ENVIRONMENTAL QUALITY OF WILMINGTON AND NEW HANOVER COUNTY WATERSHEDS, 2023

by

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Executive Summary

This report represents results of Year 26 of the Wilmington Watersheds Project. Water quality data are presented from a watershed perspective, regardless of political boundaries. The 2023 program involved 5 watersheds and 18 sampling stations. In this summary we first present brief water quality overviews for each watershed from data collected between January and December 2023. 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; also two sites in Barnards Creek upstream in Carriage Hills are currently being sampled. Note that several months in summer and early fall were not sampled due to late receipt of funds from the city. From funding sourced by the NC Attorney General's office we were able to sample sediments in 20 wet detention ponds in Wilmington for phosphorus, metals and PAHs.

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. In 2023 five samples were collected at two upper creek sites near Carriage Hills close to a wet detention pond (CHP-U and CHP-D). Turbidity was low, dissolved oxygen was fair, but both stations suffered from high fecal coliform counts. One minor algal bloom occurred at CHP-U.

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. The uppermost site, BC-RD, is on upper Clear Run at Racine Dr., and subsequently drains downstream to BC-CA, Clear Run at College Acres. The two lower sites currently sampled are BC-NB, Bradley Creek north branch at Wrightsville Ave., and BC-SB, Bradley Creek south branch at Wrightsville Ave.). Three sites were sampled five times in 2023; BC-CA was not sampled as there was ongoing stream rehabilitation work at this site in 2023.

High turbidity and suspended solids in 2023 were not problematic. Dissolved oxygen was likewise in Good condition at all three sites. Nutrients were elevated in BC-RD compared with the other sites on Wrightsville Avenue. Algal blooms were not a problem during our sampling trips in 2023. Fecal coliform bacteria counts were moderate at BC-NB but excessive at BC-RD and BC-SB, which had geometric mean counts of 5,165 and 337 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 2023, on six occasions at BMC-AP3 and BMC-PP, and three occasions at BMC-AP1. Fecal coliform conditions were rated Poor at the lowermost station BMC-PP at Princess Place and Good or Fair the upper two sites BMC-AP1 above and BMC-AP3 below Anne

McCrary Pond, the regional wet detention pond on Randall Parkway. Dissolved oxygen concentrations were Good at the upper two sites and Poor at BMC-PP.

We note that nitrate declined during passage through the detention pond, but dissolved oxygen and pH increased, as well as turbidity, TSS and total phosphorus. An algal bloom occurred at AP3 and BMC-PP in May 2023. Several water quality parameters showed an increase in pollutant levels along the creek from the outfall 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.

<u>Futch Creek</u> – 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 2023. New Hanover County employed a consulting firm to sample this creek and data may be requested from the County.

<u>Greenfield Lake</u> – This lake drains a watershed of 2,465 acres, covered by about 37% impervious surface area with a population of about 10,630. In the past this urban lake has suffered from low dissolved oxygen, algal blooms, periodic fish kills and high fecal bacteria counts. The lake was sampled at three tributary stream sites and three in-lake sites on 8 occasions. Of the tributaries of Greenfield Lake, Squash Branch (GL-SQB, near Lake Branch Drive), Jumping Run Branch at 17^{th} Street (JRB-17) and Jumping Run Branch at Lakeshore Dr (GL-JRB), GL-SQB suffered from major low dissolved oxygen problems, GL-JRB had minor DO problems, and GL-2340 in the main lake had major low DO issues.

Algal blooms are chronically problematic in Greenfield Lake and have occurred during all seasons. In 2023 a massive summer-fall blue-green algal bloom of *Anabaena* began in early May. Post-June summer sampling did not occur since funding was not present, but when sampling resumed in fall the blooms were much reduced. 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 2023. In 2023 all three tributary stations exceeded the fecal coliform State standard on >55% of occasions sampled and rated Poor; the in-lake stations were in Good condition for fecal bacteria except for GL-2340, rated Poor.

Greenfield Lake is currently on the NC 303(d) list for impaired waters due to excessive algal blooms. The thesis work of former 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) were awarded restoration planning funds for 2020-2022 and UNCW has competed sampling in support of future nutrient reduction efforts on Jumping Run Branch. Data show the Willard Street Wetland, between Willard St., 15^{th} St. and 16^{th} 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. Plans for restoration have been completed by River Watch, NCSU and Moffat & Nichol. The City currently has a dredging opwration underway at Squash Branch to remove phosphorus laden sediments, with UNCW monitoring the results.

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 2023 the creek was sampled at four tidal sites on five occasions.

Low dissolved oxygen was encountered only once in Hewletts Creek in 2023. Turbidity was low and did not exceed the state standard, and no major algal blooms occurred. Fecal coliform bacteria counts were excessive at MB-PGR, but low at the other sites except for June 2023; note that the geometric mean of fecal bacteria counts at HC-3 in the lower creek was over the state shellfishing standard due to a singly high incident in June.

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 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 2008-2023. 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, is normally sampled by UNCW under the auspices of the Lower Cape Fear River Program (LCFRP). However, due to ongoing bridge construction at our sampling site no data were collected for 2023.

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 resource re-allocation, sampling was suspended here for 2023.

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 2023 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 (18 sites sampled for fecal coliforms) showed 17% to be in Good condition, 28% in Fair condition and 55**%** in Poor condition. Dissolved oxygen conditions (measured at the surface) system-wide (18 sites) showed 61% of the sites were in Good condition, 22% were in Fair condition, and 17% were in Poor condition. For algal bloom presence, measured as chlorophyll *a*, 89% of the 18 stations sampled were rated as Good, 11% as Fair and 0% as Poor. For turbidity, 100% of sites were Good. 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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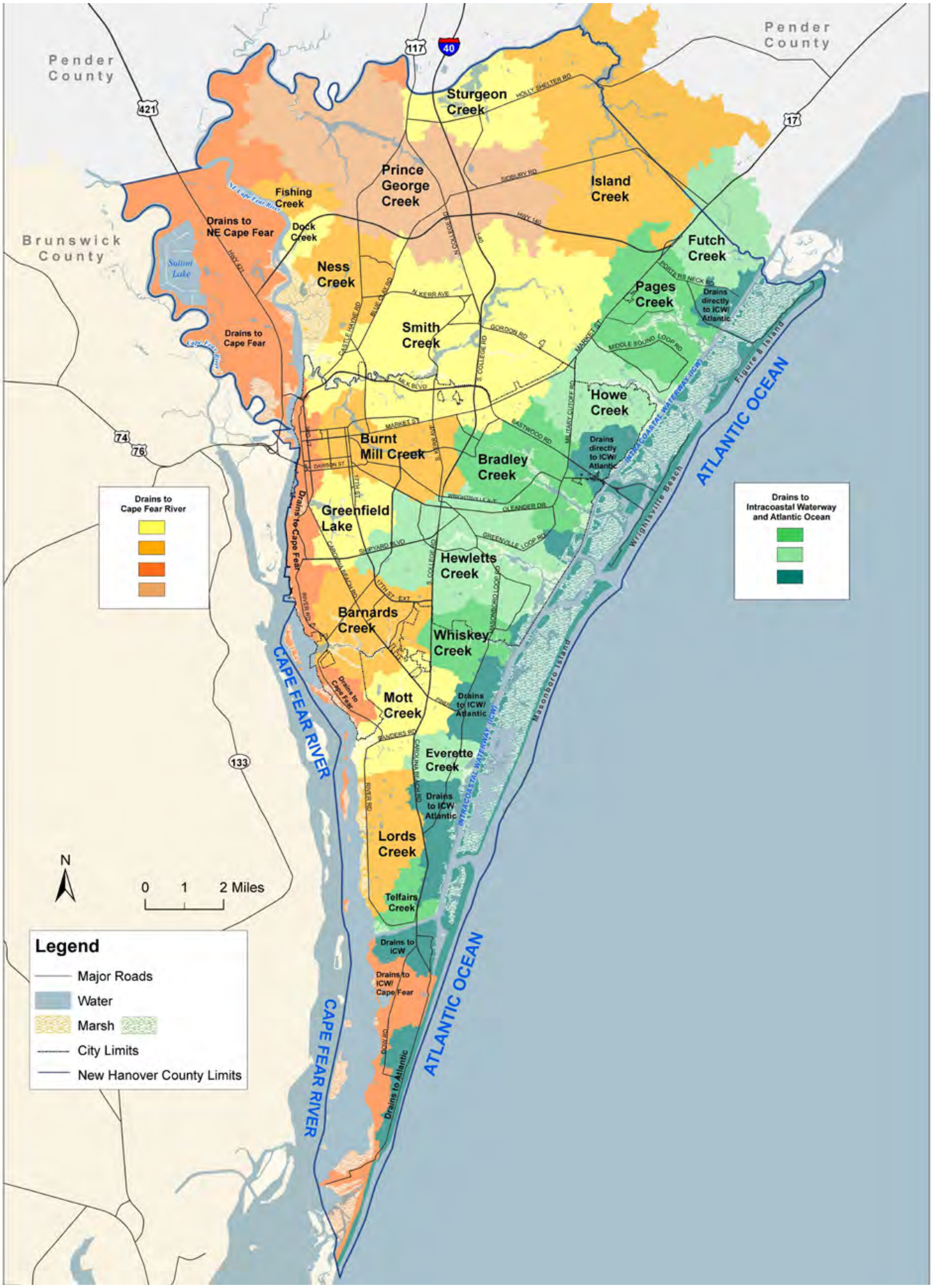


Plate 1. Wilmington and New Hanover County watersheds 2014 map by Wilmington Stormwater Services. Station coordinates are in Appendix C.

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) 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 26 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 2020 sampling at lower Barnards and Motts Creeks, Howe Creek and Whiskey Creek were suspended to emphasize upper Bradley Creek and the Greenfield Lake watershed, both of which are scheduled for restoration measures; in fall 2021 sampling at two locations in upper Barnard's Creek near Carriage Hills wet detention pond was initiated.

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 5 to 12 occasions at 20 locations within the Wilmington City watersheds between January and December 2023. A station on Smith Creek that was normally sampled as part of the Lower Cape Fear River Program and reported here was not sampled due to access issues. Field parameters were measured at each site using a YSI EXO 3 or Pro DSS Multiparameter Water Quality sonde linked to a YSI EXO or Pro DSS display unit. Individual probes within the instrument measured water temperature, pH, dissolved oxygen, turbidity, salinity, and conductivity. The YSI 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 to 24 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.

In summer and fall 2022 the sediments of 20 wet detention ponds within the City of Wilmington were collected and scanned for key metals and PAHs. Collection were made by sampling the upper 5 cm of sediments with plastic tubes, mixing several samples together in a bowl, then using the composite for analyses (see cover photo). Samples were frozen and sent to a state-certified laboratory for analyses of various metals and polycyclic aromatic hydrocarbons (PAHs). Results from individual ponds were reported in last year's annual report. The overall results, including statistical analyses, are presented in Chapter 13 (see also Mallin and Cahoon 2024).

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

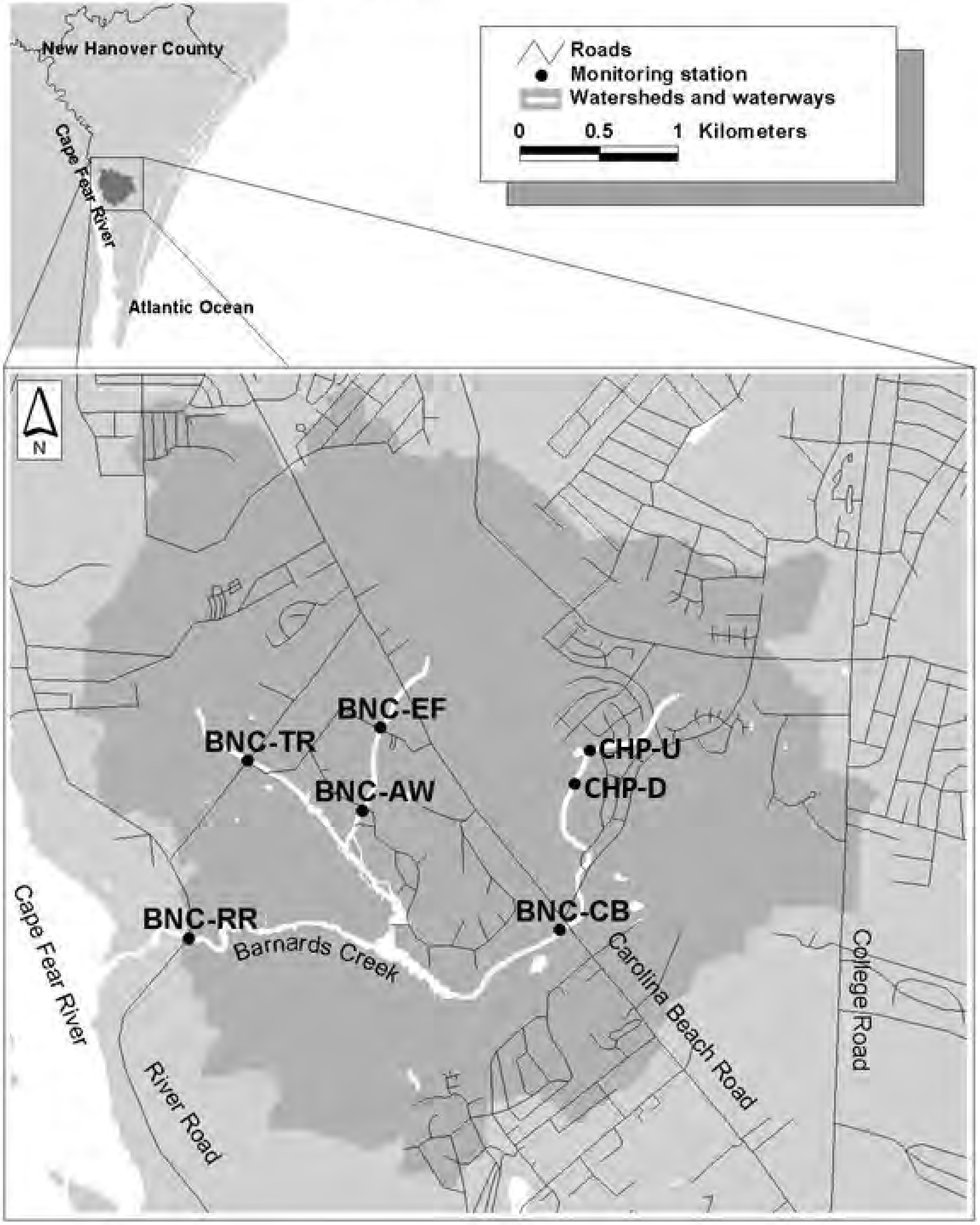
Lower Barnard's Creek drains single family and multifamily housing upstream of Carolina Beach Rd. in the St. Andrews Dr. area and along Independence Boulevard near the Cape Fear River. Another major housing development (River Lights) is well under construction between Barnards and Motts Creeks. This 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. In October 2021 the City commenced funding UNCW to sample two locations on upper Barnards Creek adjacent to Carriage Hills wet detention pond, CHP-U and CHP-D.

