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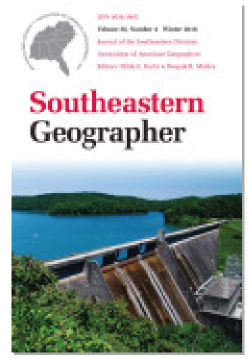

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Surface Water Quality and Landscape Gradients in the North Carolina Cape Fear River Basin

The Key Role of Fecal Coliform

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Although relationships between specific land types and water quality have been well established, studies that observe these relationships across large heterogeneous landscapes are less common. This paper seeks to add to the growing body of literature related to how various land use configurations might influence the geography of surface water quality across a large, heterogeneous river basin network like the Cape Fear River Basin (CFRB) in North Carolina. Findings suggest that fecal coliform bacteria concentrations that exceeded state standards were positively associated with transitional land types (i.e. mixed forest and low density developed–open space (< 20 percent impervious surfaces)), especially when these land types encircled urbanization in the upper reaches of the river basin in both 2001 and 2006. As a result, it is argued that the transition from mixed forest and low density developed–open space to a more urban environment provides a series of well recognized human activities within the landscape gradient that can increase fecal coliform counts.

Aunque las relaciones entre los tipos específicos de tierra y la calidad del agua han sido bien establecidos, los estudios que observan estas relaciones a través de grandes paisajes heterogéneos son menos comunes. En este trabajo se pretende añadir al creciente cuerpo de literatura relacionada con la forma en que varias configuraciones de uso de la tierra pueden influir en la geografía de la calidad del agua de superficie a través de una red de cuencas hidrográficas amplia y heterogénea como la cuenca del río Cape Fear (CFRB) en Carolina del Norte. Los resultados sugieren que las concentraciones de bacterias coliformes fecales que excedieron las normas estatales se asociaron positivamente con tipos de tierra de transición (es decir, bosques mixtos y baja densidad desarrollado–espacio abierto (<20 por ciento de las superficies impermeables)), sobre todo cuando estos tipos de tierra rodeaban urbanización en la parte alta de la cuenca del río. Como resultado, se argumenta que la transición de bosque mixto y baja densidad desarrollado–espacio abierto a un entorno más urbano ofrece una serie de

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actividades humanas bien reconocidos dentro del gradiente de paisaje que se puede aumentar el recuento de coliformes fecales.

KEY WORDS: Water quality, land use, fecal coliform, watersheds, river basins

PALABRAS CLAVE: calidad del agua, usos de la tierra, coliformes fecales, las cuencas hidrográficas, cuencas fluviales

INTRODUCTION

There are over 3.6 million miles of rivers and streams in the United States, each exhibiting unique characteristics that are physically, biologically, and chemically influenced by the diverse landscapes they traverse (US EPA 2010). Much of the literature has focused on the inter-relationships between various land use configurations and surface water quality have been grounded in, but not limited to, geography, hydrology, aquatic biology, and environmental planning (Meybeck and Helmer 1989, Arnold and Gibbons 1996, Booth and Jackson 1997, Liu et al. 2000, Tong and Chen 2002, Rothenberger et al. 2009, Tu 2011). Although there is a growing literature that highlights relationships between specific land types and surface water quality, the U.S. Environmental Protection Agency (EPA) estimates that only 19 percent of streams and rivers have been fully assessed by federal and state agencies (US EPA 2013).

Some studies have observed significant relationships between different land types and water quality across different geographical scales (Aspinall and Pearson 2000, Tong and Chen 2002, Kelsey et al. 2004, Schoonover and Lockaby 2006, Tu et al. 2007, Wilson and Weng 2010, Tu 2011, Crim et al. 2012, Huang et al. 2013). However, these studies typically considered relationships at the local watershed scale or by observing a specific portion of a river basin. Although various federal and state agencies have conducted extensive studies related to water quality and land types, spatial analysis of larger river basins is less common in the geography literature, because of the large spatial context and complexity of these heterogeneous landscapes. Analysis of the spatial variation of surface water quality within a river basin context is critical if we are to better understand how different landscape features and activities in different portions of the basin impact the geospatial characteristics of surface water resources throughout the entire river basin network.

Bacterial pathogens (such as fecal coliform) in surface water systems historically have been linked to agricultural and development activities and the presence of specific landscape features. These features and activities may include increases in impervious surfaces, high livestock density, and failing wastewater treatment plant infrastructure. Relationships between urban and suburban development and non-point sources of fecal concentrations in surface waters have also been well documented. Mallin et al. (2000) and Holland et al. (2004) observed that fecal coliform pollution in tidal creeks in North and South Carolina was positively correlated with watershed population and percent of developed land, and particularly correlated with percent impervious surface coverage. In coastal watersheds of South Carolina, Kelsey et al. (2004) observed high fecal concentrations in populated areas that were likely contributed by the high concentrations of domestic pets (i.e. dogs and cats) associated with human populations. Government agencies have also played a vital role in identifying the spatial patterns and sources of fecal coliform bacteria in surface water systems. The USGS (2003) observed water quality trends across watersheds in Virginia primarily representative of urban, agricultural, and mixed land types. They found that fecal sources were highly variable and key contributors included human, wildlife, and domesticated pet waste as well as various land use activities. In addition to nonpoint sources of fecal microbes, urban and suburban watersheds frequently contain point sources of fecal inputs that are typically associated with wastewater treatment spills and leaks that contribute significantly to unpredictable fecal "spikes" in surface water systems.

Across rural landscapes, sources of fecal pollution may be highly variable and are typically related to human activities. Potential sources of fecal microbes may result from the presence of livestock on the landscape, spraying livestock waste onto fields, and failing septic systems or high density of septic systems. Changes in agricultural practices may also increase fecal concentrations in surface waters. Over the past few decades, the concentrated animal feeding operation (CAFO) industry has emerged as a common practice in the United States and Europe as pasture livestock production has moved from the field to large building facilities (Mallin and Cahoon 2003, Rothenberger et al. 2009, Mallin et al. 2015). CAFO activities on the landscape include livestock holding facilities, related waste lagoons, and spray fields that are often located adjacent to the facilities. As a result, the development of CAFOs and related activities can trigger a variety of landscape changes that may result in habitat fragmentation and the reduction of continuous forestland. Some of the adverse effects of these practices include increases of pathogens and nutrients entering groundwater supplies and surface waters both adjacent to and downstream of CAFO sites (Mallin et al. 2015). This process can lead to the eutrophication of water bodies, often resulting in hypoxic conditions (i.e. low dissolved oxygen) that alter both the quality and quantity of surface water resources and aquatic habitats across multiple geographical scales (Mallin and Cahoon 2003, Burkholder et al. 2007).

