ABSTRACT

HARDESTY, DEANNA MARIE. Quantitative and Spatial Assessment of Groundwater Characteristics in Eastern North Carolina, USA. (Under the direction of Dr. John King).

The coastal zone has been subject to examination due to its economic and ecologic importance. This area is threatened by sea level rise around the world and in the United States. The Atlantic coast has been identified as a hot spot of sea level rise in recent years, and rates of sea level rise in North Carolina have historically been higher than eustatic rates. Sea level rise can affect the depth to the groundwater in coastal zones, pushing the top of the aquifer toward the soil surface. This can affect plant health and the ability of coastal communities to thrive. This research uses publicly available groundwater monitoring data to quantify changes in groundwater depth over time, as well as to spatially examine patterns in the datasets. This research asks the questions (1) if there are detectable trends in groundwater depth in coastal North Carolina, (2) if groundwater monitoring wells placed by the NCDWR are spatially clustered, (3) if we can identify areas of high salinity, high rate of groundwater depth change from available groundwater monitoring data and (4) if groundwater depth and quality in shallow, unconfined aquifers are correlated with proximity to hydrologic features within the coastal zone.

Results of this research indicated that 80% of wells in the coastal zone exhibit some kind of significant trend in groundwater depth over time. Results also indicate that there are several significant clusters of groundwater monitoring well locations. Rate of change of groundwater depth over time and salinity values also exhibit local high-value clustering, which may have implications for the ecologic health of the coastal zone. Regression analyses revealed that rate of change in groundwater depth is weakly correlated with distance to drainage ditches, although rate of change was not correlated with distance to other hydrologic features. Water quality was

not significantly correlated with distance to hydrologic features. Understanding the spatial variability, as well as the magnitude of changes in aquifer characteristics across the coast, will be crucial to protecting the ecological and economic interests of communities within the coastal zone of North Carolina and worldwide.

Quantitative and Spatial Assessment of Groundwater Characteristics in Eastern North Carolina, USA.

by
Deanna Marie Hardesty

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Natural Resources Management

Raleigh, North Carolina

2021

APPROVED BY:

Dr. John S. King
Chair of Advisory Committee

Dr. Marcelo Ardón Sayao

Dr. Joshua Gray

DEDICATION

To my Grandfather – who missed this milestone in my life but is no doubt the reason I am here.

BIOGRAPHY

Deanna grew up outside of Baltimore, Maryland. She found her way to science at a young age working at the National Aquarium in Baltimore and eventually obtained a degree in Marine Biology from the University of North Carolina at Wilmington. During this time, she worked in labs that were interested in everything from chemical marine ecology to marine taxonomy. Her first publication, *Studies of North Carolina marine algae XIV: increased diversity of flattened offshore* Gracilaria (Gracilariales, Rhodophyta) *species revealed by DNA sequences of contemporary specimens and the G. mammillaris holotyp*e reported four new species for North Carolina and described one novel species.

After graduating from UNCW, Deanna went on to work as a researcher in the Department of Cell Biology and Physiology within the University of North Carolina at Chapel Hill's School of Medicine studying kidney development and function. She spent three years in this capacity before deciding to attend graduate school at North Carolina State University.

ACKNOWLEDGEMENTS

Thank you to Dr. John King for overseeing this thesis and to Dr. Marcelo Ardón and Dr. Joshua Gray for aiding in the analysis that this work required and the editing of the final product. Thank you also to Dr. Maricar Aguilos for her help in the statistical analysis and visualization of the data presented in this thesis. Thank you to the Department of Forestry and Environmental Resources at North Carolina State University for funding this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction and Background

The global coastal zone has been subject to examination due to its economic and ecologic importance (Barbier et al., 2011; Costanza et al., 1998). Coastal zones provide valuable ecosystem services that range from coastal protection and erosion control to tourism, education, and recreation (Barbier et al., 2011). Because of the benefits associated with living in these areas, the coastal zone also tends to be highly populated. Worldwide, the coastal zone is estimated to contain about 10% of the world's population, despite making up just 2% of land area (McGranahan et al., 2007). It is estimated that these populations could increase by as much as 50% in the coming decade (Neumann et al., 2015). Increasing populations in the global coastal zone expose large numbers of people to the hazards that are associated with these areas, including storms and sea level rise (Befus et al., 2020; Rotzoll & Fletcher, 2012).

