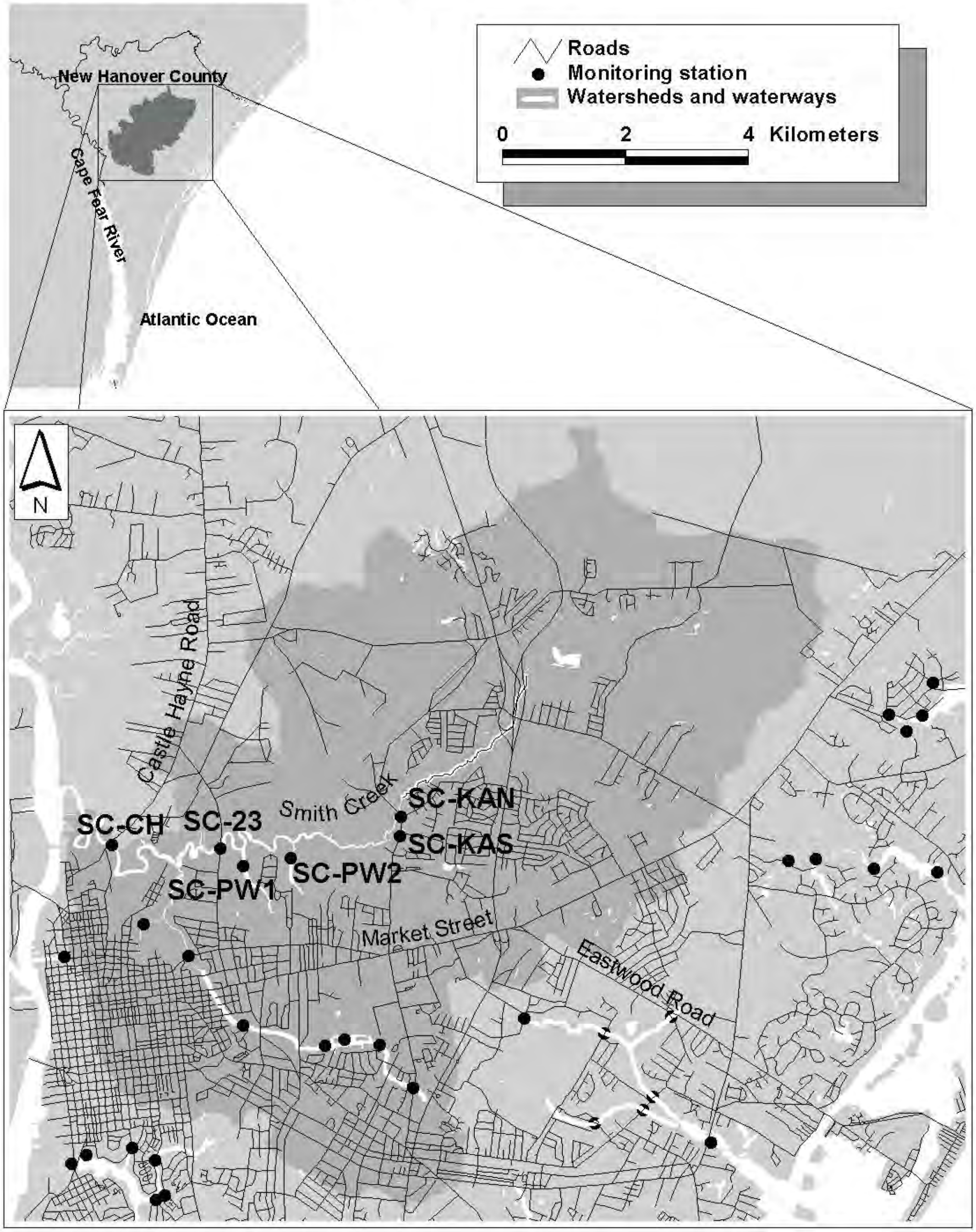
The dissolved oxygen standard for Smith Creek, which is rated as C Sw waters, is 4.0 mg/L, and was violated on one occasion in our 2020 samples for a Good rating. The North Carolina turbidity standard for estuarine waters (25 NTU) was not exceeded in our 2020 samples, and TSS concentrations were not excessive.

Ammonium was low in 2020 (Table 11.1), although nitrate in this creek is relatively high compared to other tidal creeks. Total nitrogen and total phosphorus were low to moderate. There were no major algal blooms in 2020, just a minor bloom of 26 µg/l chlorophyll *a* in July. Fecal coliform bacterial concentrations exceeded 200 CFU/100 mL on only one of 11 sampling occasions at SC-CH in 2020, for a Good rating (Table 11.1).