Another consideration when observing the spatial context of surface water quality across a large spatial scale, such as a river basin, are the variations and or changes on the landscape that result in different and often complex landscape patterns or gradients. Landscape gradients may exist due to natural features in the landscape such as geological, climatic, and topographical patterns as well as anthropocentric changes to the landscape that may be driven by socioeconomic decisions. As a result, gradients are far likelier to occur than sharp land use boundaries. These sorts of land use gradients may include forest land being converted to agricultural or urban areas or as more recent trends suggest, agricultural land being converted to urban areas (Wear et al. 1998, Schoonover et al. 2005, Grimm et al. 2008). Grimm et al. (2008) note that when considering urban form, various types of landscape gradients radiate from urban centers from both small and large cities, often resulting in landscape gradients at both the local and regional scales.

The literature has also suggested that transitional landscapes, including less developed areas surrounding the urban core, may experience changes in stream water quality as a direct result of an increase in human disturbances to the landscape. Transitional landscapes may have different landscape configurations and transitional patterns such as urban to suburban, rural to suburban, and forest to rural and or suburban land-use types. During landscape transitions, especially from forestland or rural land to suburban, the percentage of impervious surface and related stormwater infrastructure may increase. This is typically in the form of residential and commercial development, an increase in spatially dispersed road networks, or changes in agricultural practices. Several studies have noted adverse impacts to stream quality in watersheds with impervious surfaces as low as 5 to 20 percent (Schueler 1994, Booth and Jackson 1997, Mallin et al. 2000, Schoonover et al. 2005, Walsh et al. 2005 and others). Understanding the spatial distribution of land types, resulting patterns and changes throughout a river basin is important in the analysis of water quality data, because it helps us to better understand how landscape activities in one reach of the basin may be impacting water quality throughout the entire river basin network.

Study Objectives

This paper adds to the growing body of literature related to how various land use configurations might influence the geography of surface water quality across a large, heterogeneous river basin network like the North Carolina Cape Fear River Basin (CFRB). Most prior studies have largely focused on the local watershed scale or on a specific portion of a river basin. We will argue that fecal coliform is one of the most volatile water quality indicators in the CFRB, and one that most frequently exceeds either state or federal water quality standards and, therefore, merits additional attention. Second, it is hypothesized that the geography of fecal coliform across the CFRB is partially explained by certain unique land use gradients. In particular, we will suggest that high fecal coliform counts are more likely in areas with both mixed forest and low density developed–open space (i.e. < 20 percent impervious surface; includes large single-family lot-sizes, parks, golf courses) land types especially in the more urbanized Upper Cape Fear physiographic region. It is argued that the transition from mixed forest to low density developed–open space to a more urban environment provides a series of well recognized human activities within the landscape gradient that can increase fecal coliform counts. As a result, the primary objectives of this study are to understand (1) relationships between specific land types and surface water quality across the entire river basin network, (2) the extent to which these relationships vary across the three physiographic regions of the study area and, (3) how changes in land types impact water quality during two distinct time periods. It is anticipated that observing relationships between land types and water quality across a large hydrological network, and related heterogeneous landscape, will assist in illustrating the extent of these relationships across the entire river basin network. By implementing multiple assessment methods, this study may establish a framework for future research endeavors that seek to address the extent to which specific land types may be impacting water resources over large spatial extents. This will assist resource agencies and decision makers in developing more comprehensive plans that address how socio-economic decisions and related human activities impact the landscape and surface water resources across multiple geographical scale within a single river basin.

METHODOLOGY

Study Area

The Cape Fear River Basin (CFRB) is one of North Carolina's largest river basins (23,734 km^2), and it includes all or portions of 26 counties that contains approximately 25 percent of the state's population and 17 percent of the state's land area (NC DENR EE 2012). The Cape Fear River itself is approximately 320 km long, originating in Chatham County, at the confluence of the Haw and Deep Rivers (NC DENR 2005, NC DENR 2012). The basin displays a southeastern orientation and is divided into three distinct physiographic regions: the Upper (i.e. Piedmont region), Middle (i.e. Sandhills region), and Lower CFRB (i.e. Coastal region) each with distinct soil types and landscape characteristics. As a result, the basin encompasses different aquatic ecosystems, including wetlands, backwater systems, tidal creeks and other estuaries that provide wildlife habitat for over 30 federally listed endangered species (NC DENR EE 2012). The CFRB basin also provides water resources for residential, commercial, and industrial uses (NC DENR 2005). In addition to being the most populated river basin in North Carolina, the CFRB is also the most industralized, with 203 permitted municipal and industrial wastewater dischargers contributing point source pollution inputs to its surface waters (NC DENR 2012). Water quality monitoring stations are located throughout the river basin's surface water network (Figure 1). According to NC DENR (2012), there are over 480 km of impaired stream segments in the CFRB, meaning that stream water quality does not meet standards (e.g. recreation, drinking water supply) set by the state regulatory agency. From 2000 to 2010, the basin's population increased 24.3 percent with approximately 195 people per square mile and it is expected to increase from 3 million to about 5 million people over the next 20 years in largely urban or urbanizing areas (NC DENR 2012).

Land Use/Land Cover (LULC) Assessment

In order to classify land use types and patterns across the CFRB, National Land Cover Database (NLCD) imageries for 2001 and 2006 were downloaded from the Multi-Resolution Land Characteristics Consortium database website. At the time of this study, this was the most recent classified land cover imagery available from the MRLC program. Observing the metadata related to the 2001 and 2006 NLCD imagery, one will note several temporal differences across the physiographic regions. The NLCD imagery representing "2001" for the Middle and Lower reaches of the basin was taken on May 11, 2000 and for "2006" the imagery was taken on April 21, 2007. For the Upper reaches of the basin, the "2001" imagery was taken on October 7, 1999 and for "2006", the imagery was taken on October 15, 2005. For the purposes of this study, the imagery dates will be referred to 2001 and 2006 to be consistent with other