Sea level rise has been a coastal hazard of particular concern, as rates of sea level rise are predicted to increase globally in the coming years (Stocker, 2014). Elevated sea levels have the potential to increase coastal flooding, damage infrastructure, and detrimentally affect the ability of communities to participate in agricultural activities (Befus et al., 2020; Kirwan & Gedan, 2019; Rotzoll & Fletcher, 2012). Importantly, rising sea levels have the potential to affect both the coastline and connected inshore systems such as aquifers. Aquifer depth at the coast is influenced by sea level, and rising sea levels can drive changes in groundwater depth below the surface (Befus et al., 2020; Masterson & Garabedian, 2007; Michael et al., 2013; Rotzoll & Fletcher, 2012). Decreasing groundwater depth in coastal aquifers is driven by seawater that has infiltrated the aquifer at the land/sea interface, with influxes of sea water pushing the top of the water table closer to the soil surface (Michael et al., 2013). Changes in groundwater depth can then drive inshore flooding and inundation of vegetation along the coast (Befus et al., 2020).

Flooding is not an ubiquitous response to sea level rise in coastal zones, as aquifer response to sea level rise can depend on vadose zone thickness; for example, areas with thick vadose zones (referred to here as flux-limited) are able to accommodate a decrease in groundwater depth driven by sea level rise without a subsequent increase in overland flow or surface saturation due to the ability of the unsaturated space within the soil matrix to hold an increased volume of water (Befus et al., 2020; Michael et al., 2013). However, areas with thin vadose zones (referred to here as topography-limited) are not able to accommodate a decrease in groundwater depth due to a limited unsaturated zone, and rising sea levels associated with these areas can drive an increase in overland flow and soil saturation as the top of the water table intersects with the soil surface (Befus et al., 2020; Masterson & Garabedian, 2007; Michael et al., 2013; Rotzoll & Fletcher, 2012).

An influx of seawater has implications not only for groundwater depth, but also groundwater quality, especially in topography-limited systems. These systems are particularly vulnerable to saltwater intrusion, which threatens the supplies of drinking water in coastal communities as well as agricultural activities along coastlines (Kirwan & Gedan, 2019; Michael et al., 2013). If the influx of sea water at the land/sea interface increases with sea level rise, the dense, infiltrating marine layer eventually forces freshwater at the top of the aquifer out of the soil matrix where it becomes overland flow (Masterson & Garabedian, 2007; Michael et al., 2013). The resulting decrease in the thickness of the freshwater layer allows more seawater to infiltrate into the aquifer, potentially leading to its salinization (Befus et al., 2020; Masterson et al., 2014; Michael et al., 2013).

Topography-limited zones are then of particular concern, as these areas are potentially the most at-risk of experiencing the negative effects of decreased groundwater depth associated with rising sea levels. Globally, as many as half of the world's coastlines may be at risk of saltwater intrusion driven by altered groundwater hydrology due to coastal topography that limits groundwater movement in the vadose zone, and many low-lying areas are predicted to see some of the highest rates of population growth in the coming years (Michael et al., 2013; Neumann et al., 2015). These coastal populations often rely on groundwater resources and available land area to support their communities and commerce. Increased flooding and salinization can alter the availability of fresh drinking water as well as the viability of croplands that economically sustain many coastal communities (Bhattachan, Emanuel, et al., 2018; Nicholls & Cazenave, 2010; Oude Essink et al., 2010). Saturation and salinization of groundwater and associated soils can result in reduced crop yields or total loss of agricultural fields due to the detrimental effects of saturation and salinity on vegetation that is not adapted to these conditions (Barrett-Lennard et al., 1988; Kirwan & Gedan, 2019; Michael et al., 2013; Oude Essink et al., 2010).