The 2023 data (Table 2.1) show minor dissolved oxygen issues, but low turbidity and low total suspended solids (TSS). Nutrients were generally low; there was one minor algal bloom at CHP-U, and both sites exceeded the state fecal coliform standard sufficient to be rated Poor, with geometric means at CHP-U and CHP-D at 281 and 357 CFU/100 mL, respectively.

Table 7.1. Selected water quality parameters at sites upstream (CHP-U) and downstream (CHP-D) of Carriage Hills wet pond in upper Barnards Creek, 2023 as mean (standard deviation) / range, inorganic N/P ratios as mean / median, fecal coliform bacteria presented as geometric mean / range, n = 5 samples collected.

Parameter	CHP-U	CHP-D
Salinity (ppt)	0.1 (0) 0.1-0.1	0.1 (0) 0.1- 0.1
Turbidity (NTU)	4 (3) 2-7	3 (1) 2-4
TSS (mg/L)	5.9 (3.8) 1.3-11.3	3.8 (1.3) 2.7-6.0
DO (mg/L)	6.4 (1.4) 3.9-7.4	6.3 (0.9) 4.8-7.0
Nitrate (mg/L)	0.032 (0.022) 0.010-0.060	0.034 (0.023) 0.010-0.060
Ammonium (mg/L)	0.040 (0.050) 0.010-0.120	0.040 (0.050) 0.010-0.120
TN (mg/L)	0.540 (0.270) 0.180-0.820	0.770 (0.680) 0.180-1.900
Orthophosphate (mg/L)	0.026 (0.015) 0.010-0.050	0.022 (0.013) 0.010-0.040
TP (mg/L)	0.062 (0.022) 0.040-0.090	0.042 (0.031) 0.010-0.090
N/P inorganic	5.6 6.6	8.0 5.0
Chlorophyll *a* (µg/L)	8 (7) 0-19	9 (4) 4-13
Fecal col. (CFU/100 mL)	281 23-4,500	357 55-1.450

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 New Hanover County. There has been massive 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 another site, BC-RD on Racine Drive (see cover photo) was added in July 2021. Stream restoration activities are ongoing for this upper branch (also called Clear Run) and sampling at BC-CA was suspended in 2023 due to restoration related construction at the site. The drainage area for BC-RD is approximately 90% impervious surface coverage. Thus, there were five samples collected at most sites in 2023. Sampling at BC-CA began again in January 2024 with cessation of construction in that area.

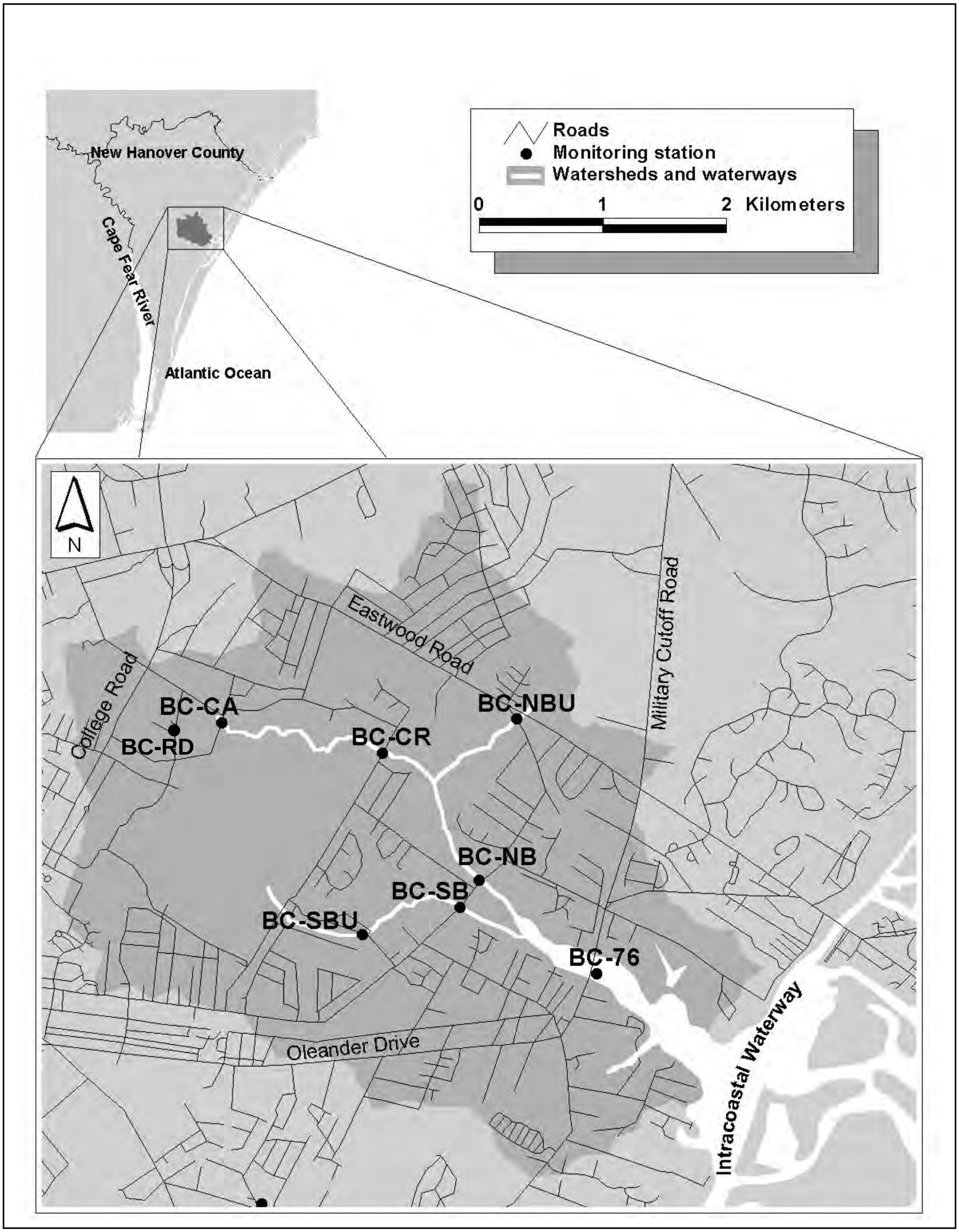
Turbidity was not a problem during 2023; the standard of 25 NTU was not exceeded (Table 3.1). There are no NC ambient standards for total suspended solids (TSS), but UNCW considers 25 mg/L high for the Coastal Plain. As such, TSS reached 24.5 and 26.3 mg/L on one occasion in our 2023 samples. Dissolved oxygen did not go below standard (< 5.0 mg/L) during our 2023 collections.

Nitrate concentrations were low to moderate at all sites, but ammonium was elevated above 0.300 µg-N/L on several occasions at all three sites (Table 3.1). Orthophosphate concentrations were low in general at all the sites. Algal blooms did not occur at our sites in 2023. Median nitrogen to phosphorus ratios at BC-NB and BC-SB were high; as orthophosphate was low but ammonium was unusually high. Fecal coliform bacteria counts were moderate at the two stations on Wrightsville Avenue (Table 3.1) but counts were high at BC-RD with a geometric mean of 5,165 CFU/100 mL, and a maximum of 12,000 CFU/100 mL 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 (>90%) 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, 2023. Data as mean (SD) / range, N/P ratio as mean/median, fecal coliform bacteria as geometric mean / range, n = 6 samples collected. BA-CA was not done in 2023 due to restoration construction work at the site.

Station	BC-RD	BC-CA	BC-NB	BC-SB
Salinity (ppt)	0.1 (0.1) 0.1-0.2		24.2 (14.1) 0.3-35.2	16.8 (12.3) 0.3-34.6
DO (mg/L)	5.8 (0.7) 4.8-6.8		6.8 (1.0) 5.9-8.5	6.6 (1.2) 5.4-8.5
Turbidity (NTU)	4 (3) 1-9		6 (6) 1-17	8 (13) 1-31
TSS (mg/L)	3.7 (1.8) 1.3-5.6		16.1 (5.8) 8.3-24.5	14.6 (7.2) 6.5-26.3
Nitrate (mg/L)	0.06 (040) 0.01-0.10		0.03 (0.05) 0.01-0.11	0.02 (0.03) 0.01-0.08
Ammonium (mg/L)	0.49 (0.44) 0.02-0.99		0.32 (0.33) 0.01-0.69	0.19 (0.17) 0.01-0.43
TN (mg/L)	1.27 (0.54) 0.76-2.01		0.67 (0.38) 0.38-1.20	0.65 (0.37) 0.22-1.02
Orthophosphate (mg/L)	0.03 (0.02) 0.01-0.05		0.03 (0.03) 0.01-0.07	0.02 (0.02) 0.01-0.05
TP (mg/L)	0.13 (0.10) 0.04-0.28		0.13 (0.14) 0.03-0.36	0.10 (0.30) 0.04-0.28
N/P	17 16		42 22	24 19
Chlorophyll *a* (µg/L)	4 (2) 2-7		3 (2) 1-7	4 (2) 2-6
Fecal coliforms (CFU/100 mL)	5,165 1,250-12,000		83 14-6,000	337 82-1,550

Figure 3.1. Bradley Creek watershed and sampling sites.



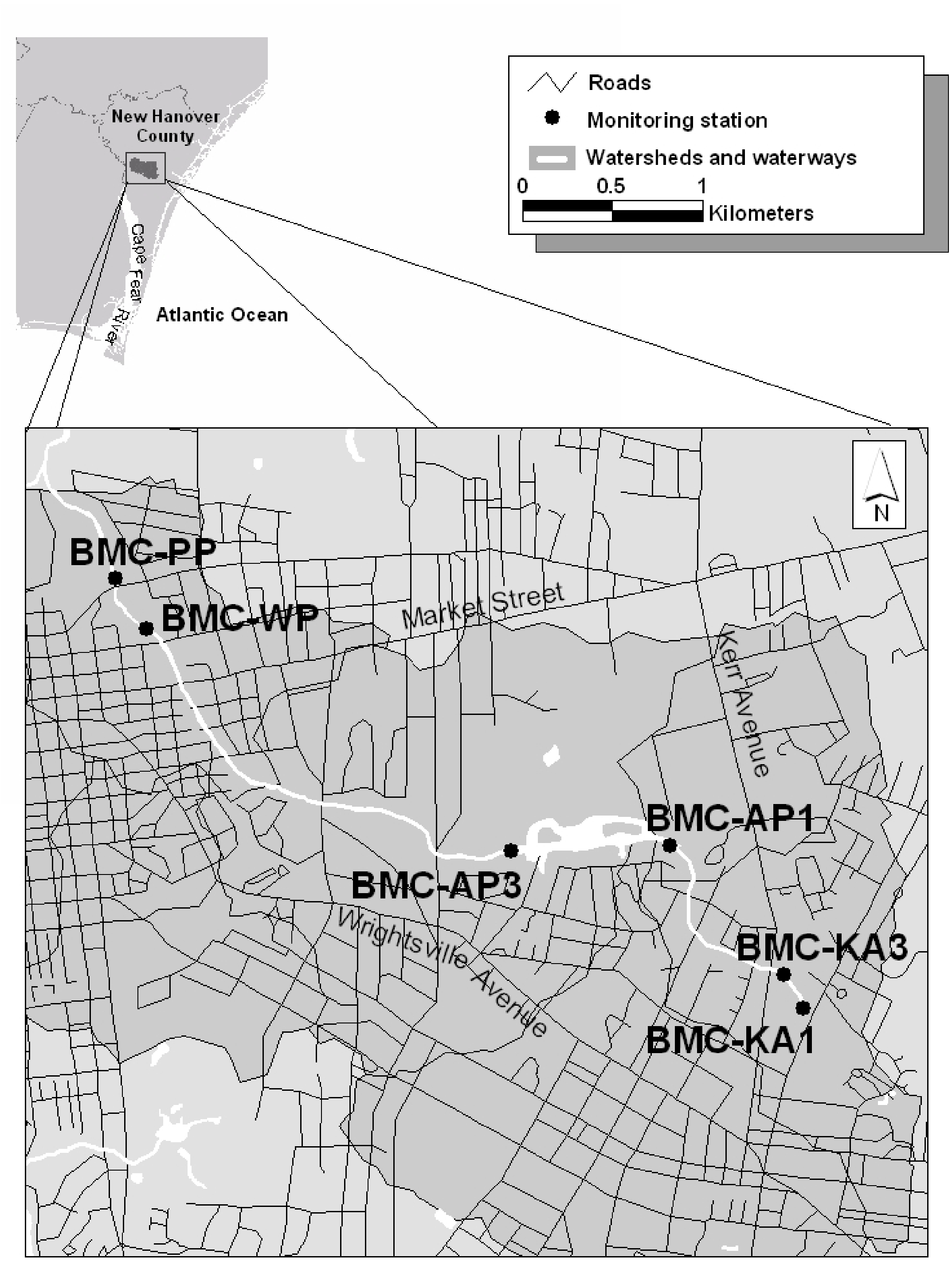
4.0 Burnt Mill Creek

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), water hyacinth overgrowths in 2021

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; 2009b; 2010; 2011; Mallin and Cahoon 2024). 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. We note that in 2021 there was a large nuisance growth of water hyacinth *Eichhornia crassipes* that completely blocked the creek.