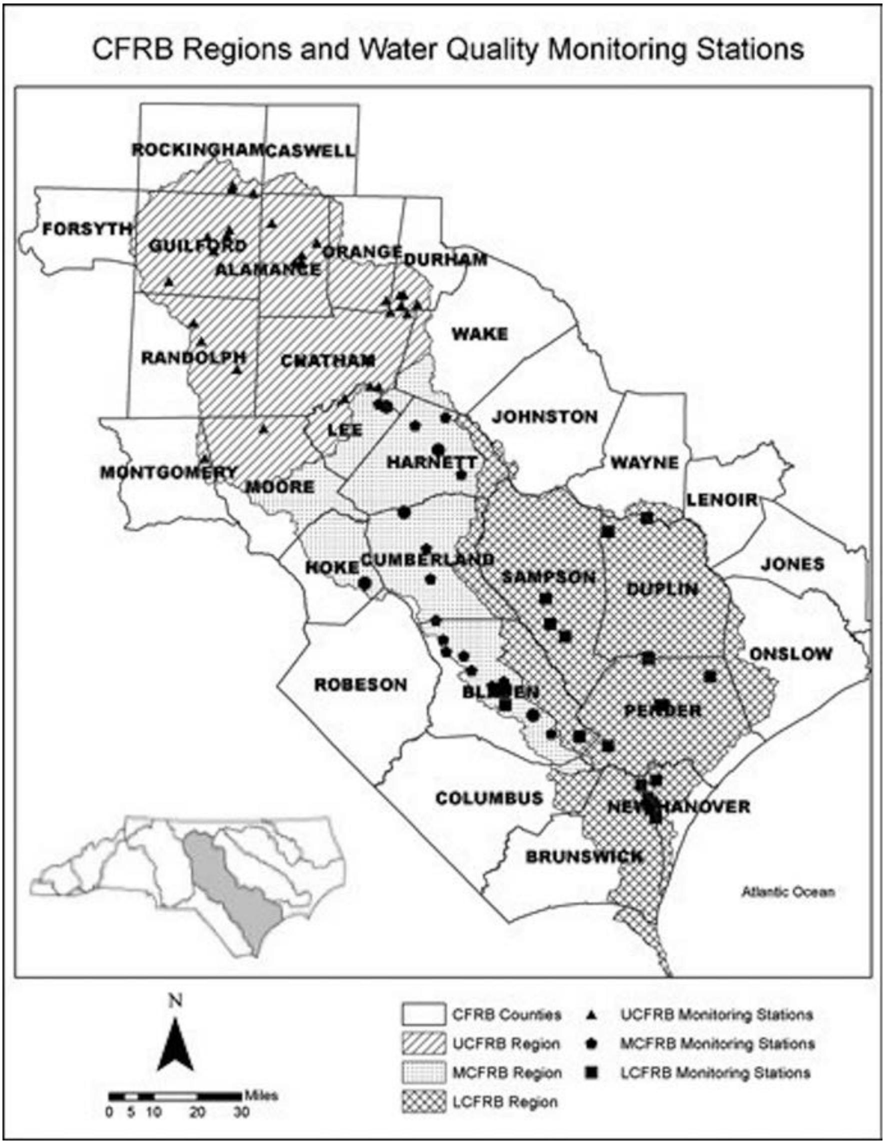

Figure 1. Cape Fear River Physiographic Regions and Water Quality Monitoring Stations. Source: Inset map: USGS 2016.

studies that have applied this dataset (MRLC 2012). In an effort to represent the amount of each land type within the basin, percentages of each LULC were calculated using ArcGIS 10 and converted into percent (km^2) for each land type.

Watershed Delineation

Using Geographic Information System (GIS) methods similar to Rothenberger et al. (2009) and Merwade (2012), watersheds within each hydrologic unit that contain water quality monitoring stations were identified. These monitoring stations served as surface water drainage points and the landscape upstream of these stations were delineated using ArcGIS Hydro tools in addition to digital elevation models (DEMs) (30m) provided by the US Department of Agriculture's Geospatial Data Gateway (USDA 2012). Once these drainage patterns were identified, we imported the NLCD land cover imagery into the ArcGIS system to calculate the percent of a given LULC type within each watershed for each of the 72 water quality monitoring stations included in this study. This will assist in understanding and illustrating surface water system flow patterns, the percent of a given LULC type within a single watershed, and changes in land types from 2001 and 2006.

Water Quality Analysis and Ancillary Data Sources

Water quality data were downloaded from the Cape Fear River Basin Coalition's water quality database that was initially established by the NC DENR (Department of Environment and Natural Resources). The water quality stations in the CFRB chosen for this analysis are monitored monthly by State-approved discharger coalitions (the Lower Cape Fear River Program, the Cape Fear Middle Basin Coalition and the Upper Cape Fear River Coalition) for various biological, chemical, and physical water quality parameters. Field samples are collected by either University laboratories or consulting firms contracted by the coalitions. Each water sample taken adheres to laboratory sampling and analysis techniques certified by the NC DENR Division of Water Resources (DWR). Data for stations throughout the three physiographic regions of the study area were not available until October 2000. As a result of this and the limitation previously noted for the MRLCs NLCD LULC data, this study analyzed water quality data from October 2000 to October 2001 and October 2006 to October 2007. The monthly samples at each station were aggregated to construct annual averages for each water quality parameter at all 72 stations observed in this study. Although monthly samples and annual averages do not always capture abrupt daily changes in water quality, this dataset is the only established monitoring program that provides state-certified water quality data for the entire river basin. Table 1 illustrates the sources for and official government standards, where available, for the water quality parameters analyzed in this study. Ambient standards are available for dissolved oxygen (DO) and fecal coliform bacteria, but no official ambient standards currently exist for nitrite-nitrate nitrogen (NO_2-NO_3), ammonium nitrogen (NH_3-N) and phosphorus (P)) although several surrogate measures were utilized in this paper. The NC DENR standards were used to determine if a water quality sample was considered impaired for its specified or designated use (e.g. drinking water, recreational activities).

Table 1. Sources and NC DENR Standards/EPA Criteria for Water Quality Parameters for the Cape Fear River Basin.

Water Quality Parameter	**NC DENR Standard**	**US EPA Criteria**	**Potential Sources and Seasonal Differences**
Fecal coliform	Maximum 400 col/100ml for all streams except SA HQW (43 col/100ml).	Currently working with state to develop new criteria based on more specific fecal characteristics.	Human sources may include wastewater treatment plant discharges, failing septic systems. Animal sources may include domestic pets, livestock, animal operations, and wildlife.
Dissolved Oxygen (DO)	Minimum 4 mg/L except SA HQW and SC (minimum 5 mg/L)	In most stream types, levels below 5.0 mg/L cause stressful conditions for aquatic ecosystems.	Increases with an increase in a streams contact with the atmosphere, high stream flow events, low temperature or produced by plants during photosynthetic processes. Decreases may result from an increase in nutrients, high temperature, urban and agricultural runoff, land clearing, untreated sewage, and salinity.
Nitrite-Nitrate Nitrogen (NO_2-NO_3)	No ambient standard	No ambient standard	Anthropocentric sources include wastewater treatment plants, runoff from fertilized lawns and cropland, failing septic tanks, runoff from animal manure storage areas, and industrial discharge.
Ammonium Nitrogen (NH_3-N)	No ambient standard	No ambient standard	Natural sources may come from soil and rocks, the atmosphere, tissues of living and dead organisms.
Phosphorus (P)	No ambient standard	No ambient standard	Phosphorus is typically scarce in water under natural conditions. Seasonal differences may be related to precipitation events and/or crop rotation schedules, which may dictate when fertilizers are applied.