Table 11.1. Selected water quality parameters in Smith Creek watershed as mean (standard deviation) / range, 2020, n = 11 samples collected.

Parameter	SC-CH	
	Mean (SD)	Range
Salinity (ppt)	4.7 (5.0)	0.1-15.2
Dissolved oxygen (mg/L)	9.0 (4.0)	3.0-14.0
Turbidity (NTU)	9 (3)	4-14
TSS (mg/L)	9.9 (5.8)	2.6-20.3
Ammonium (mg/L)	0.061 (0.028)	0.030-0.100
Nitrate (mg/l)	0.132 (0.157)	0.010-0.410
Total nitrogen (mg/L)	0.946 (0.348)	0.340-1.710
Total phosphorus (mg/L)	0.324 (0.372)	0.080-1,420
Chlorophyll *a* (µg/L)	5.0 (7.0)	0-26
Fecal col. /100 mL (geomean / range)	83	19-319

Figure 11.1 Smith Creek watershed

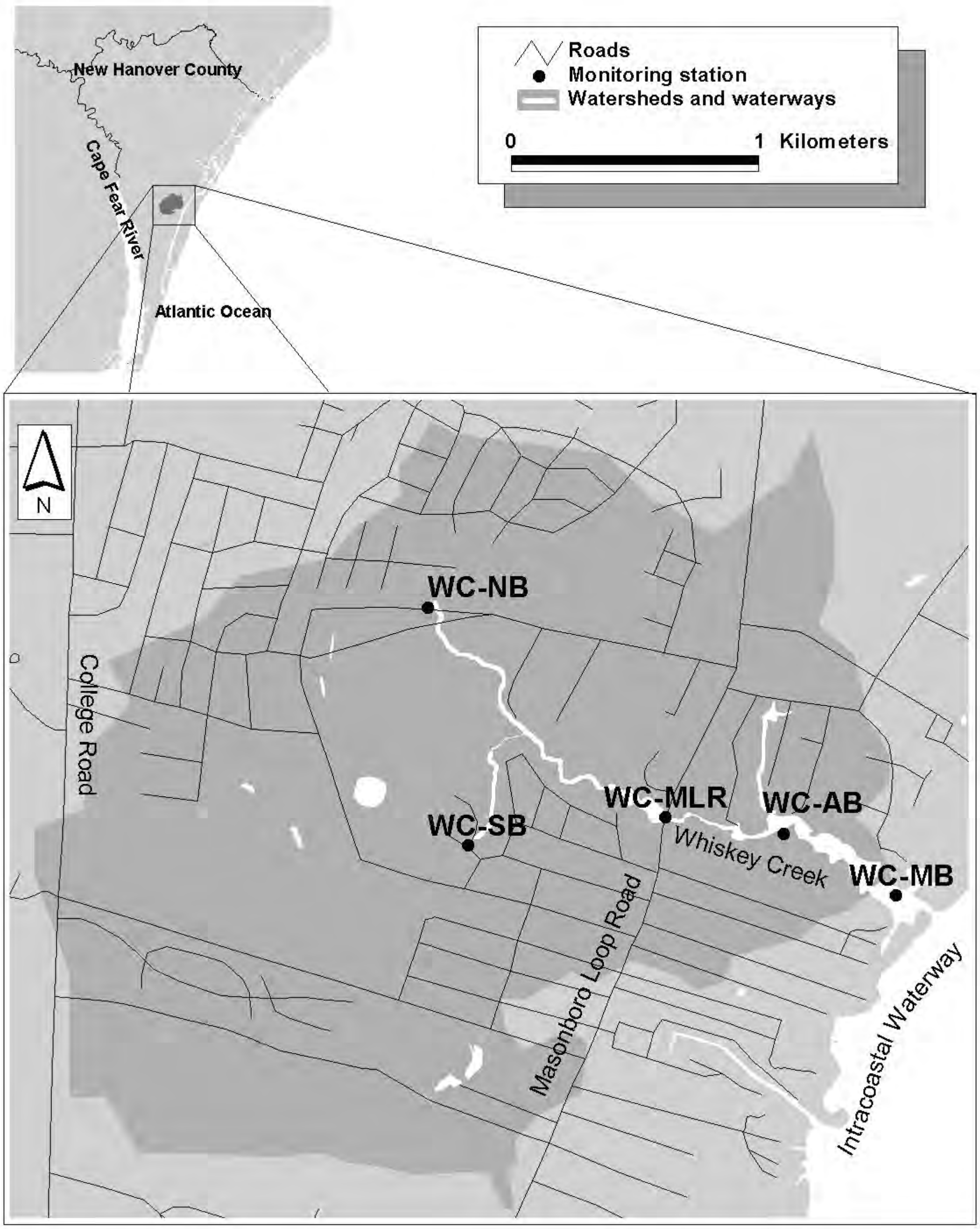


12.0 Whiskey Creek

Snapshot
Watershed area: 2,078 acres (842 ha)
Impervious surface coverage: 25.1% (2014)
Watershed population: 7,980
Overall Water Quality: Good-Fair
Problematic pollutants: Occasional high fecal coliform counts; occasional minor low dissolved oxygen issue

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). Due to resource reassignment, sampling is currently suspended on this creek.

Figure 12.1. Whiskey Creek. Watershed and sampling sites.



13.0 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.

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.

Iraola, N.D. 2018. Uncovering the sources of nutrient pollution to eutrophic Greenfield Lake, N.C. M.S. thesis, University of North Carolina Wilmington, Wilmington, N.C.

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., 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. 2000. Effect of human development on bacteriological water quality in coastal watersheds. *Ecological Applications* 10:1047-1056.

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.

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.

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., 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. 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., 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., M.R. McIver, A.R. Robuck and J.D. Barker. 2015. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2014*. UNCW-CMS Report 15-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, E.J. Wambach and A.R. Robuck. 2016. Algal blooms, circulators, waterfowl and eutrophic Greenfield Lake, N.C. *Lake and Reservoir Management*. 32:168-181.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant, Communications in Soil Science and Plant Analysis, 15:12, 1409-1416, DOI: 10.1080/00103628409367568