<u>Sampling Sites</u>: During 2023 samples were collected on six occasions from BMC-PP and BMC-AP3, and three occasions at BMC-AP1 (sampling at that site ended as City priorities changed in summer 2023) (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.



The Upper Creek

About one km downstream from Kerr Avenue along Randall Parkway is the large regional wet detention pond known as Ann McCrary Pond. Data were collected at the input (BMC-AP1) on three occasions and the outflow (BMC-AP3) stations on six occasions in 2023. Dissolved oxygen concentrations were within standard on all sampling occasions at BMC-AP3 and below standard once at BMC-AP1. DO and pH both showed an 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 2023 sampling, but on average there was a slight increase through the pond. Total suspended solids concentrations were low to moderate on most sampling occasions in 2023, but there was a considerable increase through the pond on average (Table 4.1). Fecal coliform concentrations at both Ann McCrary Pond stations were generally low, exceeding the state standard only once at BMC-AP3 (Table 4.1). There was a reduction in average fecal coliform counts during passage through the regional detention pond (Table 4.1). In 2023 there was one major algal bloom of 92 µg/L chlorophyll *a* at Station BMC-AP3, and minor blooms of 26 µg/L at BMC-AP1 and 25 µg/L at BMC-AP3. There was an increase in chlorophyll *a* between AP1 and AP3. Regarding nutrients, there was a decrease in nitrate concentrations through the pond, but an increase in TP between AP1 and AP3 (Table 4.1).

Lower Burnt Mill Creek

The Princess Place location (BMC-PP) was the only lower creek station sampled in 2023. One parameter that is key to aquatic life health is dissolved oxygen. Dissolved oxygen at BMC-PP was below standard (< 5.0 mg/L) on four 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.

The North Carolina water quality standard for chlorophyll *a* is 40 µg/L. In 2023 there was a bloom of 34 µg/L at BMC-PP. 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).

In waters where the inorganic N/P ratio is well below 16 (the Redfield Ratio for algal nutrient composition; Hecky and Kilham 1988) 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. At AP-1, mean and median N/P rations were near the Redfield Ratio, but after passage though the pond N/P ratios dropped to 9 and 9, respectively (below the Redfield Ratio), indicating that the algae and macrophytes in the pond took up more N relative to P. Ratios increased downstream at BMC-PP to 14 and 11, respectively along with increases in nutrients, especially N.

Important from a public health perspective are fecal coliform bacteria counts. AP-1 and AP-3 had geometric means below the state standard, but BMC-PP had a geometric mean of 255 CFU/100 mL. That station exceeded the State standard for human contact waters (200 CFU/100 mL) on two occasions in our 2023 samples. Fecal coliform counts were greater than the State standard on 33% of sampling occasions at BMC-PP, and on 18% of occasions at AP-3. Whereas geometric mean fecal coliform counts at BMC-AP3 were 36 CFU/100 mL, counts then increased along the passage to the Princess Place location (geometric mean 255 CFU/100 mL; Fig. 4.2), as in previous years. It is likewise notable that nitrate, ammonium, total phosphorus and orthophosphate 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, 2023

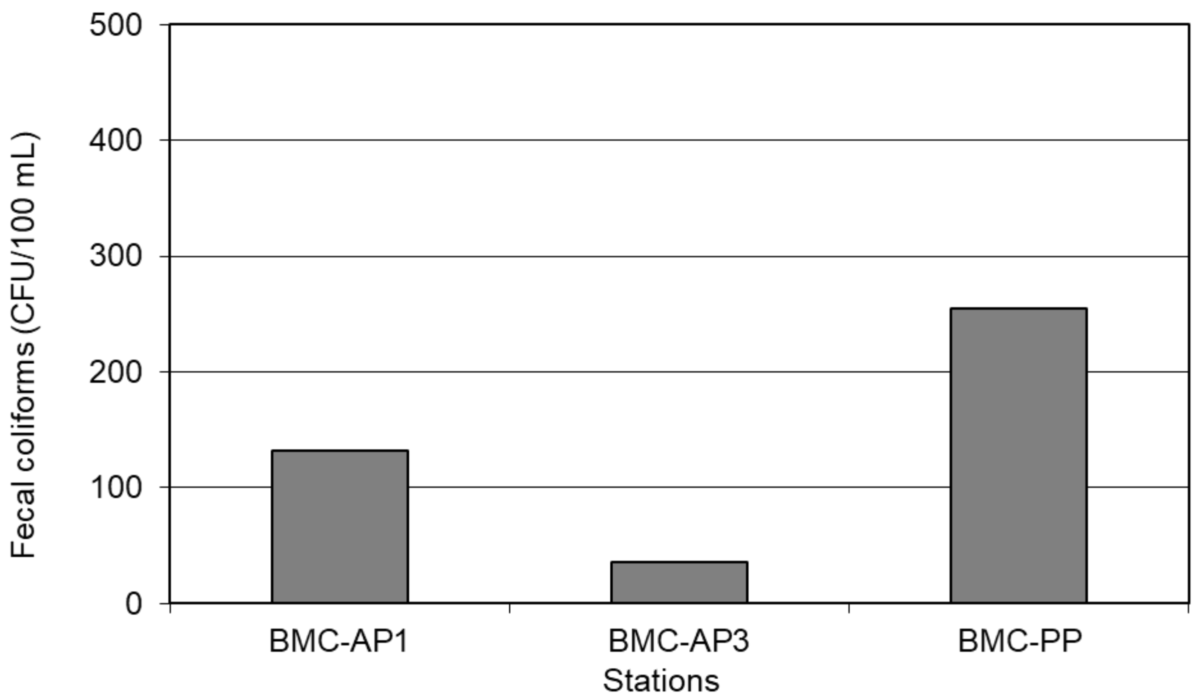
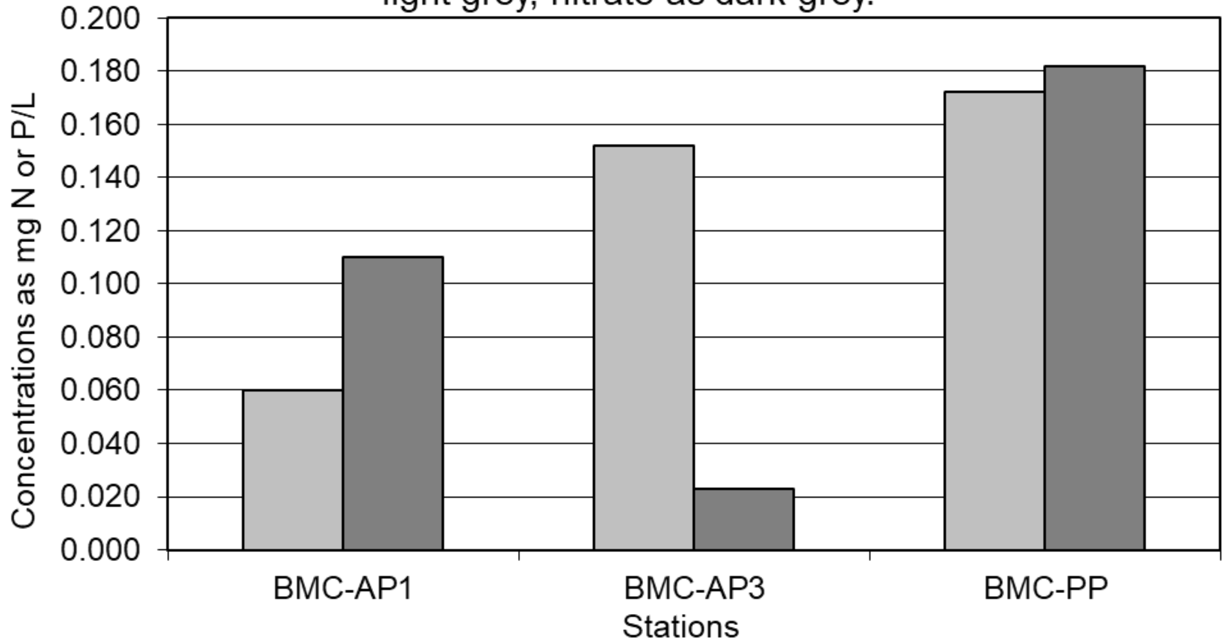


Table 4.1. Water quality data in Burnt Mill Creek, 2023, as mean (standard deviation)/range. Fecal coliforms as geometric mean; N/P as mean/median, n = 6 samples collected, except AP-1 which had three samples taken due to site change priorities.

Parameter	BMC-AP1	BMC-AP3	BMC-PP
DO (mg/L)	6.1 (3.5) 2.7-9.6	10.2 (0.6) 9.1-10.7	5.4 (1.6) 3.4-7.7
Cond. (μS/cm)	270 (6) 266-277	214 (21) 181-235	782 (566) 380-1,831
pH	7.0 (0.1) 6.9-7.1	7.9 (0.2) 7.6-8.1	7.2 (0.1) 7.1-7.4
Turbidity (NTU)	4.7 (4.0) 1.0-9.0	8.3 (3.0) 6.0-14.0	4.0 (1.3) 2.0-5.0
TSS (mg/L)	1.2 (3.2) 1.3-7.6	11.4 (6.3) 4.9-20.7	7.0 (2.7) 3.7-11.9
Nitrate (mg/L)	0.110 (0.044) 0.080-0.160	0.023 (0.022) 0.010-0.060	0.182 (0.074) 0.060-0.270
Ammonium (mg/L)	0.027 (0.015) 0.010-0.040	0.053 (0.049) 0.010-0.120	0.075 (0.034) 0.010-0.100
TN (mg/L)	0.717 (0.350) 0.360-1.060	0.877 (0.692) 0.410-2.170	0.870 (0.416) 0.400-1.610
OrthoPhos. (mg/L)	0.023 (0.006) 0.020-0.030	0.020 (0.006) 0.010-0.030	0.047 (0.020) 0.020-0.070
TP (mg/L)	0.060 (0.020) 0.040-0.080	0.152 (0.107) 0.060-0.320	0.172 (0.122) 0.070-0.410
N/P molar ratio	12.8 14.0	8.7 8.9	14.3 10.7
Chlor. *a* (μg/L)	11 (13) 1-26	28 (32) 10-92	12 (12) 1-34
FC (CFU/100 mL)	132 105-150	46 3-728	150 105-132

To summarize, in some years Burnt Mill Creek has had problems with low dissolved oxygen (hypoxia) at the Princess Place station BMC-PP, and in 2023 most samples were below standard. One major algal bloom occurred in May 2023 at BMC-AP-3 (92 µg/L chlorophyll *a*; also in May a minor bloom occurred at BMC-PP (34 µg/L). The N/P ratios in the lower creek indicate that inputs of nitrogen were likely to stimulate algal bloom formation in 2023, 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 BMC-PP and occasionally at the upper sites. 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 total phosphorus and nitrate concentrations by station for Burnt Mill Creek, 2023; TP as light grey, nitrate as dark grey.

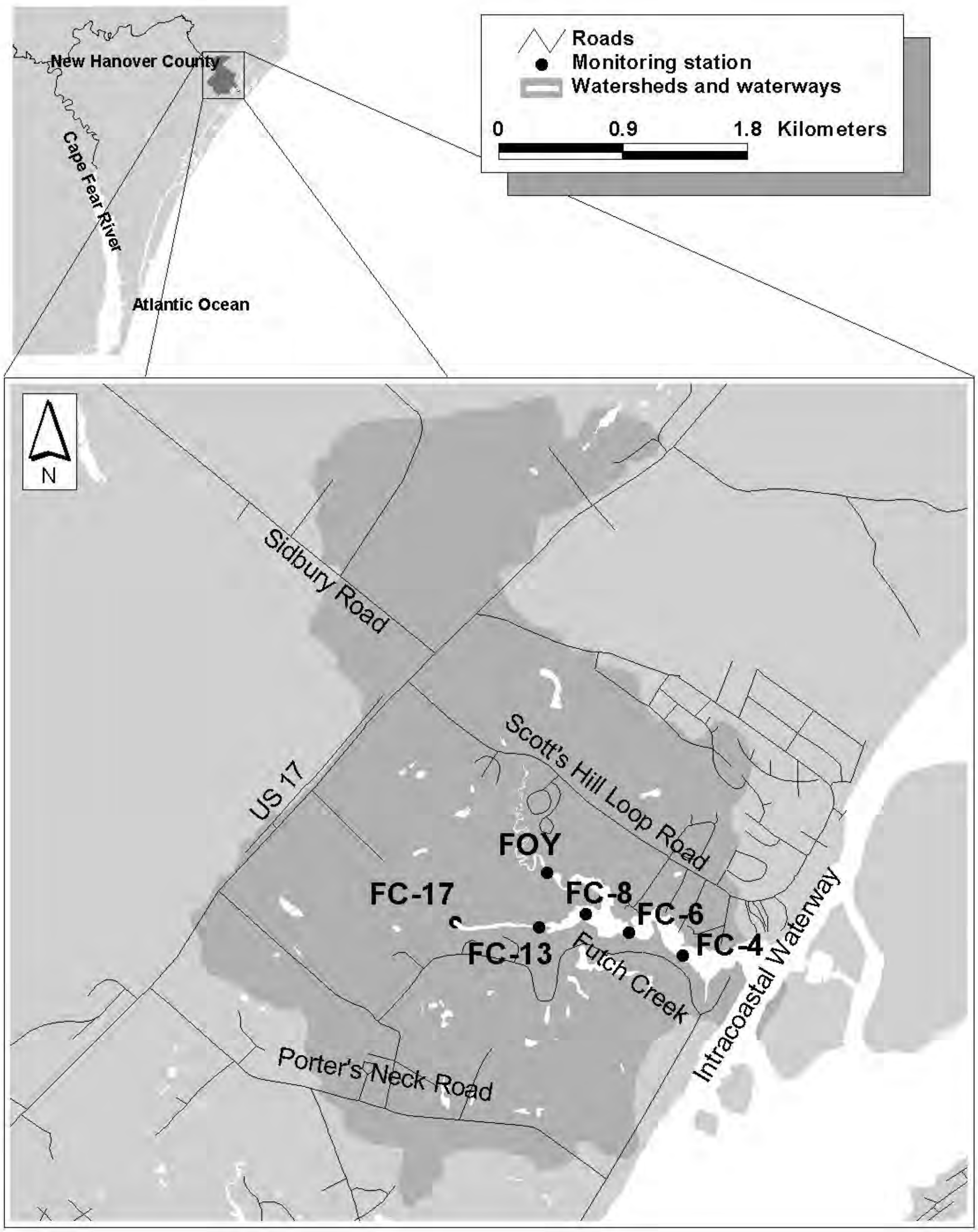


5.0 Futch Creek

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. A private firm is sampling Futch Creek for the County and the County should be contacted for information.