Sources: US EPA (2013), Cape Fear River Basin Coalitions Water Quality Monitoring Data (2012).

To account for the impact of precipitation on water quality, we included a control variable total precipitation (centimeters per year) derived from the weather station located closest to each water quality monitoring station; detailed surface water flow data were not consistently available across the entire river basin. This may assist in observing how surface runoff from specific land-use types may be impacting surface water quality. An additional control variable livestock head by permit was also included to account for the potential impact of the presence of livestock located at CAFOs present during the study period. Monthly total precipitation data was downloaded from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center while livestock (i.e. cattle and swine) head counts for state and federally permitted operations, including CAFOs, were obtained from NC DENR DWR. The livestock data indicated the maximum number of livestock head allowed annually at a given CAFO site that is permitted by the NC DENR. However, some facilities were not included in this analyses. First, the cattle and swine facilities were not regulated until 1993. Second, poultry CAFO locations and head counts are not provided by the state of North Carolina agencies to the public (Mallin and Cahoon 2003). In an effort to identify potential impacts to surface water quality from point sources of pollution, National Pollution Elimination Discharge System (NPDES) permits and NC DENR Sanitation and Sewer Overflow (SSO) reports were also reviewed. The SSO reports indicated the specific location and amount of pollution occurring during an infrastructure failure or spill. Finally, to determine if potential regional difference in water quality exists throughout the river basin, a coded variable represented the Upper, Middle, and Lower CFRB physiographic regions.

Statistical Analysis

Based on prior studies and available data (Schueler 1994, Arnold and Gibbons 1996, Mallin et al. 2000, Mallin and Cahoon 2003, Potter et al. 2004, Schoonover et al. 2005, Carle et al. 2005, Burkholder et al. 2007, Brabec 2009, Cookson and Schorn 2009, Rothenberger et al. 2009, Tu 2011), the dependent and independent variables list in Table 2 will be analyzed in an effort to understand and spatially illustrate relationships between water quality and LULC types throughout the Cape Fear River Basin from 2001 to 2006.

Using SPSS 22.0, a step-wise linear regression analysis was designed to identify the most powerful predictors of surface water quality across the CFRB from 2001 to 2006. Since water quality data can be highly variable due to both human activities and natural climatic conditions, a natural log transformation was applied to the annual averages of each water quality parameter for each of the 72 water quality monitoring stations under investigation. Coefficients of the log transformation were multiplied by 100 to determine the percent change corresponding to a one unit change in the independent variable had on each water quality parameter's concentration levels as described by the USGS (2015) and Yuncong and Migliaccio (2011). Since annual averages do not capture episodic events, each monthly sample was also observed to understand monthly and seasonal changes in each parameter.

Based on several multicollinearity (MC) tests no serious MC problems were found in the selected models. We also tested the

Table 2. Dependent and independent variables of interest.

Dependent Variables	Independent Variables
Annual Average Dissolved Oxygen	Percent Land-Use/Land-Cover Type (km^2)
Annual Average Mean fecal coliform	Number of Permitted Livestock Head by Permit (CAFOs permitted by NC DENR)
Annual Average Ammonium Nitrogen (NH_3-N)	Total Precipitation
Annual Average Nitrate-Nitrite Nitrogen (NO_2-NO_3)	Type of Physiographic Region
Annual Average Phosphorus (P)	

potential for MC for all of the dependent variables (see Table 2) and did not observe MC issues for any of the regression models. In addressing potential spatial autocorrelation in the water quality data due to water quality monitoring station locations within the river basin network, it should be noted that a large majority of the stations are mutually exclusive and in the few cases where the stations are nested (i.e. located in the same watershed), they were largely separated by substantive physical distances (on average, roughly 30 miles) so that the influence of an upstream station on a downstream location was considered negligible in most cases

RESULTS AND DISCUSSION

Geospatial Characteristics of Surface Water Quality

The descriptive statistics for the water quality parameters (Tables 3 and 4) suggest that several water quality metrics were relatively stable with small variances by both location or over time. These included dissolved oxygen (DO), ammonium nitrogen (NH_3-N), and phosphorus (P). Each of these parameters generated relatively low standard deviations with annual averages that changed little from 2001 to 2006 and there was little variability on a monthly basis. In regards to DO, this was expected because aggregating the monthly samples into annual averages means that the typically lower DO readings of the summer months were masked by the seasonally higher DO levels in cooler months. Observing the monthly samples for each of the 72 stations during the warmer months (i.e. June to September) revealed that 9 stations had monthly samples that failed the NC DENR standard in 2001 and 13 stations failed the standard in 2006, with a majority of these monitoring stations being located in the Lower CFRB for both years. Although, the annual average for nitrite-nitrate nitrogen (NO_2-NO_3) was relatively unchanged over time, the standard deviation was slightly higher in 2006 suggesting some variability. This may be related, in part, to an increase in human activities on the landscape that resulted in elevated NO_2-NO_3 inputs to surface waters of the CFRB. Although the NC DENR has not established nutrient standards, using data from 1,366 streams Dodds et al. (1998) concluded that total phosphorus (TP) concentrations > 0.075 mg/L were characteristic of eutrophic streams. It should be noted that the average TP during both study periods well exceeded this threshold (see Tables 3 and 4). Thus, overall P concentrations in the CFRB can

Table 3. CFRB water quality descriptive statistics of 72 monitoring stations in 2001.

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding NC DENR Standards
Fecal coliform (col/100ml)	18	3,618	415	707	19 (26%)
DO (mg/L)	4.17	11.02	8.08	1.13	0
NO_2-NO_3-N (mg/L)	0.05	9.22	1.27	1.87	No ambient standard
NH_3-N (mg/L)	0.03	0.82	0.12	0.13	No ambient standard
P (mg/L)	0.03	2.14	0.27	0.30	No ambient standard

Table 4. CFRB water quality descriptive statistics of 72 monitoring stations for 2006.

Water Quality Parameters	Minimum	Maximum	Mean	Standard Deviation	Number of Stations with Annual Averages Exceeding NC DENR Standards
Fecal coliform (col/100ml)	24	1,472	318	327	23 (32%)
DO (mg/L)	5.03	10.65	8.06	1.15	0
NO_2-NO_3-N (mg/L)	0.06	12.54	1.32	2.29	No ambient standard
NH_3-N (mg/L)	0.03	0.32	0.07	0.044	No ambient standard
P (mg/L)	0.03	1.72	0.19	0.25	No ambient standard

be considered high, although there was little variability over time. Regarding nitrate and ammonium, research in the lower CFRB in blackwater streams determined that concentrations of nitrate or ammonium > 0.50 mg/L significantly stimulated chlorophyll a and BOD in these systems (Mallin et al. 2004). Ammonium nitrogen (NH_3-N) for stations in this study were relatively stable, although monitoring station monthly samples and annual averages frequently exceeded >0.50 mg/L.