Increased soil saturation or inundation at the surface in these topography-limited areas can be detrimental to upland plants. Saturated soils require adaptations for survival as they tend to be hypoxic, limiting oxygen both to the plants and microbes that inhabit the soils (Barrett-Lennard, 2003). These conditions can lead to reduced plant metabolism, growth, nutrient uptake, and ability to transpire, as well as increased root death and lower recruitment ability (Barrett-Lennard, 2003; Barrett-Lennard et al., 1986, 1988; Else et al., 2008; Huang et al., 1995; Kirwan et al., 2007; Trought & Drew, 1980). Once these stressors cause upland species to die off or become unable to regenerate, the affected plant community can be re-colonized by species better adapted to the altered hydrologic regime (Hayden et al., 1995; Robichaud & Bégin, 1997).

Increased groundwater salinity also has the ability to affect the health of plant communities in coastal ecosystems; salinity has been identified as a driver of reduced species richness and coastal forest mortality (Kirwan & Gedan, 2019; Masterson et al., 2014; Smart et al., 2020). The effects of high salinity on plant health include decreased adult and seedling growth, as well as increased mortality and recruitment failure (Barrett-Lennard, 2003; Johnson & Young, 1993; Kirwan et al., 2007). When combined with increased flooding, the effects of salinity stress are compounded and result in a higher loss of species richness and alterations to the composition of plant communities along the coast (Baldwin & Mendelssohn, 1998). Because of this, losses of plant communities may be an indicator of an altered hydrologic regime.

The United States is among the countries with the highest coastal populations in the world and is also experiencing growth in the coastal zone (Neumann et al., 2015). Coastal counties in the United States in 2017 contained 29% of the country's population, despite making up less than 1% of U.S. counties, and their population grew 85% between 1960 and 2008 (Wilson & Fischetti, 2010). These communities, like others around the world, are at high risk of being affected by rising sea levels. High rates of sea level rise pose a danger to coastal ecosystems along the eastern United States coast and have the potential to displace thousands of people within the coastal zone while also threatening billions of dollars in losses of gross domestic product (Haer et al., 2013; Sallenger et al., 2012). The current impact of sea level rise can already be seen along the Atlantic and Gulf coasts in the losses of wetlands and infrastructure as areas have become inundated, submerged, or more susceptible to coastal hazards like hurricanes (Haer et al., 2013; Robichaud & Bégin, 1997; Rotzoll & Fletcher, 2012). The Atlantic Coast, in particular, has been identified as an area of high relative sea level rise that is predicted to have the second largest amount of coastal land area, compared to the Pacific and Gulf coasts, submerged as sea levels rise (Sallenger et al., 2012).

Ecosystem loss, and more specifically coastal forest loss, can be seen along the Atlantic coast as areas marked by expansive stands of dead and dying trees underlain by shrubs and herbaceous plants colonizing the soil surface (Kirwan & Gedan, 2019). Some of this mortality can be seen along the North Carolina coast in areas such as Dare, Hyde, and Tyrrell counties (Smart et al., 2020; Taillie et al., 2019). Areas with a thin vadose zone that would be considered topography-limited tend to be found in humid, low-lying, and low sloping areas with poorly draining soils, such as the Lower Coastal Plain in North Carolina (Befus et al., 2020; Michael et al., 2013; Moorhead & Brinson, 1995). This area has also experienced historically high rates of sea level rise compared to global rates, which are also expected to increase with climate change (Kemp et al., 2011; Sallenger et al., 2012). The topography of the North Carolina coastal plain also puts the area at risk of saltwater intrusion into coastal aquifers as sea levels rise (Befus et al., 2020; Michael et al., 2013; Moorhead & Brinson, 1995). Evidence of changing regimes in coastal North Carolina has been identified in the increasing number of transitioning forest areas along the coast (Bhattachan, Emanuel, et al., 2018; Smart et al., 2020; Taillie et al., 2019).