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, low dissolved oxygen, and nutrient loading in tributaries, high BOD and algal blooms in main lake, sediments contaminated with metals, PAHs and phosphorus

Three stations on tributaries to Greenfield Lake were sampled for a full suite of physical, chemical and biological parameters on 10 occasions in 2023 (Table 6.1, Fig. 6.1). Some tributary stream sites suffered from low dissolved oxygen (DO), as GL-SQB (Squash Branch, formerly called GL-LB) showed DO concentrations below the state standard (DO < 5.0 mg/L) on 75% of sampling occasions (Table 6.1; Appendix B). Station GL-JRB (Jumping Run Branch) had substandard DO on two sampling occasions, while JRB-17 had no violations. 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 likewise low at the stream stations (Table 6.1).

Nitrate, ammonium and TN concentrations were highest at GL-SQB with JRB-17 and GL-JRB also elevated (Table 6.1). Highest phosphorus concentrations occurred at 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. The chlorophyll *a* concentration was high in September at GL-JRB with a bloom of 31 µg/L. The geometric mean fecal coliform bacteria counts for 2023 exceeded the state standard at all three tributary stations (Table 6.1), and the fecal coliform standard was exceeded on >45% of sampling dates at all three stations.

Table 6.1. Mean and (standard deviation) / range of selected field water quality parameters in tributary stations of Greenfield Lake, 2023. Fecal coliforms (FC) given as geometric mean, N/P ratio as mean / median; n = 10 samples collected.

Parameter	JRB-17	GL-JRB	GL-SQB (formerly GL-LB)
DO (mg/L)	7.1 (1.4) 5.7-9.3	6.8 (2.3) 3.0-10.5	4.2 (2.1) 2.1-8.8
Turbidity (NTU)	3 (3) 1-8	2 (1) 1-3	2 (2) 1-6
TSS (mg/L)	4.7 (5.6) 1.3-20.0	3.8 (2.0) 1.3-7.5	6.0 (4.4) 1.3-12.5
Nitrate (mg/L)	0.14 (0.07) 0.01-0.26	0.10 (0.06) 0.03-0.21	0.30 (0.13) 0.02-0.49
Ammon. (mg/L)	0.15 (0.13) 0.01-0.50	0.06 (0.04) 0.01-0.12	0.12 (0.07) 0.03-0.23
TN (mg/L)	0.95 (0.39) 0.36-1.61	0.91 (0.58) 0.33-1.91	1.20 (0.38) 0.64-1.96
Ortho-P. (mg/L)	0.05 (0.04) 0.01-0.13	0.05 (0.04) 0.02-0.12	0.06 (0.04) 0.03-0.15
TP (mg/L)	0.47 (0.68) 0.04-2.20	0.24 (0.36) 0.01-1.23	0.28 (0.37) 0.06-1.29
Inorganic N/P ratio	20 19	10 11	19 21
Chlor. *a* (µg/L)	5 (4) 1-12	10 (8) 2-31	4 (4) 1-13
FC (CFU/100 mL)	470 150-6,000	344 120-344	404 137-6,500

Three in-lake stations were sampled on 12 occasions (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 (< 5.0 mg/L) did not occur at GL-P and once at GL-YD in 2023 (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 May of 24 mg/L at GL-YD, concurrent with an algal bloom of 93 µg/L as chlorophyll *a*. In-lake fecal coliform concentrations exceeded the standard three times at GL2340, once at GL-YD and not at all at GL-P.

Concentrations of all inorganic nutrients in-lake were mixed with highest nitrate at the upstream station GL-2340, but highest TN and TP at the lower stations where the highest algal biomass was (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 at GL-2340 can likely be limited by P due to the higher N at that upper lake location, but ratios at GL-YD and GL-P were low, indicating that algae 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, although P can stimulate blooms at GL-2340 at times (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; in 2023 an extensive bloom of the blue-green *Anabaena spiroides* was sampled in May and June (then sampling was forced to cease until new funding arrived). As such, two blooms exceeding the North Carolina water quality standard of 40 μg/L of chlorophyll *a* were sampled at GL-YD and one at GL-P, but none at GL-2340. For the year 2023, chlorophyll *a* exceeded the state standard on 10% of occasions sampled. The North Carolina Division of Environmental Quality placed this lake on the 303(d) list in 2014 for high chlorophyll. Biochemical oxygen demand (BOD5) for 2023 was elevated at GL-YD and GL-P in summer-fall (Table 6.1) with a maximum of 87 mg/L in at GL-P in May. 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; Iraola et al. 2022).

Table 6.2. Mean and (standard deviation) / range of selected field water quality parameters in lacustrine stations of Greenfield Lake, 2023. Fecal coliforms (FC) given as geometric mean, N/P ratio as mean / median; n = 10 samples collected.

Parameter	GL-2340	GL-YD	GL-P
DO (mg/L)	5.0 (1.5) 3.3-8.0	9.4 (2.2) 6.0-12.6	10.0 (3.4) 5.6-15.6
Turbidity (NTU)	1 (1) 0-3	3 (5) 0-15	2 (4) 0-12
TSS (mg/L)	2.7 (2.7) 1.3-9.0	4.4 (4.7) 1.3-16.1	4.4 (7.1) 1.3-23.8
Nitrate (mg/L)	0.22 (0.18) 0.01-0.57	0.01 (0.01) 0.01-0.02	0.01 (0.00) 0.01-0.01
Ammonium (mg/L)	0.06 (0.08) 0.01-0.26	0.06 (0.-09) 0.01-0.25	0.05 (0.06) 0.01-0.16
TN (mg/L)	0.82 (0.52) 0.26-2.10	1.01 (0.97) 0.15-3.44	0.87 (0.74) 0.33-2.65
Orthophosphate (mg/L)	0.05 (0.05) 0.01-0.16	0.05 (0.05) 0.01-0.16	0.09 (0.09) 0.01-.027
TP (mg/L)	0.27 (0.34) 0.02-1.19	0.32 (0.40) 0.04-1.30	0.33 (0.39) 0.03-1.21
N/P molar ratio	19 13	9 2	3 2
Fec. col. (CFU/100 mL)	155 38-1,200	10 3-230	8 3-100
Chlor. *a* (µg/L)	2 (2) 1-6	30 (60) 2-195	16 (28) 3-93
BOD5	3.0 (1.7) 2.0-7.0	3.5 (3.0) 2.0-11.0	11.9 (28.2) 2.0-87.0

Figure 6.1. Greenfield Lake watershed.

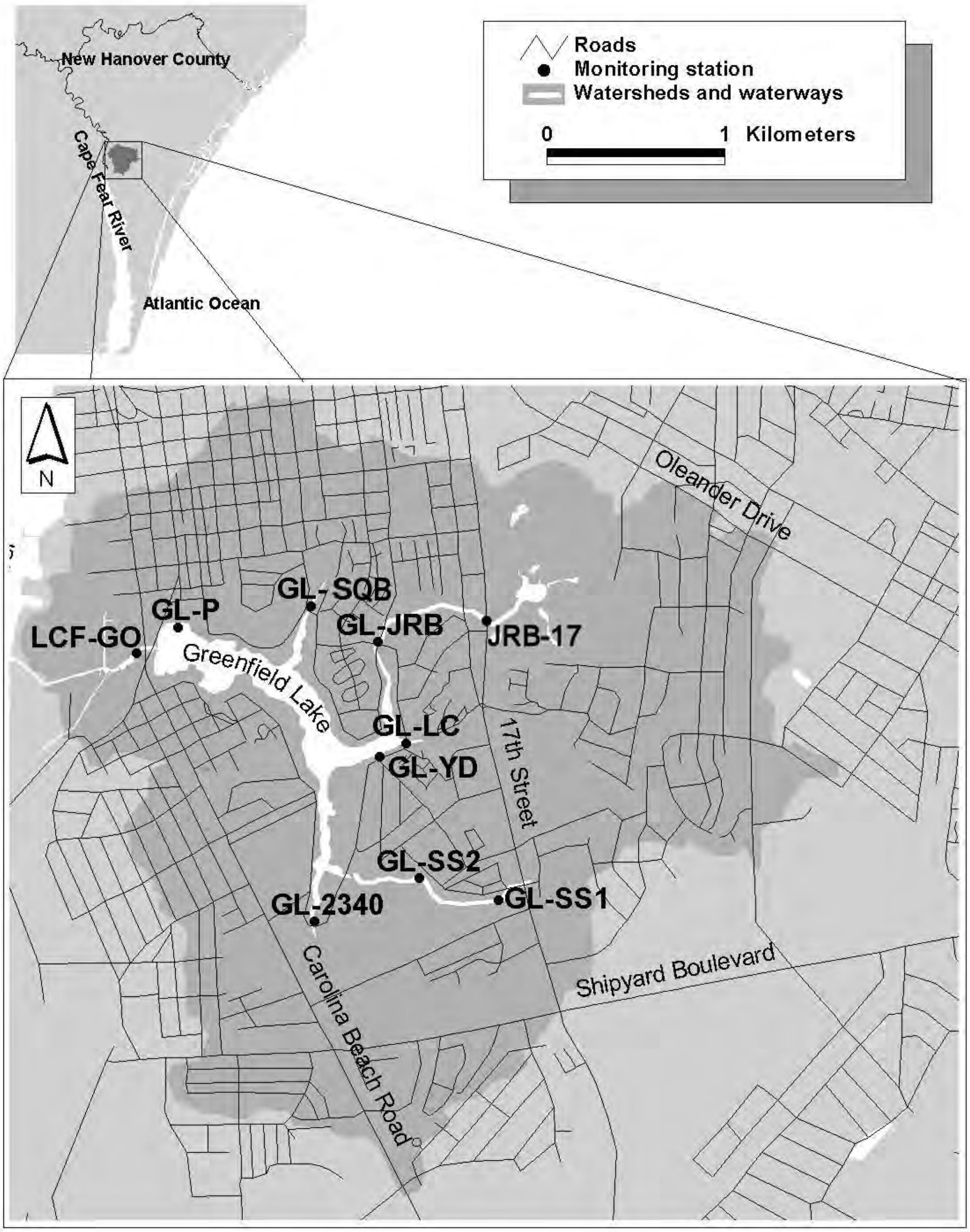
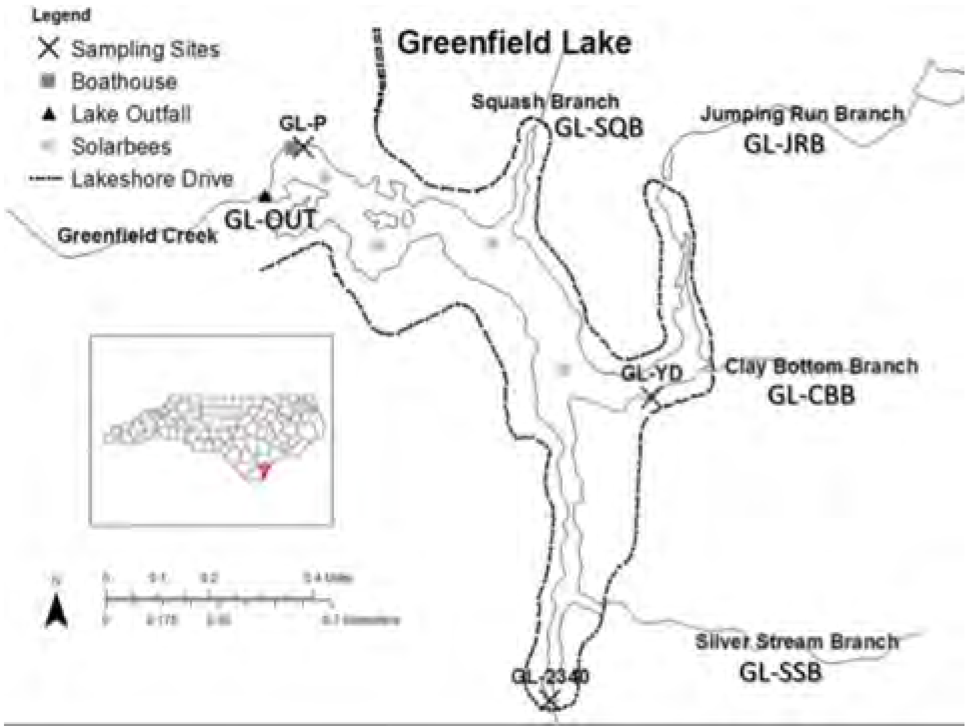


Figure 6.2. Greenfield Lake feeder stream stations sampled at various times; note that GL-SQB is also known as GL-LB, and GL-CBB is also known as GL-LC.