Parsons, TR, Maita Y, Lalli, CM. 1984 A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, Oxford.

[NCDENR] North Carolina Department of Environment and Natural Resources 2003. Amended effective 1 April 2003. “Redbook” - Surface waters and wetlands standards (NC Administrative Code 15A NCAC 02B .0100 & .0200). Raleigh, North Carolina.

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.

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

Wetzel, R.G.. 2001. Limnology: Lake and River Ecosystems, 3rd edition. 3rd ed. San Diego (CA): Academic Press.

14.0 Acknowledgments

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15.0 Appendix A. North Carolina Water Quality standards for selected parameters (NCDENR 2003; 2005). 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); for designated “swamp” waters it is 4.0 ppm
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

16.0 Appendix B. UNCW ratings of sampling stations in Wilmington watersheds based on 2020, where available, for chlorophyll *a*, dissolved oxygen, turbidity, and fecal coliform bacteria (human contact standard) based in part on North Carolina state chemical standards for freshwater or tidal saltwater.

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-RD	G	P	P	P
	BC-CA	G	P	F	P
	BC-SB	G	F	F	P
	BC-NB	G	F	G	P
Burnt Mill Creek	BMC-AP1	G	G	G	P
	BMC-AP3	G	G	G	G
	BMC-PP	G	P	G	P
Greenfield Lake	JRB-17	G	G	G	P
	GL-JRB	G	F	G	P
	GL-LC	F	P	G	P
	GL-LB	G	P	G	P
	GL-2340	P	G	G	F
	GL-YD	P	G	G	F
	GL-P	F	G	G	G
Hewletts Creek	HC-3	G	G	G	P
	NB-GLR	G	G	G	P
	MB-PGR	G	G	G	P
	SB-PGR	G	G	G	P
	PVGC-9	G	G	G	P
Smith Creek	SC-CH	G	G	G	G

17.0 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-RD	N 34.23249	W 77.87071
	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
	JRB-17	N 34.21300	W 77.92480
	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

18.0 Appendix D. Sampling station sub-watershed drainage area and percent impervious surface coverage, 2015 (compiled by Anna Robuck).