However, it is the fecal coliform metric that demonstrated the largest absolute change from 2001 to 2006. In 2001, the annual average of fecal coliform counts was 415 colony-forming units (CFU)/100ml with a relatively high standard deviation (i.e. 707) compared to an annual average of 318 CFU/100ml in 2006 and a much lower standard deviation (i.e. 327). Perhaps more importantly, the fecal coliform annual average exceeded the NC DENR standard at one in four water quality monitoring stations in

2001, and one in three stations in 2006 even though the overall average declined over time. In addition, monthly samples were highly variable (e.g. 200 CFU/100ml to 12,000 CFU/100ml) with drastic changes at stations located throughout the basin. The spatial distribution of stations with annual averages that exceeded state fecal coliform standards in the CFRB are illustrated in Figures 2 and 3 for 2001 and 2006. The 19 stations (26 percent of the total) that exceeded the state standard for fecal coliform in 2001 are located exclusively in the Upper and Middle regions of the CFRB (see Figure 2). A majority of the stations that exceeded the state standard for fecal are located in urbanizing watersheds in the Upper CFRB which were characterized by low intensity developed–open space surrounded by both agricultural (i.e. pasture/hay) and mixed forest landscapes. Some of these stations are located in watersheds that include portions of highly urbanized cities like Greensboro, Durham, and Burlington. The remaining monitoring stations were largely located in rural watersheds characterized by a mix of land use types including mixed forest, low intensity developed–open space, and agricultural land in Montgomery, Randolph, and Chatham counties. Although these stations are located in watersheds with different landscape characteristics, they all contained transitional land types (i.e. low intensity developed–open space and mixed forest) where human activities on the landscape appear to be increasingly altering the landscape that surrounds urban centers. Broadly similar trends seem to occur in 2006 (see Figure 3) with a few exceptions.

Given the wide variety of landscapes characteristics of watersheds with high fecal coliform concentrations, it appears that even for a single physiographic region, like the Upper CFRB, the explanation for high fecal coliform concentrations in surface water systems can be highly variable and may derive from both point source and non-point sources, highlighting the spatial complexity of this water quality metric. Furthermore, it is possible that the types of land use arrangements in each watershed may be key predictors of the variability in fecal coliform concentrations observed in this study. Due to the significant role that fecal coliform plays in shaping water quality throughout the CFRB network, at least in terms of exceeding NC DENR standards, we now turn to a regression analysis to determine which land types best explain the spatial variation of this important water quality metric.

Fecal Coliform Across the Cape Fear River Basin 2001: The Key Predictors

Although this regression analysis focuses primarily on the land use characteristics of the CFRB it should be noted that two control variables—total precipitation and livestock headcount—were also included in this analysis as well as a coded variable that represented the three physiographic regions of the CFRB (i.e. Upper, Middle, and Lower). The step-wise regression analysis for fecal coliform in 2001 revealed that four predictor variables were key factors in shaping the spatial distribution of fecal coliform concentrations across the river basin (Table 5). The R-squared value of the model was 0.48 ($p < 0.05$) suggesting that 48 percent of the variation in fecal coliform can be explained by location of the monitoring station in the Upper CFRB, the percentage of the land use in the watershed is open space or mixed forest classification, and total precipitation.

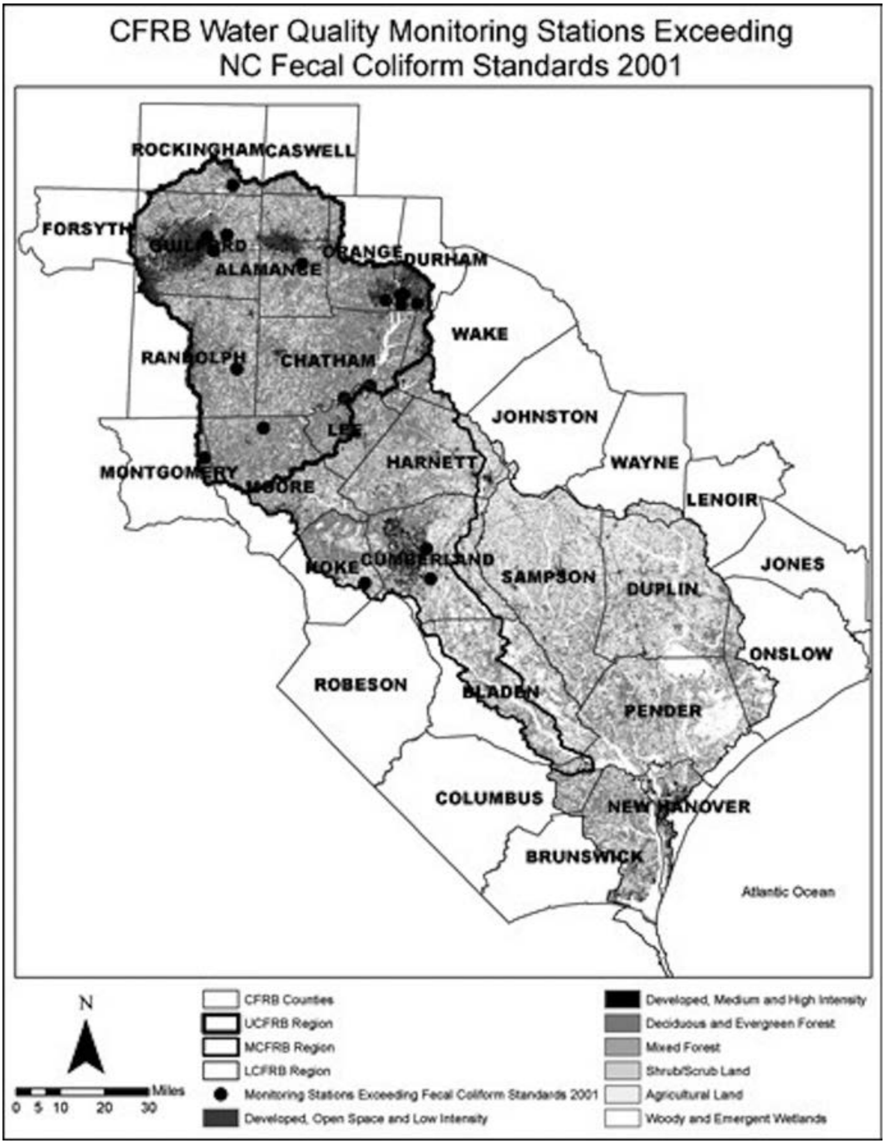

Figure 2. Cape Fear River Basin Stations with Annual Averages Exceeding Fecal Coliform Standards in 2001.