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: Good-Fair
Problematic pollutants: occasional high fecal bacteria, minor algal bloom issues

Hewletts Creek was sampled five times at four tidally influenced areas (HC-3, NB-GLR, MB-PGR and SB-PGR) - 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 (Table 7.2). Dissolved oxygen was within standard on all sampling occasions except one deviation to 4.9 mg/L.

Nitrate concentrations were low at all sites except MB-PGR (Table 7.1) which receives inputs from the Wilmington Municipal Golf Course (Fig. 7.1; Mallin and Wheeler 2000). Ammonium concentrations were low to moderate at most sites but highest at HC-3. Possible due to excretia from the oyster reefs upstream. Total nitrogen was low to moderate at all sites. Orthophosphate concentrations were low, and total phosphorus concentrations ranged from low to moderate. Mean N/P ratios were high in most sites except MB-PGR, indicating that at times P can stimulate algal growth at most of these sites. The chlorophyll *a* data (Tables 7.1) showed that no major blooms occurred during the sampling runs; HC-3 had one minor bloom of 21 µg/L chlorophyll *a* in June. 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 the State standard once each at SB-PGR, NB-GLR and HC-3, but exceeded standard on all five sampling occasions at MB-PGR, where the geometric mean was 765 CFU/100 mL. The geometric mean of fecal bacteria counts at HC-3 was 34 CFU/100 mL, above the shellfishing standard of 14 CFU/100 mL (due to one high incident of 8,500 CFU/100 mL in June.

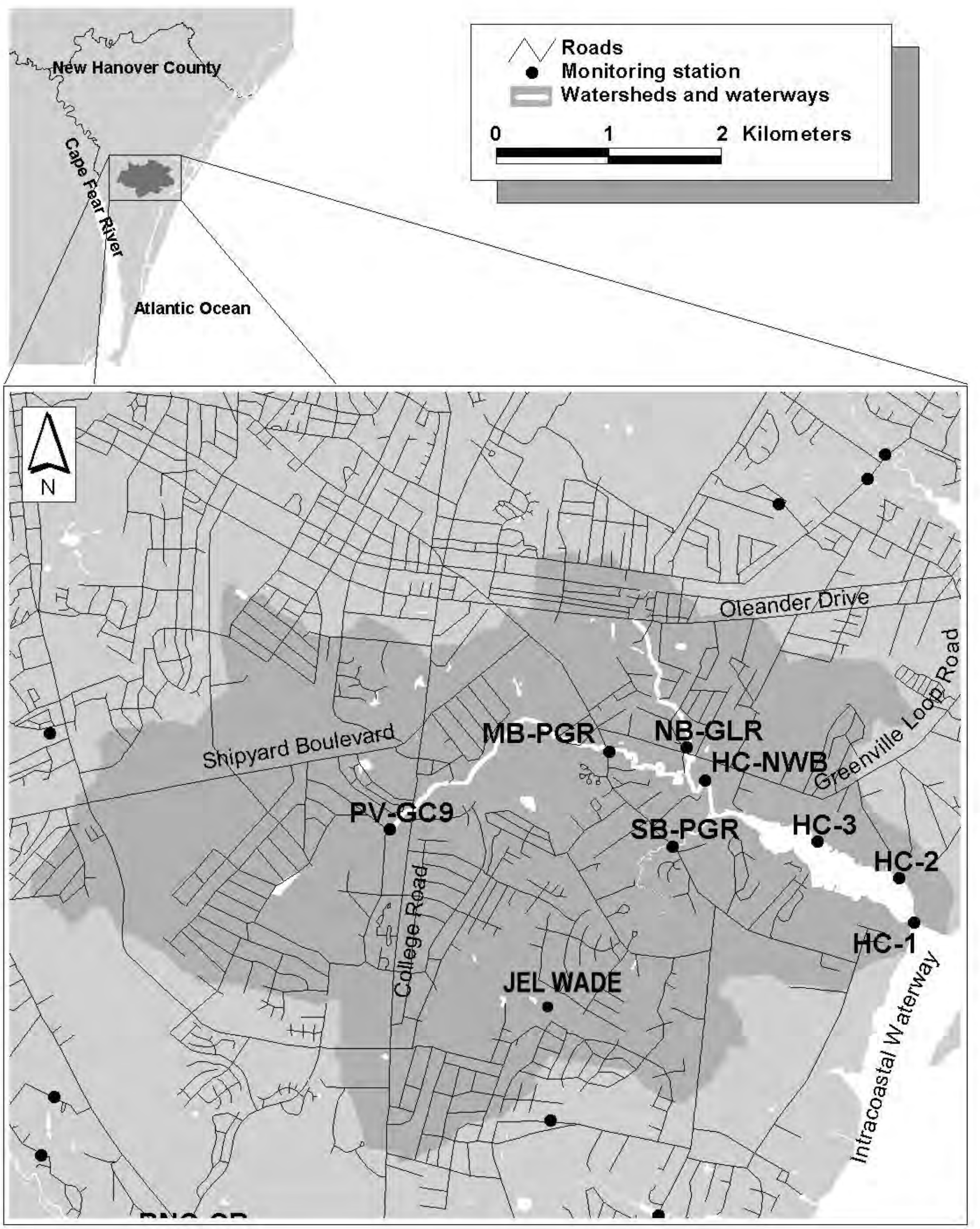


Figure 7.1. Hewletts Creek watershed.

Table 7.1. Selected water quality parameters at stations in Hewletts Creek watershed, 2023, as mean (standard deviation) / range, fecal coliforms as geometric mean / range, n = 5 samples collected.

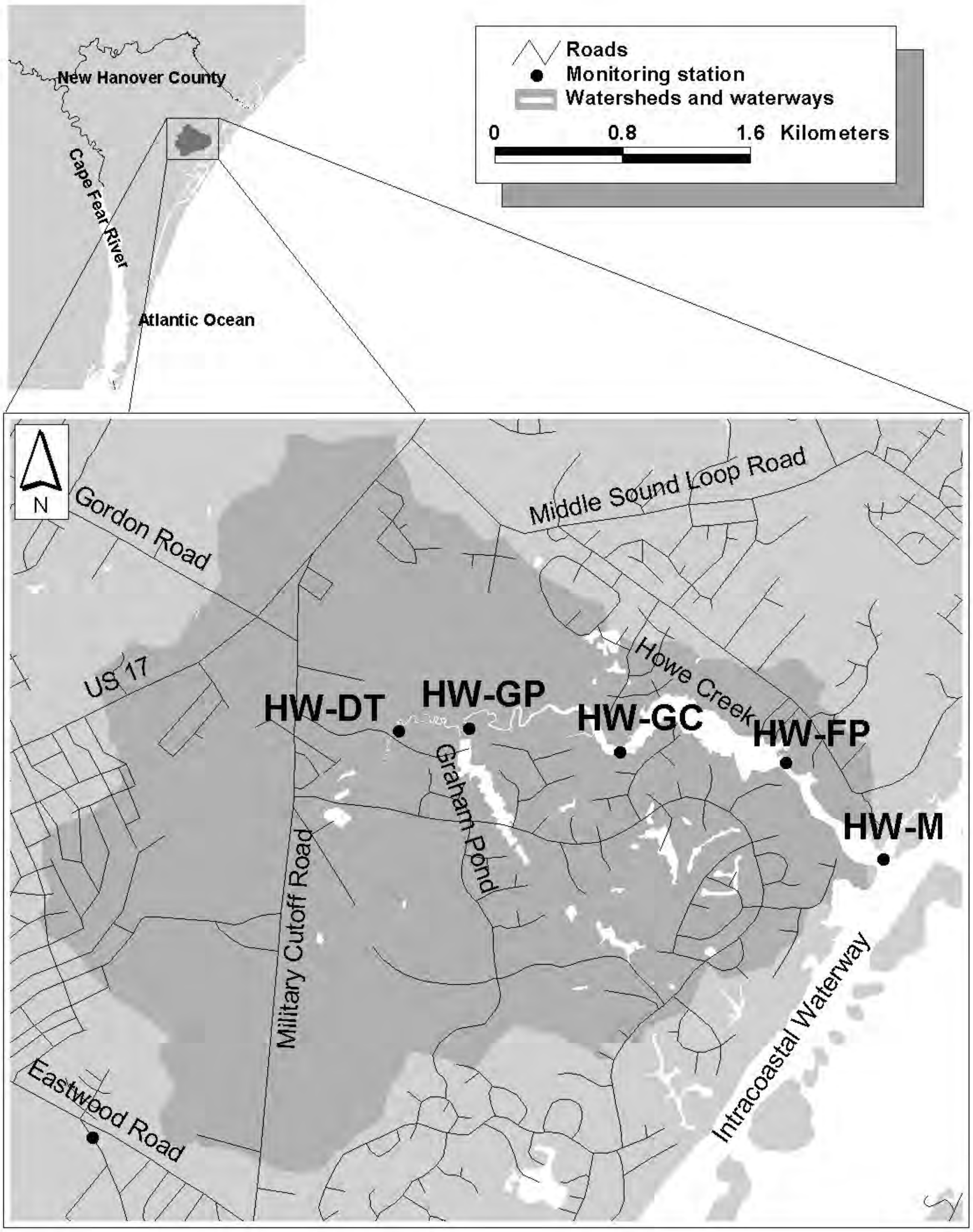
Parameter	SB-PGR	MB-PGR	NB-GLR	HC-3
Salinity (ppt)	26.0 (14.1) 1.1-35.5	3.6 (7.4) 0.1-16.6	19.3 (12.3) 0.4-34.9	28.5 (11.9) 10.7-34.7
Turbidity (NTU)	4 (4) 1-10	3 (2) 1-6	6 (6) 2-15	4 (5) 0-12
TSS (mg/L)	15.9 (17.6) 9.3-21.2	4.2 (2.1) 1.3-6.8	13.4 (3.9) 8.5-18.0	14.5 (5.1) 10.4-21.7
DO (mg/L)	6.7 (1.1) 5.9-8.3	6.8 (1.3) 4.9-8.1	6.6 (1.2) 5.6-8.5	7.6 (0.9) 6.7-8.7
Nitrate (mg/L)	0.04 (0.04) 0.01-0.10	0.17 (0.11) 0.01-0.29	0.04 (0.04) 0.01-0.11	0.03 (0.04) 0.01-0.09
Ammonium (mg/L)	0.24 (0.26) 0.01-0.66	0.02 (0.02) 0.01-0.06	0.21 (0.19) 0.01-0.48	0.40 (0.36) 0.01-0.74
TN (mg/L)	0.62 (0.28) 0.27-1.04	0.69 (0.27) 0.27-0.95	0.72 (0.58) 0.05-1.35	0.85 (0.38) 0.44-1.30
Orthophosphate (mg/L)	0.03 (0.02) 0.01-0.06	0.03(0.01) 0.02-0.05	0.02 (0.02) 0.01-0.06	0.03 (0.02) 0.01-0.06
TP (mg/L)	0.07 (0.05) 0.01-0.14	0.08 (0.03) 0.05-0.12	0.15 (0.09) 0.08-0.31	0.06 (0.02) 0.03-0.08
Mean N/P ratio Median	53 49	15 14	27 20	55 23
Chlor *a* (µg/L)	5 (4) 1-12	6 (4) 0-13	4 (3) 1-8	6 (10) 0-21
Fecal coliforms (CFU/100 mL)	46 5-9,500	765 275-3,500	188 19-188	34 3-8,500

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 resource re-allocation, sampling was suspended for the time being starting in 2020.

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

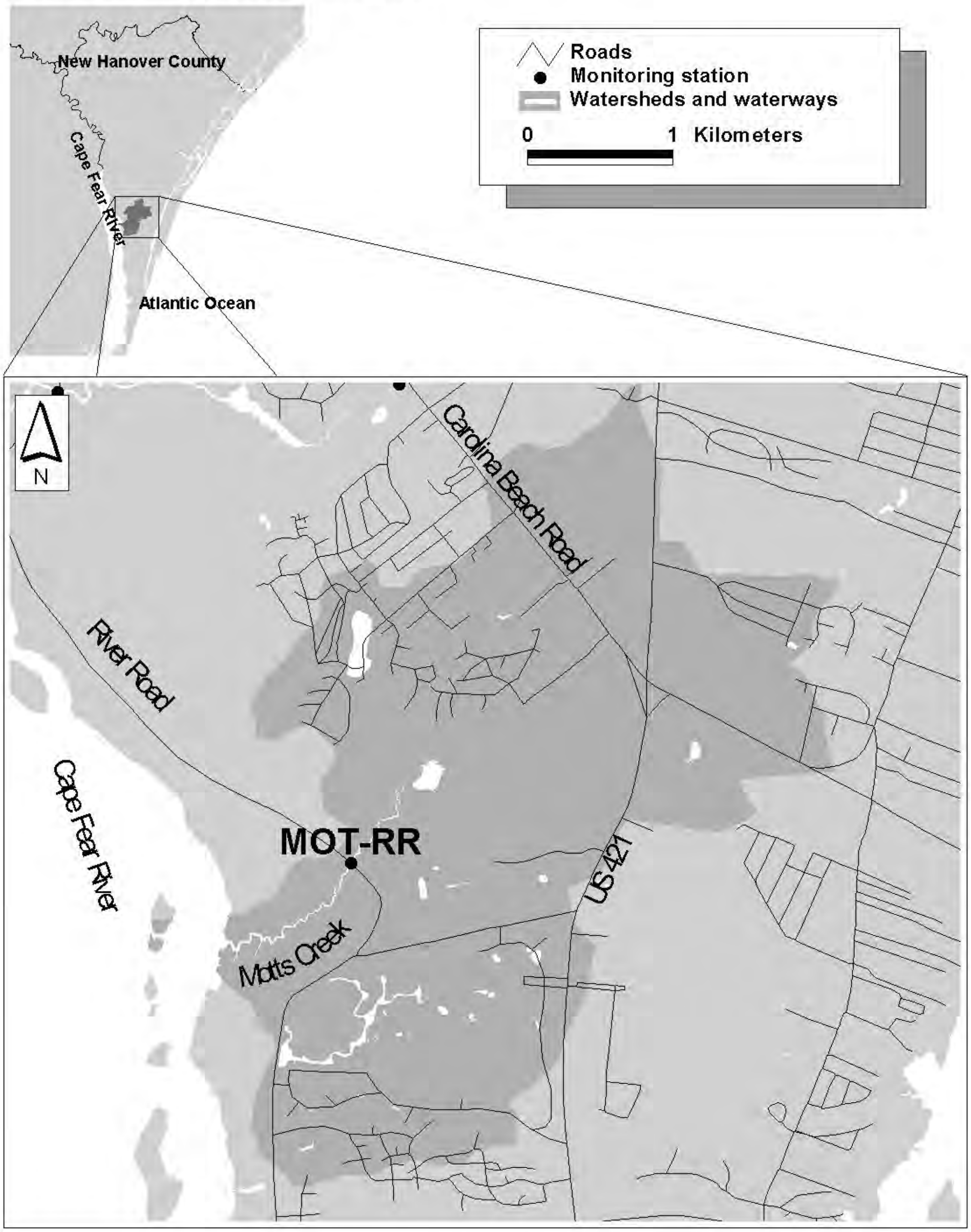


9.0 Motts Creek

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 resource re-assignment, city sampling is currently suspended on this creek.