Sampling Station	Catchment Polygon Area (acres)	Percent Impervious
Hewletts Creek		
PVGC-9	1296.1	27.5%
MB-PGR	2044.5	27.5%
NB-GLR	876.4	29.8%
SB-PGR	1480.2	27.4%
HC-NWB	3185.1	27.4%
HC-3	5117.5	26.6%
HC-2	5557.1	25.3%
HC-M	5642.2	25.0%
Barnards Creek		
BNC-EF	154.6	20.8%
BNC-TR	277.4	25.5%
BNC-AW	196.0	22.2%
BNC-CB	1077.8	31.6%
BNC-RR	3437.3	25.3%
Burnt Mill Creek		
BMC-KA1	191.4	63.3%
BMC-KA3	195.1	62.3%
BMC-AP1	995.1	46.2%
BMC-AP2	1036.4	44.9%
BMC-AP3	1537.2	42.3%
BMC-GS	256.9	47.8%
BMC-WP	2981.9	39.5%
BMC-PP	3030.8	39.3%
BMC-ODC	772.0	47.8%
Bradley Creek		
BC-SBU	439.5	28.0%
BC-NBU	683.6	33.5%
BC-RD	98.5	90.0%
BC-CA	372.1	82.0%
BC-CR	649.7	46.3%
BC-SB	1022.3	28.9%
BC-NB	2047.6	31.9%
BC-76	3589.0	29.8%
Whiskey Creek		
WC-NB	211.6	31.1%
WC-SB	734.7	25.2%

WC-MLR	1378.1	26.0%
WC-AB	1552.2	25.5%
WC-MB	1643.3	25.0%
Futch Creek		
FC-13	726.6	25.6%
FC-17	692.5	25.9%
FC-FOY	2261.0	6.6%
FC-8	1086.6	24.2%
FC-6	3447.4	12.0%
FC-4	3651.2	12.4%
Greenfield Lake		
GL-SS1	140.2	66.8%
GL-SS2	264.1	53.4%
GL-2340	422.2	73.6%
JRB-17	595.4	22.3%
GL-JRB	795.8	25.9%
GL-LC	94.2	63.6%
GL-YD	978.0	30.4%
GL-LB	130.8	49.2%
GL-P	2402.4	37.8%
Motts Creek		
MOT-RR	2350.1	27.7%
Howe Creek		
HW-DT	1255.2	29.4%
HW-GP	1794.3	25.5%
HW-GC	2368.2	25.0%
HW-FP	2737.1	23.8%
HW-M	3103.6	23.0%
Smith Creek		
SC-KAN	10605.4	19.5%
SC-KAS	2153.5	39.5%
SC-23	14803.3	22.6%
SC-CH	15837.8	22.5%
Pages Creek		
PC-BDUS	345.1	25.7%
PC-H	1019.7	22.8%
PC-WB	1444.6	22.9%
PC-BDDS	357.8	27.7%
PC-LD	2296.4	22.2%
PC-OP	1788.9	15.7%
PC-CON	1949.5	15.2%
PC-OL	4378.8	18.7%
PC-M	4615.9	18.3%

19.0 Appendix E. University of North Carolina at Wilmington reports and papers concerning water quality in Wilmington and 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.

Mallin, M.A., L.E. Bohrer, M.R. McIver and S. Protopappas. 2013. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2012*. UNCW-CMS Report 13-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.G. Lemon and M.R. McIver. 2014. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2013*. UNCW-CMS Report 14-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, A.R. Robuck and J.D. Barker. 2015. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2014*. UNCW-CMS Report 15-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A. and M.R. McIver. 2016. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2015*. UNCW-CMS Report 16-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver and N. Iraola. 2017. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2016*. UNCW-CMS Report 17-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver and N. Iraola. 2018. Environmental Quality of Wilmington and New Hanover County Watersheds, 2017. UNCW-CMS Report 18-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, N. Iraola, L.B. Cahoon and A.E. Grogan. 2019. Environmental Quality of Wilmington and New Hanover County Watersheds, 2018. UNCW-CMS Report 18-01, Center for Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, N.D. Iraola and A.E. Grogan. 2020. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2019*. UNCW-CMS Report 20-01, Center for Marine Science, University of North Carolina 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.

Chudoba, E.A., M.A. Mallin, L.B. Cahoon and S.A. Skrabal. 2013. Stimulation of fecal bacteria in ambient waters by experimental inputs of organic and inorganic phosphorus. *Water Research* 47:3455-3466.

Mallin, M.A., M.R. McIver, E.J. Wambach and A.R. Robuck. 2016. Algal blooms, circulators, waterfowl and eutrophic Greenfield Lake, N.C. *Lake and Reservoir Management*. 32:168-181.

Burtchett, J.M., M.A. Mallin and L.B. Cahoon. 2017. Micro-zooplankton grazing as a means of fecal bacteria removal in stormwater BMPs. *Water Science and Technology*.75:2702-2715.

Duernberger, K.A., C.R. Tobias and M.A. Mallin. 2018. Processing watershed-derived nitrogen in a southeastern USA tidal creek: An ecosystem-scale ^{15}N tracer study. *Limnology and Oceanography* 63:2110-2125.