Given the changes in hydrology that could be forced by the combination of increased rates of sea level rise and topography-limited hydrology, there is the possibility that changing groundwater hydrology is influencing plant health and recruitment along the North Carolina coast. Forest transition may be a symptom arising from the problems of decreasing groundwater depth and increasing groundwater salinity. The North Carolina Division of Water Resources (NCDWR) has operated and maintained groundwater monitoring wells since the 1970s in order to examine the availability of groundwater and identify any areas that may be experiencing aquifer overuse (NCDWR, 2020, 2021a). The NCDWR has also collected water quality measurements from groundwater monitoring wells due to concerns regarding saltwater intrusion and potential groundwater pollution (NCDWR, 2021a). The goals of this water quality monitoring have been to obtain a baseline quality from ambient water quality measurements in order to develop water quality standards for North Carolina aquifers, and to identify and monitor potential and existing pollution sources (NCDWR, 2021a).

These data sample several aquifers and aquifer systems throughout North Carolina, including 3 United States Principal Aquifers and 9 local North Carolina aquifers (Table 1, Figure 3). The United States Geological Survey defined U.S. Principal Aquifers as those that are regionally extensive and having the potential to be used as a source of freshwater (Trapp Jr. & Horn, 1997). The Principal Aquifers examined in this study included the Castle Hayne aquifer, the Northern Atlantic Coastal Plain aquifer system, and the Surficial Aquifer system. These aquifers and aquifer systems are extensive and span from New Jersey south to the North Carolina/South Carolina border, with the Northern Atlantic Coastal Plain aquifer system estimated to cover the largest area (Trapp Jr. & Horn, 1997). The Castle Hayne aquifer has historically been used for industry and public support, with the main threat to the aquifer being saltwater intrusion (Lyke & Coble, 1987; Trapp Jr. & Horn, 1997). This is especially true in North Carolina, where saltwater intrusion is driven by groundwater pumping to support phosphate mining (Lyke & Coble, 1987). The Northern Atlantic Coastal Plain system has mainly been used for public water supplies, as well as agriculture and industry support (Trapp Jr. & Horn, 1997). This aquifer system is also threatened by saltwater intrusion driven by groundwater pumping (Trapp Jr. & Horn, 1997). The Surficial Aquifer System has also mainly been used to support public water supplies but is threatened mostly by surface contamination and agricultural runoff due to the nature of non-confinement and proximity to the soil surface (Trapp Jr. & Horn, 1997).

The local aquifers sampled are smaller aquifers within North Carolina that are not used on a regional scale for water supplies in the same way as Principal Aquifers. The local aquifers sampled in this study include Black Creek, Castle Hayne, Lower Cape Fear, Peedee, Surficial, Upper Cape Fear, Yorktown, Beaufort, and the Lower Cretaceous (Table 1). Beaufort and the Lower Cretaceous aquifers are considered minor aquifers due to their smaller extent, while the rest are considered major local aquifers (NCDWR, 2021b). The average elevation of these aquifers ranges from -11 ft relative to MSL to -767 ft relative to MSL and range from an areal extent of 7,300 mi^2 (the Lower Cretaceous aquifer) to 25,000 mi^2 (the local Surficial aquifer) (NCDWR, 2021b; Winner & Coble, 1989). These aquifers contain diverse sediments, including sand, limestone, silt, clay, shell beds, and occasionally gravel and their spatial extent spans the entire North Carolina Coastal Plain (NCDWR, 2021b; Winner & Coble, 1989).

Given the variation in aquifers sampled, as well as the variation in the spatial locations of the wells placed by the NCDWR, there is some expected natural variability in these measured data. These values represent static points in space and time; however, groundwater depth and water chemistry are variable over space and time; this gives an importance to understanding the spatial heterogeneity of these measurements across the area being monitored (Taillie et al., 2019). The coastal counties that form the study area of this research are not homogenous, and water depth and quality measurements may reflect that heterogeneity (Brinson et al., 1995; Daniels et al., 1971; Moorhead & Brinson, 1995; Smart et al., 2020).