Figure 9.1 Motts Creeks watershed

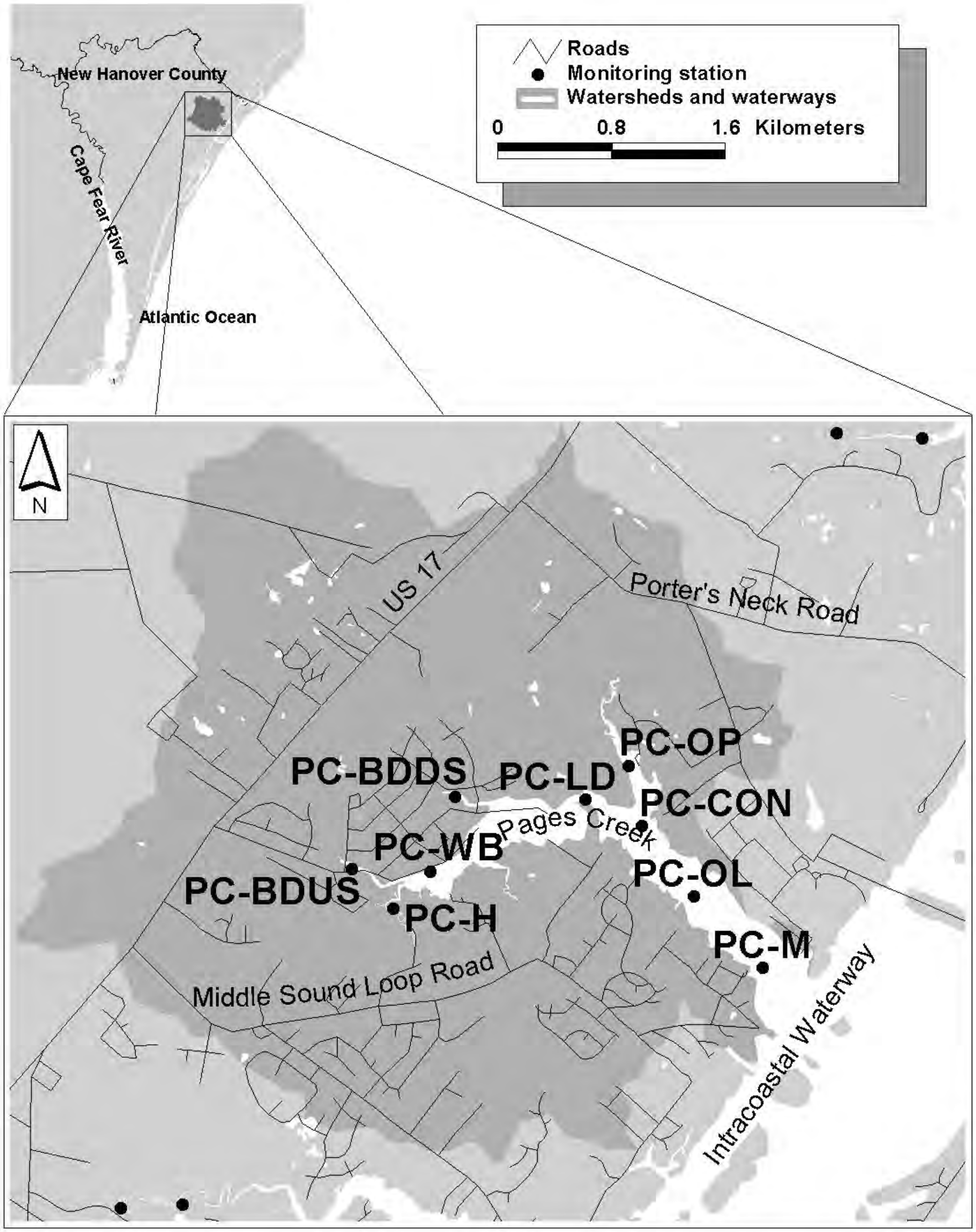


10.0 Pages Creek

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 Protection & 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.

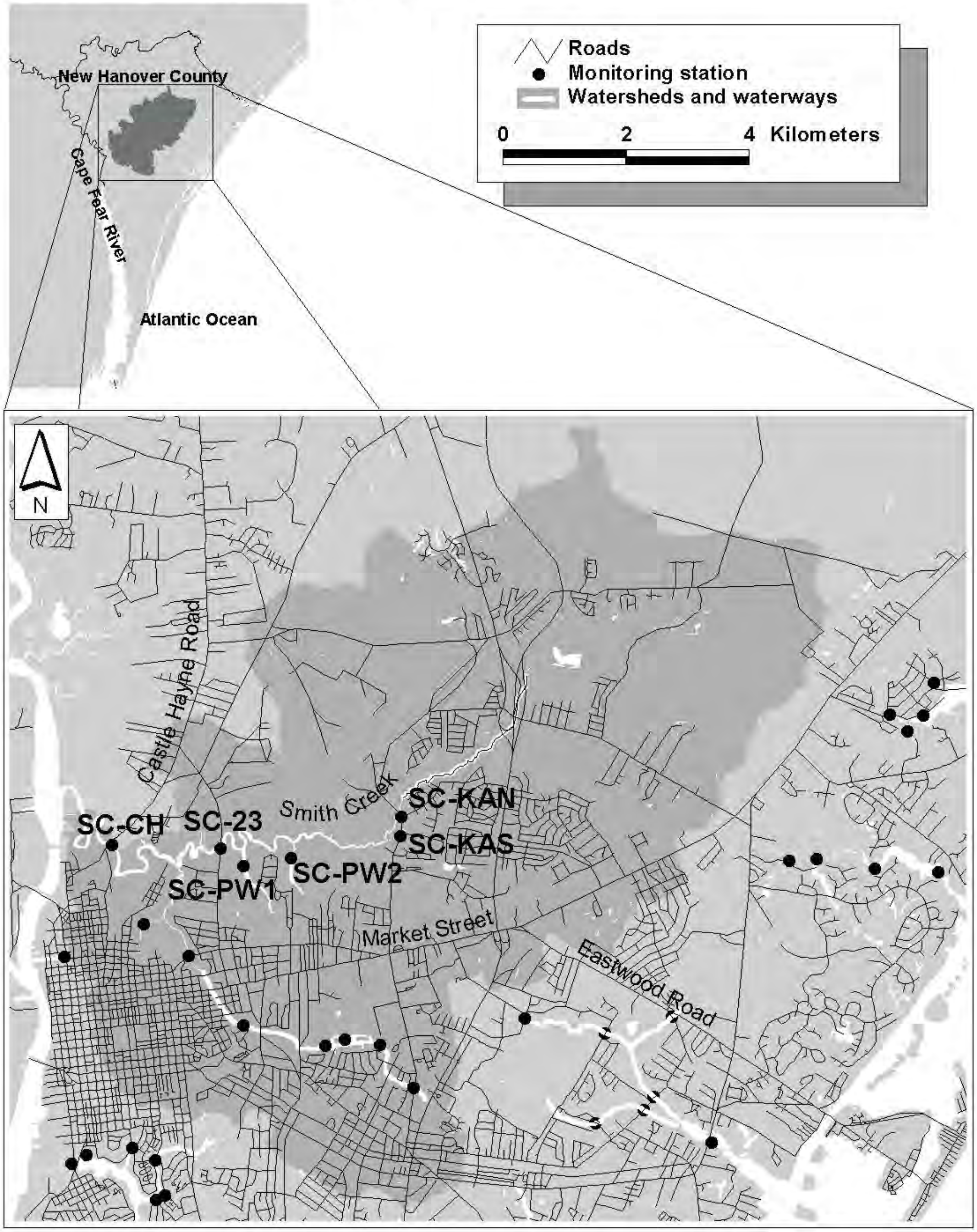


11.0 Smith Creek

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 normally 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 normally summarized below (Table 11.1). However, note that in 2023 no samples were collected as bridge construction was ongoing all year at the sampling station. Sampling has begun again in 2024.

Figure 11.1 Smith Creek watershed

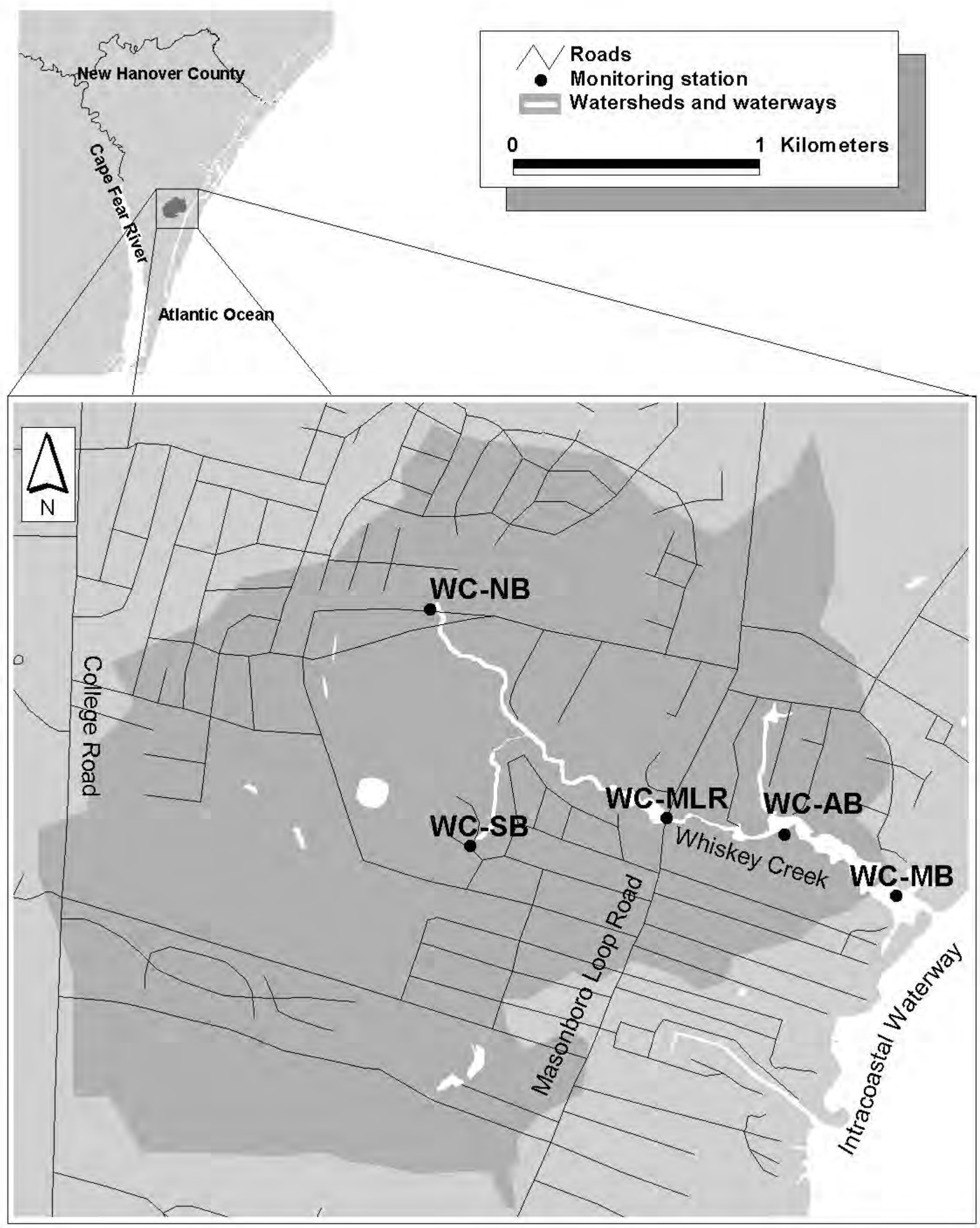


12.0 Whiskey Creek

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.



Chapter 13.0 Sediment Metals and PAH Sampling Study Overall Results

As noted in the Methods, in summer and fall 2022 the sediments of 20 wet detention ponds within the City of Wilmington were collected and scanned for key metals and PAHs. Collections were made by sampling the upper 5 cm of sediments with plastic tubes, mixing several samples together in a bowl, then using the composite for analyses (see cover photo). Samples were frozen and sent to a state-certified laboratory for analyses of various metals and polycyclic aromatic hydrocarbons (PAHs). We were also interested in sediment phosphorus (P) for its various contributions to eutrophication (Mallin and Cahoon 2020). As such, sediment P was quantified in Dr. Cahoon's laboratory at UNCW using two methods, water soluble and Melich II, for extractive, refractory P (see Parsons et al. 1984; Mehlich 1984). The set of 20 ponds included Carriage Hill Pond in the Barnard's Creek basin, and three inflow areas to Ann McCrary Pond in the Burnt Mill Creek basin, and Municipal Golf Course Pond 1.