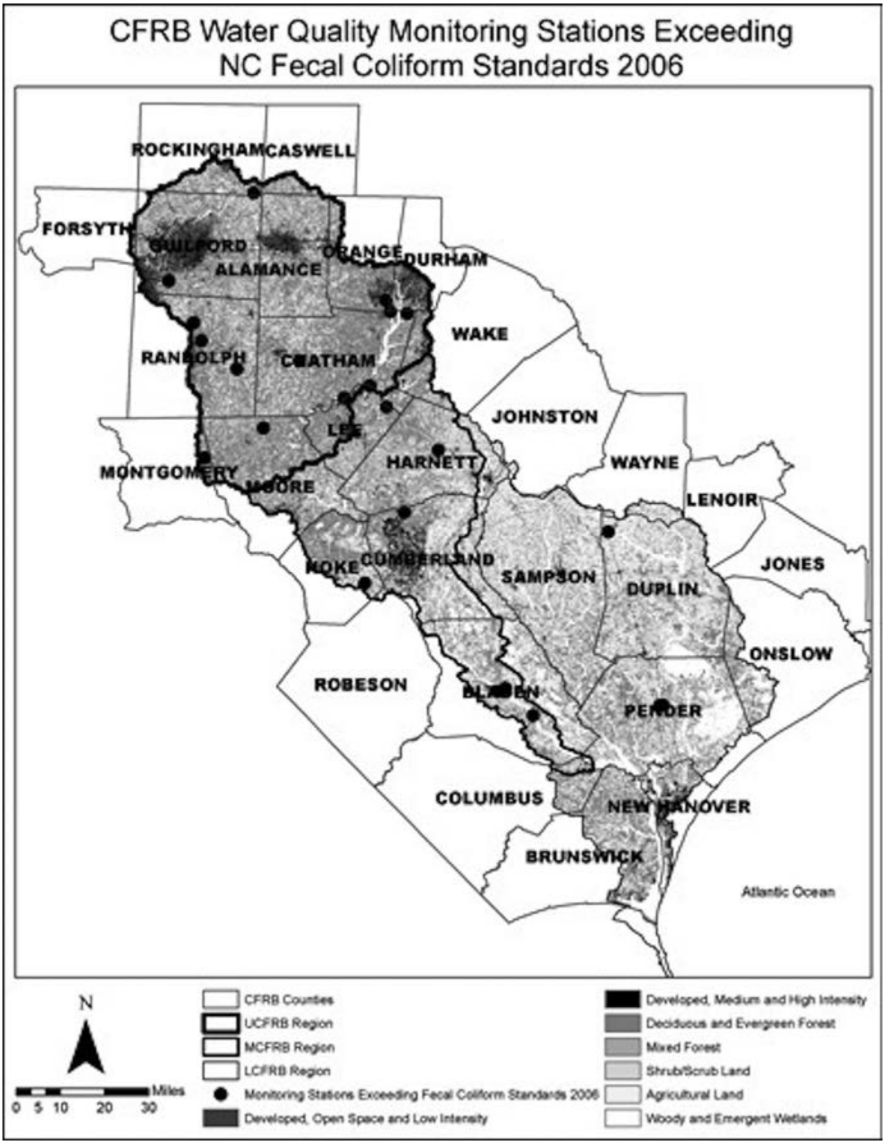

Figure 3. Cape Fear River Basin Stations with Annual Averages Exceeding Fecal Coliform Standards in 2006.

Table 5. Regression model summary of fecal coliform across the Cape Fear River Basin for 2001. The final regression model for fecal coliform from 2001 can be formally expressed as follows:
Log FC *(2001) = 6.56 + 0.74* UCFRB *+ 0.05* DOS *+ 0.16* MF *– 0.07* PT
where UCFRB *= Upper Cape Fear River Basin,* DOS *= Percent Developed, Open Space,* MF *= Percent Mixed Forest,* PT *= Total Precipitation.*

Independent Variables	Unstandardized b Coefficient	Exponent Value	Percent Change
Constant	6.56		
UCFRB Region	0.74	2.10	110%
Percent Developed, Open Space	0.05	1.05	5%
Percent Mixed Forest	0.16	1.18	18%
Total Precipitation 2001	−0.07	0.93	−7%
All p-values <0.05	**R^2 = 0.48**		

The regression analysis suggests that the relationship between fecal coliform concentrations and the Upper CFRB region in 2001 was positive. Compared to the other regions of the study area, fecal coliform concentrations at stations located in the Upper CFRB were 110 percent higher. The Upper CFRB region represented the most highly urbanized region in the CFRB with development largely concentrated in and around the cities of Greensboro, High Point, Jamestown (Guilford County), Burlington (Alamance County), Durham (Durham and Orange Counties), and Chapel Hill (Orange County). Furthermore, several of the water quality monitoring stations that experienced "spikes" in fecal coliform concentrations were located in the Upper CFRB region. These stations not only experienced drastic changes in the annual average of fecal coliform concentrations but also experienced extremely elevated fecal coliform concentrations from month to month. Stations experiencing these extreme changes in fecal concentrations were located in watersheds primarily characterized by both urban and rural land use types. However, one common similarity among these watersheds was that they all contained transitional land types primarily represented by mixed forest and low intensity developed–open space.

When considering associations between specific land types and fecal concentrations, the model predicted that as the percentage of low intensity developed–open space (i.e. < 20 percent impervious surfaces) increased by one percentage point, fecal coliform concentrations would increase by 5 percent, holding all other predictor variables constant. In 2001, low intensity developed–open space accounted for only 3 percent of all land classifications in the CFRB. Despite representing a small percentage of the land types present across the entire CFRB, this type of land use appears to be significantly linked to increases in fecal concentrations throughout the river basin. By contrast, denser forms of development did not feature in the final model, possibly because this type

Figure 4. Suburban development on the fringe of mixed forest land in the Cape Fear River Basin, NC in 2015. Source: Mallin, 2015.

of development has well-developed water and sewer systems that are frequently monitored as well as more compact wastewater system infrastructure (i.e. pipes) that may not traverse a large spatial extent. In addition, once a dense urban center is developed, large changes to the landscape may be limited. It is also possible that much of the developed–open space land lies along more rural landscape gradients where regulatory oversight is laxer and or the wastewater infrastructure traverses a larger spatial extent that may include crossing more surface water systems. Rural areas are also more commonly associated with septic systems in the absence of WWTPs. These systems have been linked to surface and subsurface fecal inputs to surface waters as observed by Cahoon et al. (2006).