The NCDWR states that monitoring efforts were often undertaken in areas where there was concern over groundwater resources, whether that concern was related to groundwater availability or quality (NCDWR, 2020, 2021a). Since wells were placed according to concern, rather than randomly across the landscape, there is the possibility that wells are clustered spatially. If there is a spatial pattern to groundwater monitoring well placement across the study area, there may also be a spatial pattern to the water depth and salinity measurements obtained from these monitoring sites. Additionally, groundwater depth is not driven solely by sea level along the coast. Hydrologic features interact with shallow, unconfined aquifers to affect belowground hydrology. For example, Brinson et al. (1995) identifies stream locations as impacting ecosystem zonation due to their influence on local hydrology. Groundwater depth relative to the soil surface decreases as distance from streams decreases, leading to a gradient of non-flood tolerant species farther from streams to flood-tolerant species closer to streams. Groundwater depth also decreases as distance from the coastline decreases due to the increasing force exerted on the groundwater by infiltrating sea water, leading to similar zonation (Befus et al., 2020; Michael et al., 2013; Moorhead & Brinson, 1995).

Distance to the coastline also has the potential to influence groundwater quality, as the dense marine layer present in coastal aquifers increases in thickness closer to the coastline; this gradient in marine layer thickness has been identified as increasing the possibility of saltwater intrusion in topography-limited aquifers like those in North Carolina’s lower coastal plain (Befus et al., 2020; Michael et al., 2013). Ardón et al. (2013) and Bhattachan et al. (2018) have identified the Albemarle-Pamlico Peninsula (APP) in eastern North Carolina as an area that is highly vulnerable to elevated rates of sea level rise driven saltwater intrusion and point out the possible detrimental effects of the high density of drainage systems that have been installed. These drainage systems may increase the vulnerability of upland environments to SLR-driven saltwater intrusion by allowing saline water to penetrate upland environments (Ardón et al., 2013; Bhattachan, Emanuel, et al., 2018). Not only could these features drive altered water quality in coastal North Carolina, but they could also lead to higher rates of change in some areas of the coastal zone than others.

The coastal zone of North Carolina is a dynamic area that has the potential to be better understood. The research presented in this thesis uses the available groundwater data to ask several questions: (1) if there are detectable trends in groundwater depth in coastal North Carolina, (2) if groundwater monitoring wells placed by the NCDWR are spatially clustered, (3) if we can identify areas of high salinity, high rate of groundwater depth change from available groundwater monitoring data and (4) if groundwater depth and quality in shallow, unconfined aquifers are correlated with proximity to hydrologic features within the coastal zone.

Due to historic rates of sea level rise in North Carolina, I hypothesize that there are detectible trends in groundwater depth that can be found in long-term monitoring data. Because the NCDWR has stated that many of these wells were placed out of specific concern, I then hypothesize that these monitoring well locations are spatially clustered. I also hypothesize that there are areas of high salinity, high specific conductance, and significantly high or low rates of groundwater depth change within our study area. Hydrologic features have been identified as having an influence on both groundwater depth and quality, and this research will use three categories of hydrologic features (coastline, streams, and drainage ditches) to test the hypothesis that both groundwater depth and quality are correlated to proximity to hydrologic feature, and that both salinity and aquifer height increase as proximity to hydrologic features decreases. Finally, I hypothesize that there are areas of high salinity, high specific conductance, and significantly high or low rates of groundwater depth change within our study area.

Figures and Tables

Figures

Figure 1: Ecosystems along the Atlantic Coast are in transition. This is observed as dead old growth within what has become marshland. Photo from Chase Brown.