Academic researchers (MacDonald et al. 2000) devised a set of guidelines for potential sediment toxicity in which harmful effects of aquatic life are likely to occur, based on experiment and/or epidemiological data. Sediment concentrations below the TEC (see Table 1 below) are concentrations where negative impacts are unlikely to occur, concentrations between the TEC and PEC are where negative effects may occur, and concentrations above the PEC are where negative effects are likely to occur.

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

Goals

Our goals were to obtain the magnitudes of sediment pollution, and try to determine what on land factors led to greater pond pollution, and what pond factors led to higher sediment pollution levels. As such, drainage areas and pond areas were computed, as well as pond age, sediment size and sediment organic composition (as loss on ignition). Methods are provided in the final report to the Attorney General's Office (Mallin and Cahoon 2024).

Table 1. Sediment quality guidelines for freshwater for selected metals and organic pollutant concentrations potentially harmful to aquatic life (as TEC (threshold effects) and PEC (probable effects; MacDonald et al. 2000), compared with the mean, standard deviations and medians of the entire detention pond set of 20, compared with the means of a control pond (Lily Pond in Carolina Beach State Park). Bolded mean concentrations exceed the TEC or PEC. Metals as mg/kg dry wt., PAHs as µg/kg dry wt.). The low concentrations of PAHs in Lily Pond represent one-half the detection limit.

Pollutant	TEC	PEC	ponds mean		ponds std. dev.	ponds median	Lily Pond mean
Metal							
Arsenic (As)	9.79	33.0	6.65	±	9.0	3.10	1.13
Cadmium (Cd)	0.99	4.98	0.73	±	0.4	0.53	0.57
Chromium (Cr)	43.4	111.0	12.36	±	12.1	7.80	0.57
Copper (Cu)	31.6	149.0	**48.30**	±	61.1	21.50	3.51
Lead (Pb)	35.8	128.0	25.36	±	52.9	11.80	10.60
Mercury (Hg)	0.18	1.06	0.06	±	0.07	0.03	0.02
Nickel (Ni)	22.7	48.6	5.69	±	6.7	2.50	1.20
Zinc (Zn)	21.0	459.0	**69.47**	±	213.1	**69.30**	**37.40**
Total PAHs	1,610.0	22,800.0	**21,480.1**	±	40,670.4	800.0	252.0
Anthracene	57.2	845.0	**251.1**	±	259.8	141.0	126.0
Benzo(a)pyrene	150.0	1,450.0	**1,560.9**	±	2,816.9	188.0	126.0
Chrysene	166.0	1,290.0	**2,101.6**	±	4,077.7	188.0	126.0
Fluoranthene	423.0	2,230.0	**3,958.5**	±	7,410.9	263.0	126.0
Pyrene	195.0	1,520.0	**3,280.1**	±	6,341.4	233.0	126.0

Table 2. The most polluted wet pond sediment sites in the Wilmington watersheds system and associated major pollutants (based on the TEC and PEC from MacDonald et al. 2000).

City Operations runoff pond	PAHs, As, Cr, Cu, Pb, Ni, Zn, Hg, P
Preston Woods (large suburban pond)	PAHs, As, Cd, Cu, Zn, Hg, P
Eastport Pond (dense suburban)	PAHs, As, Cr, Cu, Zn, P
RBDM-N (commercial area)	PAHs, As, Cd, Cu, Zn, P
RBDM (commercial area)	Cd, Cu, Pb, Zn, P
Anne McCrary regional pond, lower input	PAHs, Cu, Pb, Zn, P
Pine Valley Country Club parking lot pond	PAHs, Cu, Zn, P
Art Museum pond	Cd, Cu, Zn, P
Silver Stream wet pond (institutional, retail)	PAHs

Statistical Analysis

Summary statistical analyses were performed using Excel, with further statistical analyses performed using the Statistical Analysis System, SAS (Schlotzhauer and Littell 1997). Prior to analyses, all sediment parameters were tested for normality using the

Shapiro-Wilk Test, and non-normal data sets were log-transformed prior to correlation analysis, including all metals, PAHs and phosphorus, as well as the demographic factors watershed area and watershed impervious surface area. To assess the effect of landscape factors on sediment pollutant concentrations correlation analyses between pollutant parameters and watershed area and percent impervious surface coverage were performed. To analyze potential in-pond pollutant retention factors pollutant parameter concentrations were correlated against pond sediment grain size (as median grain size). Loss on ignition (LOI), which represents the percent organic composition of the sediments, was also tested against pollutant concentrations, as was pond age. For more detail see Mallin and Cahoon (2024).

Results

Sediment phosphorus: As noted, sediment P was quantified using two methods, water soluble and Melich II, for extractive, refractory P. The water-soluble fraction will be referred to as “labile” and the refractory as “extractive”. Among the wet ponds, labile P ranged from 0.6-46.5 µg/g; average 10.4 ± 10.6 and median 7.3 µg/g. Refractory P concentrations were far broader, with a range of 20.6-570.5 µg/g; average181.8 ± 149.6, median 117.0 µg/g. The ponds with highest sediment phosphorus included the City Operations pond, the two detention ponds in the Burnt Mill Business District near Randall Parkway, the large regional Preston Woods pond, the Eastport pond (residential), and Marsden Branch (the downstream-most tributary entering Ann McCrary regional pond on Randall Parkway, and the art museum pond (Table 2).

Sediment chemical pollutants – distribution and concentrations
In general, the most common and abundant metals encountered in polluting concentrations (i.e. exceeding the TEC or PEC; Table 1, Table 2) included copper (9 ponds), zinc (8 ponds), cadmium (6 ponds), arsenic (4 ponds) and lead (3 ponds). The individual PAHs most widespread in high concentrations were anthracene (all ponds, due to its low TEC level; Table 2), pyrene (12 ponds), chrysene and benzo(a)pyrene (10 ponds) and fluoranthene (7 ponds); note that total PAHs exceeded the TEC or PEC in 8 ponds (Table 1). Unsurprisingly, the City Operations detention pond had high levels of numerous metals and various PAHs. This pond collects drainage from the City garages and garbage truck servicing area, so various pollutants were expected. However, the suburban/residential wet ponds were a mixed bag in terms of pollutants. Two of the residential wet detention ponds, Eastport pond and Preston Woods pond were among the most polluted ponds in the system (Table 2). The Eastport pond drains a very dense suburban development with very little greenspace. The sampling teams photographed surface algal blooms and goose manure lining the shoreline. Preston Woods pond drains a very large suburban and retail area and has several storm drains entering it; its sediments were likewise substantially polluted. Other detention ponds such as moderately residential Carriage Hills pond and Sterling Place pond had very clean sediments. We were pleasantly surprised that all three ponds associated with fire stations had generally clean sediments; fire truck servicing petrochemicals and whatever firefighting chemicals the firefighters worked with on-site were collected and disposed of properly. Legion Stadium 3 is a pond that adjoins a former fire training tower, and various barrels are stored on a concrete pad behind locked gates; this pond collects drainage from the training site but its sediments were likewise clean.

The two wet ponds within golf course greens areas were likewise low in sediment metals and PAHs (note that pesticides and herbicides were not sampled). Another wet detention pond that collects runoff from one of the tees but also a course parking lot had very high PAH, Cu and Zn concentrations (Table 2); note that the parking lot is heavily used every day by golfers, staff and other club users. Sites draining institutional and commercial areas such as the ponds in the Burnt Mill Business Park (PAHs and various metals) and Silver Stream (PAHs) were polluted: Silver Stream pond forebay drains a largely commercial and institutional area. The downstream-most input to the large regional Ann McCrary Pond (Marsden Branch, AP-RA) had relatively high levels of sediment pollution, considerably higher than the other two tributary branches entering the regional pond farther upstream. The wet detention pond on the grounds of the Cameron Art Museum had Cd, Cu and Zn exceeding the TEC, but low PAH concentrations. The ponds with the lowest sediment chemical pollutant levels included a wet pond in Empie Park located near tennis courts, and our control pond, Lily Pond in Carolina Beach State Park (very low with the exception of elevated zinc, Table 1).

<u>Landscape factors impacting sediment chemical pollutants</u>: Watershed surface area was not a significant factor controlling pond sediment pollution; it was not significantly related to either metals or PAHs. However, watershed <u>impervious</u> surface coverage proved to be a driving factor. One metal, chromium (Cr), was positively related to percent impervious surface coverage (Fig. 1), and several PAHs were significantly related to impervious coverage including total PAHs (Fig. 2), anthracene, fluoranthene and pyrene. Total watershed impervious area was positively correlated with total PAHs, fluorine and pyrene ($p < 0.05$). Regarding sources, neither form of P was significantly related to watershed size. However, the concentration of water-soluble sediment P was significantly ($r = 0.465$; $p = 0.034$) related to watershed percent impervious surface coverage, although refractory P was not. Wet pond surface area was not related to sediment chemical concentrations. Pond age was also not significantly related to sediment chemical pollution. This is not surprising as there was low variability in pond age among the 20 constructed ponds; average age was 25.2 years + 7.1 years, range 10-34 years.

<u>Sediment factors influencing chemical pollutant concentrations</u>: Correlation analyses were run between sediment pollutant concentrations and key sediment characteristics. Surprisingly, most metals and PAHs were mostly not inversely related to smaller grain size with the exception of lead ($r = -0.453$; $p = 0.039$). Refractory P was, however, inversely correlated with grain size ($r = -0.453$; $p = 0.037$).

Loss on ignition (LOI), which represents the percent organic composition of the sediments, was also tested against total PAH concentration (log-transformed). Sediment organic content was a major factor associated with chemical pollutant concentrations. All metals tested were significantly ($p < 0.05$) related to increasing organic concentration, especially zinc and cadmium (Fig. 3). Also positively correlated with increasing sediment organic composition were total PAHs (Fig. 4), benzo(a)pyrene, chrysene, fluoranthene, and refractory P.

Discussion

The drainage basins that feed many of the sampled ponds accumulate and channel polluted runoff from commercial, institutional and residential areas results in significant amounts of pollution in the sediments of many tested ponds. Bottom sediments are subject to accumulation of elevated loads of phosphorus, metals and chemical pollutants, and the biota are exposed as well in such ponds. Thus, bottom sediments, especially in the forebay should be removed every two to five years. Pond construction usually requires a permit by state or municipal authorities, and there is often a checklist associated with their upkeep. Inspections are technically required periodically but in reality, depend on regulatory agency manpower availability and priorities. Sediments accumulate over time in such ponds and infilling will reduce the pond's storage capacity and effectiveness.

Watershed features and detention pond pollutant accumulation: Percent watershed impervious surface coverage has been demonstrated to be an effective proxy for the degree drainage basins are developed. In the present study watershed impervious surface was demonstrated to be a significant driver of pond sediment pollution, especially of PAHs. It is important to realize that with the exception of one of the golf course ponds (2.3% impervious cover) and the control pond (0)% impervious cover), the detention ponds sampled herein can be considered to have highly developed watersheds, with mean impervious cover percentage of 42.8% and median 43.2% (maximum 69%).

Water features within the watershed that retain runoff before entering a larger regional pond make a difference in downstream water quality. Station AP-1 is a catch basin at the upper end of the regional Ann McCrary Pond. While it has a high impervious cover of 49%, catch basin sediment chemical pollution was low, no metals exceeding the TEC and most PAHs low. This is because there is a small, constructed wetland about 1 km upstream that first captures runoff from a major traffic artery (College Road) and the associated institutional (the university) and retail runoff. An October 2006 sediment sample collected by our team from the sediments in this small wetland yielded very high PAH concentrations (total PAHs = 17,660) as well elevated fluoranthene, chrysene, pyrene, and copper. Thus, it appears that this additional, although much smaller upstream wetland serves an important buffer function regarding reducing chemical pollutant passage downstream. Station AP-DB (i.e. Downey Branch), with 42% impervious cover, also had rather low sediment metals, but a few elevated PAHs. Upstream along this branch there is an apartment complex that features some pervious pavement and a wet detention pond that overflows into the branch; in 2022 the city also widened the branch adjacent to this complex to increase retention time, and retaining pollutants. In contrast, Station AP-RA that enters the regional pond farther downstream nearest the dam showed high sediment Cu, Pb and Zn as well as very high PAHs. The stream that feeds this station, Marsden Branch, has no upstream water features to capture runoff from the 45% impervious coverage areas upstream. As such, it contained by far the highest degree of chemical pollution among its sediments.

Pond features and pollutant retention: Overall, the sediment pollutants had no significant relationship with pond size. This is not surprising, as for the ponds with welldefined forebays we sampled forebay sediments instead of the main pond (in order to collect where incoming sediments had the greatest impact. There was no significant relationship between sediment size and pollutant content with the exception of refractory P.

Most notably, there was a significant and moderately strong correlation between LOI and various pollutants, meaning that as sediment composition becomes more organic, more pollutants are retained within the pond sediments and do not flow out of the pond overflow grate to pollute downstream water bodies (i.e. tidal creeks, lakes, etc.). To enhance retention of pollutants within stormwater ponds the bottom composition to aim for appears to be about 15% organic content (Figs. 3, 4).

This gives stormwater managers and pond construction engineers a target to attain when designing such stormwater control ponds. Certainly a way to achieve this may be to plant the pond perimeters with emergent native vegetation, which over time will increase sediment organic material as well as provide other services such as denitrification, direct nutrient uptake, and food and habitat for wildlife.

Summary

- Sediment samples from 20 urban wet detention ponds were collected in summer and fall 2022; to compare, a natural control pond was sampled from Carolina Beach State park.
- Considering the entire pond set, polycyclic aromatic hydrocarbons (PAHs) were abundant in the sediments, also certain metals such as zinc, copper, cadmium, arsenic and others.
- Pollutants were low in the control natural pond, golf course ponds, fire station ponds, ponds in recreational areas, and some suburban ponds.
- Pollutants were high in ponds draining dense suburban, commercial and institutional areas.
- Watershed percent impervious surface coverage was significantly correlated with sediment chromium concentration, as well as total PAHs and several individual PAHs, demonstration it as an important factor in delivering pollutant discharge form the landscape.
- Ponds with organic sediments retained significantly more metals, PAHs and phosphorus than ones with sandier sediments, with a breakpoint at about 15% organic composition, providing a useful construction goal to enhance retention of pollutants within wet detention ponds.