In addition to the percentage of land allocated to developed–open space by watershed, the percent of land classified as mixed forest played a significant role in shaping the geography of fecal coliform across the CFRB. The relationship between percent mixed forest and fecal concentrations in 2001 was positive suggesting that as the percentage of mixed forest land increased by one percentage point, fecal coliform concentrations increased by 18 percent, holding all other predictor variables fixed. Although the MRLC classifies this land type as 20 percent tree coverage in addition to other vegetative cover, this study observed it in close proximity to land types associated with human activities. Across the CFRB, mixed forest was typically identified adjacent to

Figure 5. CAFO facilities, spray fields, and waste lagoons within mixed forest land types located in the CFRB, Duplin County, NC in 2013. Source: Mallin, 2013.

developed–open space, especially in the upper and middle basin, and was primarily adjacent to agricultural land types and in very close proximity to CAFOs in the lower basin. Figure 4 is one example of the landscape transition from mixed forest to low intensity developed–open space as observed in the middle and upper basin. In contrast, Figure 5 is an example of how CAFOs are nested within mixed forest landscapes in the lower portion of the basin. Given these observations, it is anticipated that activities related to mixed forest may include, but are not limited to, wastewater treatment plant (WWTP) spills, septic system failures, and CAFO activities. All of these activities have been linked to increases in nutrients and pathogens, including fecal coliform bacteria, in surface water systems across the nation including the CFRB (Mallin et al. 2000, Mallin and Cahoon 2003, Ahearn et al. 2005, Burkholder et al. 2007, Rothenberger et al. 2009). Although mixed forest only accounted for 2 percent of the CFRB's total landscape in 2001, the model suggested that even a small percentage increase of this land type can contribute to significant increases in fecal coliform concentrations in surface water systems throughout the basin. Furthermore, the regression analysis indicates that percent mixed forest may contribute to higher concentrations of fecal when compared to percent developed–open space (i.e. 18 percent increase versus 5 percent increase), suggesting that a variety of human activities may be contributing to higher concentrations of fecal coliform concentrations in all three of the basins' physiographic regions.

The final variable to enter the 2001 regression analysis for fecal coliform was total precipitation. The b coefficient suggested an inverse relationship existed indicating that as the total precipitation increased by one inch, fecal concentrations will decrease by seven percent across the river basin. The literature lacks consensus regarding the relationships that exist between precipitation patterns and fecal concentrations in surface water systems (Potter et al. 2004, Cahoon et al. 2006, Hill et al. 2006). However, sewage leaks and spills, as well as septic system failures occur regardless of rain events (Tavares et al. 2008). The large month-to-month changes seen at some sites would support failures in infrastructure as problematic. The duration of rainfall as well as the duration of time that passes prior to a water quality sample being collected are also important factors when considering the spatial relationships that might exist between rainfall totals and fecal concentrations in surface water systems.

Fecal Coliform Across the Cape Fear River Basin in 2006: The Key Predictors

Many of the same variables in the 2001 regression model featured in the regression analysis for 2006 including the percentage of land in a watershed primarily classified as low intensity developed–open space or mixed forest, and whether or not monitoring stations were located in the Upper CFRB. One important difference in the two models is that total precipitation was replaced by the percent scrub/shrub land classification as a key predictor variable in 2006. Overall, the R-squared value of the model was 0.31 (p-value < 0.05) suggesting that 31 percent of the spatial variation in fecal coliform concentrations can be explained by percent mixed forest, developed–open space, scrub/shrub land, and being located in the Upper CFRB region (Table 6). The first predictor variable to enter into the 2006 regression model was percent mixed forest. The model predicted that as the percent mixed forest land increased by one percentage point, fecal coliform concentrations across the basin would increase by 14 percent. This is a slightly lower percent increase in fecal concentrations when compared to the influence of percent mixed forest in the 2001 regression model (18 percent increase). As previously noted, mixed forest is defined by the MRLC as areas dominated by mixed vegetation. Similar to 2001, in 2006 this study observed this land type surrounding low intensity developed–open space especially in the Upper and Middle basins indicating that it may become more disturbed by human activities over time. In contrast, this land type was also located adjacent to CAFO activities including waste lagoons and spray fields surrounded by forest. Given these landscape configurations, the runoff from these activities may be increasing fecal concentrations on mixed forest land types, which may explain the relationships observed in the both the 2001 and 2006 regression models. Furthermore, this study observed that 66 percent of the watersheds that had a reduction in mixed forest

Table 6. Regression model summary of fecal coliform across the Cape Fear River Basin in 2006. The final regression model for fecal coliform from 2006 can be formally expressed as follows:

Log FC *(2006) = 2.87 + 0.13* MF *+ 0.03* DOS *+ 0.07* SS *+ 0.67* UCFRB

where FC *= Fecal coliform col per 100ml.,* MF *= Percent Mixed Forest,* DOS *= Percent Developed, Open Space,* SS *= Percent Shrub/Scrub Land,* UCFRB *= Upper Cape Fear River Basin Region.*

Independent Variables	Unstandardized b Coefficient	Exponent Value	Percent Change
Constant	2.87		
Percent Mixed Forest	0.13	1.14	14%
Percent Developed, Open Space	0.03	1.03	3%
Percent Scrub/Shrub Land	0.07	1.08	8%
UCFRB Region	0.67	1.96	96%
All p-values <0.05	**R^2 = 0.31**		

land from 2001 to 2006 had an increase in low intensity developed–open space, further indicating that this land type is becoming more disturbed by human activities across the river basins over time.

Percent low intensity developed–open space was the second variable to enter the regression model where a one percent increase in low intensity developed–open space resulted in a three percent increase in fecal concentrations in surface waters in the CFRB (see Table 6). Although this is a relatively small percent increase in fecal concentrations, it is fairly consistent with the 5 percent increase observed in the 2001 regression model. Similar to 2001, low intensity developed–open space can typically be found encircling urbanized areas and often serves as a transitional area between urban development and forested or agricultural land. From 2001 to 2006, 71 percent of the watersheds included in this study experienced an increase in low intensity developed–open space with the largest increases occurring in the upper reaches of the basin. Throughout the basin, low intensity developed–open space typically occurred on the periphery of urban areas including the cities of Greensboro, High Point (Guilford County), Burlington (Alamance County), Durham (Durham and Orange Counties), Chapel Hill (Orange County), Fayetteville (Cumberland County), and Wilmington (New Hanover County).

Percent shrub/scrub land was the third predictor variable to enter the regression model for 2006. The b coefficient suggested that a positive relationship existed indicating that a one percentage point increase in shrub/scrub land would increase fecal concentrations across the basin by seven percent, holding all other predictor variables constant. In relation to North Carolina's landscape, the North Carolina Wildlife Resources Commission (WRC) has noted that shrub/scrub land is typically located in the Coastal Plains region and is characterized by low woody vegetation and herbaceous plants. Shrub/scrub land in this region is typically created by disturbances including clearcutting, disking, or burning and are often found at the transition between agricultural lands and forestland and is frequently found in the understory of open pine stands (NC WRC 2013).