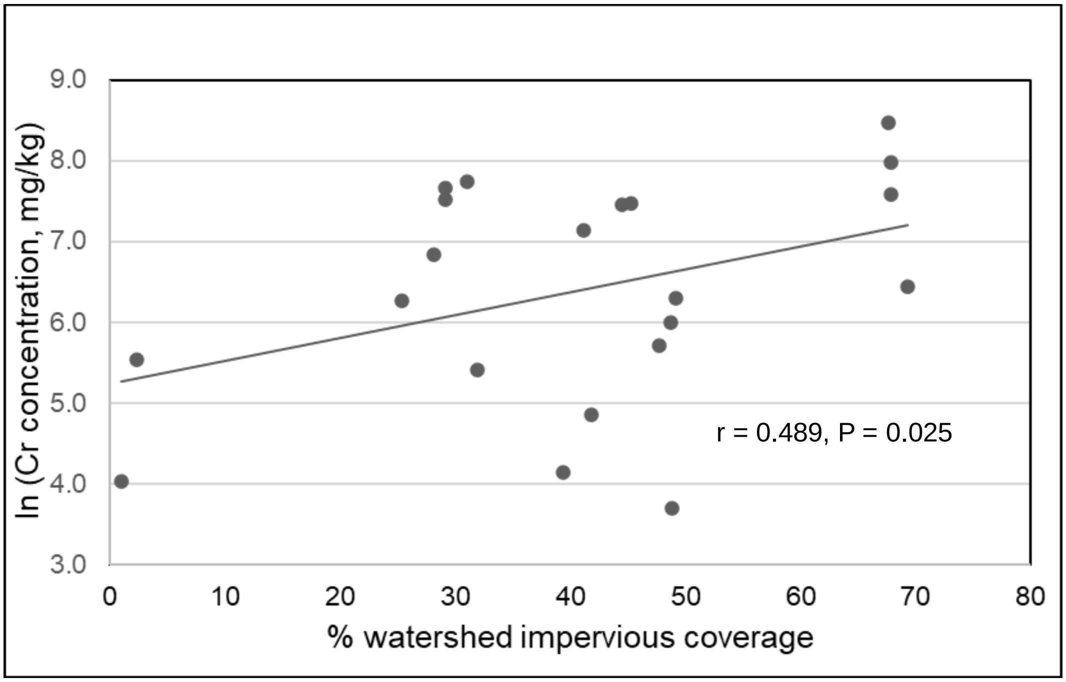


Figure 1. Sediment chromium concentration (log transformed) v percent watershed impervious surface composition.

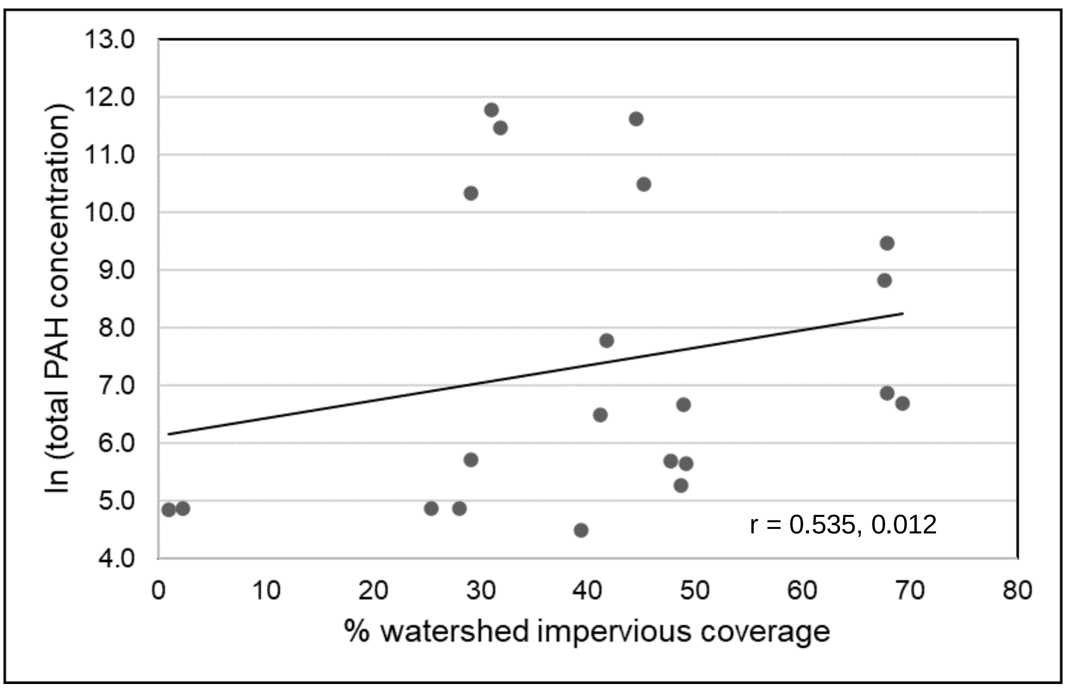


Figure 2. Sediment total PAH concentrations (log transformed) v percent watershed impervious coverage.

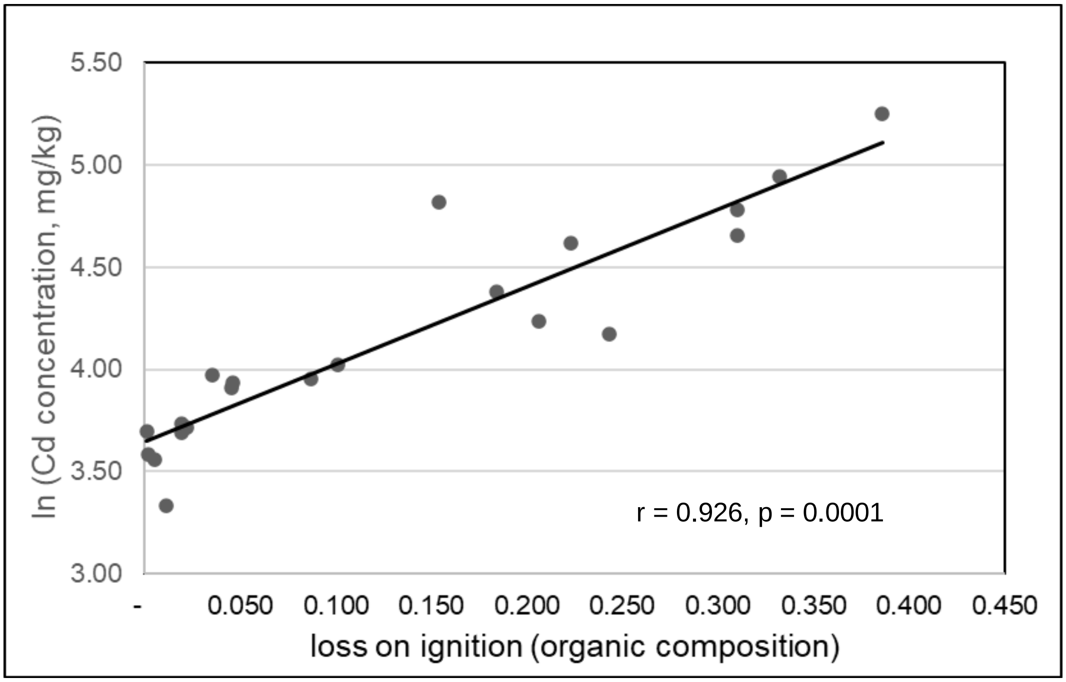


Figure 3. Sediment cadmium composition (log transformed) v loss of ignition (sediment organic composition). LOI can be multiplied by 100 to obtain % organic content.

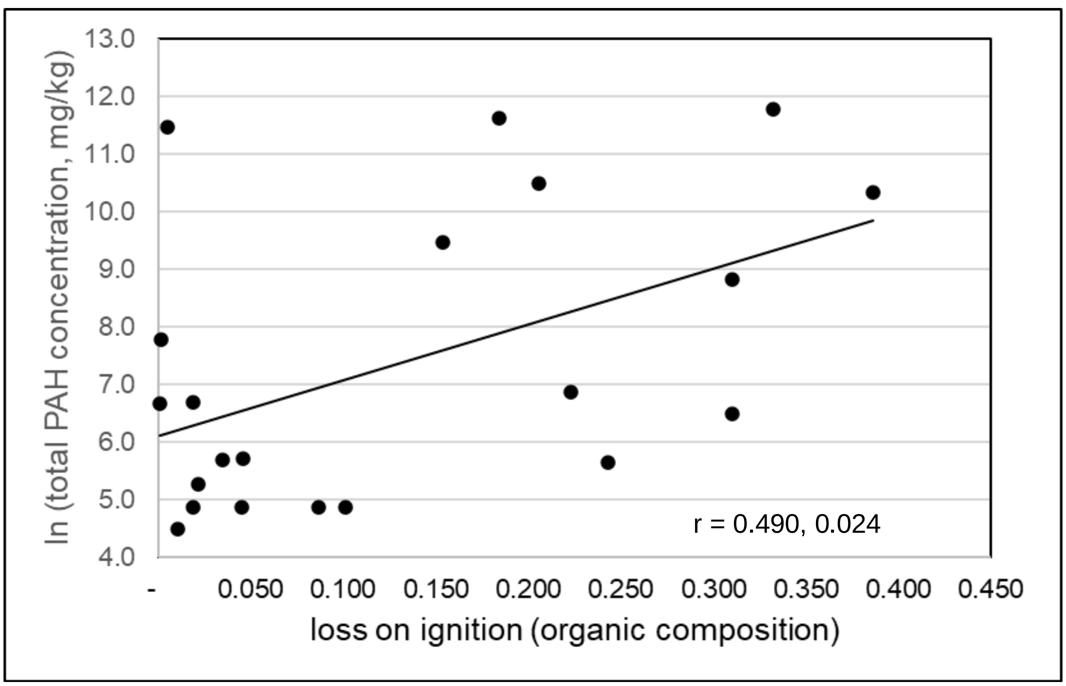


Figure 4. Sediment total PAH concentration (log transformed) v loss on ignition (sediment organic composition). LOI can be multiplied by 100 to obtain % organic content.

14.0 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., M.A. Mallin, L.B. Cahoon, D.W. Gamble and P.B. Zamora. 2022. Nutrient dynamics in a eutrophic urban blackwater lake. *Lake and Reservoir Management* 38:28-46.

MacDonald, D.D., C.G. Ingersoll and T.A. Berger. 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Archives of Environmental Contamination and Toxicology* 39:20-31.

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. and L.B. Cahoon. 2020. The hidden impacts of phosphorus pollution to streams and rivers. *BioScience.* 70:315-329.

Mallin, M.A., and L.B. Cahoon. 2024. *Investigating Publicly Owned Stormwater Control Systems as Reservoirs for Toxic Algae and Chemicals*. Final Report: 2022 – 2024. For North Carolina Environmental Enhancement Grant UNCW021PRE.

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., 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

[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.

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

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

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

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

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

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

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.

15.0 Acknowledgments

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16.0 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 streams), 25 NTU (lakes and reservoirs)
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

17.0 Appendix B. UNCW ratings of sampling stations in Wilmington watersheds based on 2023, 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	G	G	P
	BC-CA	NS	NS	NS	NS
	BC-SB	G	G	G	P
	BC-NB	G	G	G	F
Barnards Creek	CHP-U	G	F	G	P
	CHP-D	G	F	G	P
Burnt Mill Creek	BMC-AP1	G	G	G	G
	BMC-AP3	F	G	G	F
	BMC-PP	G	P	G	P
Greenfield Lake	JRB-17	G	G	G	P
	GL-JRB	G	F	G	P
	GL-SQB	G	P	G	P
	GL-2340	G	P	G	P
	GL-YD	F	G	G	G
	GL-P	G	G	G	G
Hewletts Creek	NB-GLR	G	G	G	F
	MB-PGR	G	F	G	P
	SB-PGR	G	G	G	F
	HC-3	G	G	G	F
Smith Creek	SC-CH	NS	NS	NS	NS

NS – not sampled due to ongoing bridge construction at the sampling site.

18.0 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
	CHP-U	N 34.1682	W 77.9102
	CHP-D	N 34.1680	W 77.9102
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

19.0 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-SQB	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%

20.0 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.

Mallin, M.A., M.R. McIver, A.E. Grogan and L.B. Cahoon. 2021. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2020*. UNCW-CMS Report 21-01, Center for Marine Science, University of North Carolina Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver, A.E. Grogan, Nicholas D. Picha and L.B. Cahoon. 2022. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2021*. UNCW-CMS Report 22-01, Center for Marine Science, University of North Carolina Wilmington, Wilmington, N.C.

Mallin, M.A., M.R. McIver and Nicholas D. Picha. 2023. *Environmental Quality of Wilmington and New Hanover County Watersheds, 2022*. UNCW-CMS Report 23-01, Center for Marine Science, University of North Carolina Wilmington, Wilmington, N.C.

Mallin, M.A., and L.B. Cahoon. 2024. *Investigating Publicly Owned Stormwater Control Systems as Reservoirs for Toxic Algae and Chemicals*. Final Report: 2022 – 2024 for North Carolina Environmental Enhancement Grant UNCW021PRE.

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.

Iraola, N.D., M.A. Mallin, L.B. Cahoon, D.W. Gamble and P.B. Zamora. 2022. Nutrient dynamics in a eutrophic urban blackwater lake. *Lake and Reservoir Management* 38:28-46.

Grogan, A.E., C. Alves de Souza, L.B. Cahoon and M.A. Mallin. 2023. Harmful algae blooms: a prolific issue in urban stormwater ponds. *Water* 15, 2436. https://doi.org/10.3390/w15132436.