Silviculture practices, which may include the clear cutting and or burning of vegetation, are prevalent throughout the CFRB, especially in the Middle CFRB and Lower CFRB regions. These practices often result in accelerated soil erosion that may carry non-point sources of pollution, including fecal, to nearby surface waters (Kasprak et al. 2013). Ensign and Mallin (2001) noted that increases in fecal concentrations downstream from clear cutting activities have occurred in the Lower CFRB even in the presence of a narrow vegetative buffer. Along transitional landscapes, such as shrub/scrub land, Sebestyen and Verry (2011) observed an increase in fecal pollution following the establishment of cattle grazing in a watershed that was largely converted from forestland to agricultural pasture lands. They noted that although fecal concentrations were present prior to this landscape transition, primarily from wildlife, there were dramatic increases in fecal once grazing was established. The results of this regression model suggests that shrub/scrub land can contribute a higher percentage increase in fecal concentrations (+8 percent) when compared to low intensity developed–open space (+3 percent), although mixed forest land can generate even higher changes in fecal concentrations (+14 percent). Collectively, these land types represent landscape transitions taking place in the CFRB that may be impairing water quality both locally and throughout the basin network.

The fourth and final variable to enter the 2006 regression model for fecal coliform was location of the water quality monitoring station in the Upper CFRB region. The regression model suggested that fecal concentrations for stations located in the Upper CFRB were 96 percent higher when compared to other regions across the CFRB. As previously noted, the Upper CFRB region is the most urbanized region in the CFRB and a majority of the monitoring stations' annual averages and monthly samples in this region exceeded the state standard for fecal concentrations (i.e. 400 CFU/100ml). Several of the Upper CFRB stations' monthly exceedances have been linked to WWTP spills (i.e. overflows and leaks). Unlike the 2001 regression model where the Upper CFRB region was the first variable to enter the equation, in the 2006 model the Upper CFRB region was the fourth and last variable to be included. Part of the logic for this may be linked to the fact that although the number of stations whose annual averages exceeded the state guideline for fecal in this region increased from 2001, a majority of these stations did not have "extreme" fecal counts when compared to those that exceeded state standards in 2001. As a result, the mean fecal coliform concentration in 2001 as well as the variance was higher when compared to 2006. Given the large number of WWTPs located in the Upper CFRB, it is likely that aging sewer infrastructure (Tavares et al. 2008), increases in development activities that put additional strains on these systems, and expansive stormwater systems often related to impervious surfaces have influenced the concentration of fecal coliform in surface water systems within this region (Mallin et al. 2000, Holland et al. 2004).

CONCLUSIONS AND FUTURE RESEARCH

As the population in the Cape Fear River Basin (CFRB) continues to grow, it will become increasingly important to address the geography of surface water quality throughout the basin. Although past research has highlighted some relationships that exist between land types and surface water quality at the local watershed and subbasin levels, a comprehensive study that specifically addresses the spatial distribution of these relationships across an entire river basin network has been less common. The overall goal of this research was to identify and spatially illustrate the spatio-temporal relationships between surface water quality (especially fecal coliform) and varying land types across a single heterogeneous river basin network.

While there were only small changes in land types between 2001 and 2006, specific land types were empirically linked to surface water quality impairment across this river basin, with fecal coliform bacteria emerging as a key pollution metric. When considering regional differences in surface water impairment by fecal coliform, this study illustrated that a majority of stations that exceeded the state standard (i.e. 400 CFU/100ml) were located in the Upper CFRB. This is of particular interest since the headwaters of the river basin are located in this region and activities that impair water in the upper reaches may be compounding surface water quality issues downstream. Regarding NO_2-NO_3, NH_3-N and P, we note that a primary problem with this analysis is that North Carolina lacks ambient nutrient standards. As a result, we recognize that even small increases in nutrient loading can lead to eutrophication-based problems in water bodies (Dodds et al. 1998).

Step-wise linear regression models statistically demonstrated the extent to which specific land types impacted surface waters in both 2001and 2006. Percent mixed forest was the most influential land cover that shaped the geospatial characteristics of fecal concentrations in surface water systems in both 2001 and 2006. This land type has been associated with human disturbances that may result in the development of transitional zones in which forest land is converted to agricultural and urban land types over time. Low intensity developed–open space was also identified as a land-use associated with increases in fecal concentrations, although its impact was not as significant as mixed forest land. In addition, shrub/scrub land cover was also associated with an increase in fecal concentrations in 2006. This land type has been identified with human disturbances such as land clearing and transitional areas between forestland and agricultural and urban landscapes.

The transition of forest to the urban environment provides a series of well-recognized steps that increase stream water pollution (Arnold and Gibbons 1996). As forests are removed, much transpiration capacity is lost and more runoff occurs; also, with less ground cover erosion increases. Additionally, the pollution buffering effect of streamside vegetation is reduced or removed. Overall, largely transitional landscapes that are inclusive of low intensity developed–open space and mixed forest appear to play a critical role in shaping the geography of water quality across the CFRB in both 2001 and 2006. This is an important finding because the presence of these transitional land types in landscape gradients may be impacting surface water quality on a local and regional scale in other river basin systems across the country. It is our hope that this paper is a first step towards providing a platform for research in other river basins that assesses and spatially illustrates how the geography of fecal coliform in surface water systems is directly connected to specific land gradients and configurations.

It should be noted that the national land cover classification system utilized in this paper (i.e., MRLC 2012) does not have a category for CAFO-impacted land. We know from previous analyses that CAFOs are highly concentrated sources of nutrients and fecal bacteria (Mallin and Cahoon 2003) that can cause chronic pollution to local waterways and adjacent landscapes (i.e. mixed forest) that surround CAFO facilities (Mallin et al. 2015). Thus, a more detailed land-use classification system, as well as increased rural sampling coverage at a higher spatial resolution could provide greater insight into the geography of surface water quality.

The results of this research also suggest several avenues for future research. More frequent monitoring of surface water quality in watersheds characterized by transitional land types would help improve our understanding of how specific changes to the landscape influence surface water quality across various geographical scales within a single river basin. Also, as there are approximately five million heads of swine in the Black and Northeast Cape Fear tributary basins of the CFRB (Mallin and Cahoon 2003) these rural areas are presently poorly represented by current sampling stations highlighting the needs for more monitoring stations throughout the basin. In relation to human activities on the landscape, more data are needed to address the extent to which specific activities (e.g. spraying animal waste on fields, development, and fertilizer applications) are impacting surface water resources throughout the river basin network. To better identify these relationships, more public data sources are needed that are inclusive of all CAFO activities (swine, poultry, and cattle) since it has been well established that these activities impact surface and groundwater quality and exclusion of this data is a limiting factor in analyzing these relationships throughout the basin. Finally, applying this research model to other river basins with different landscape characteristics and climatic conditions may help elevate our understanding of how various landscape configurations and human activities might impact the quality surface water resources over large heterogeneous landscapes.

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