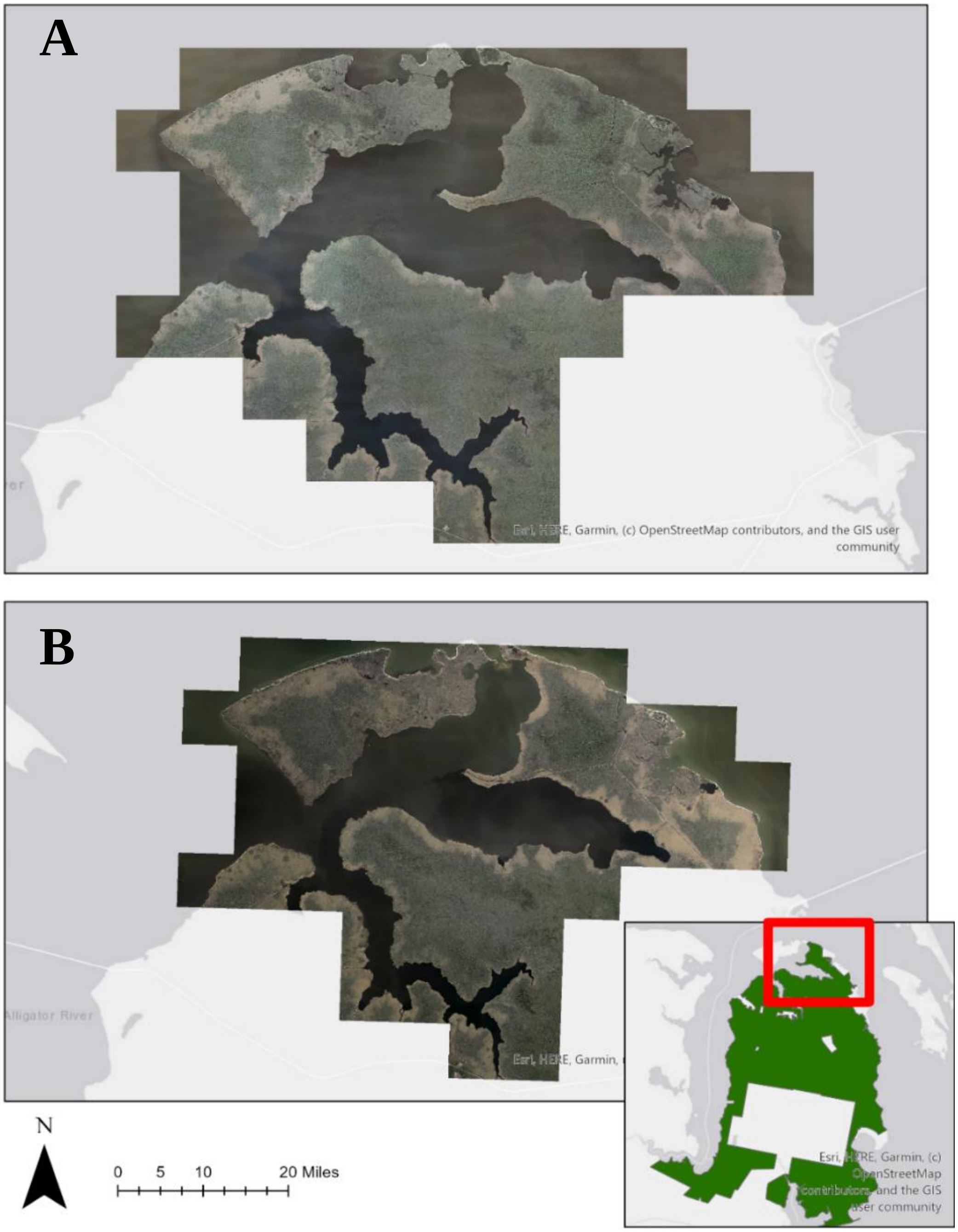

Figure 2: Orthoimagery of East Lake in Alligator River National Wildlife Refuge, Dare County, NC, USA shows a pattern of decreased forest cover and increasing marsh along the coastline from (A) 2010 to (B) 2020.

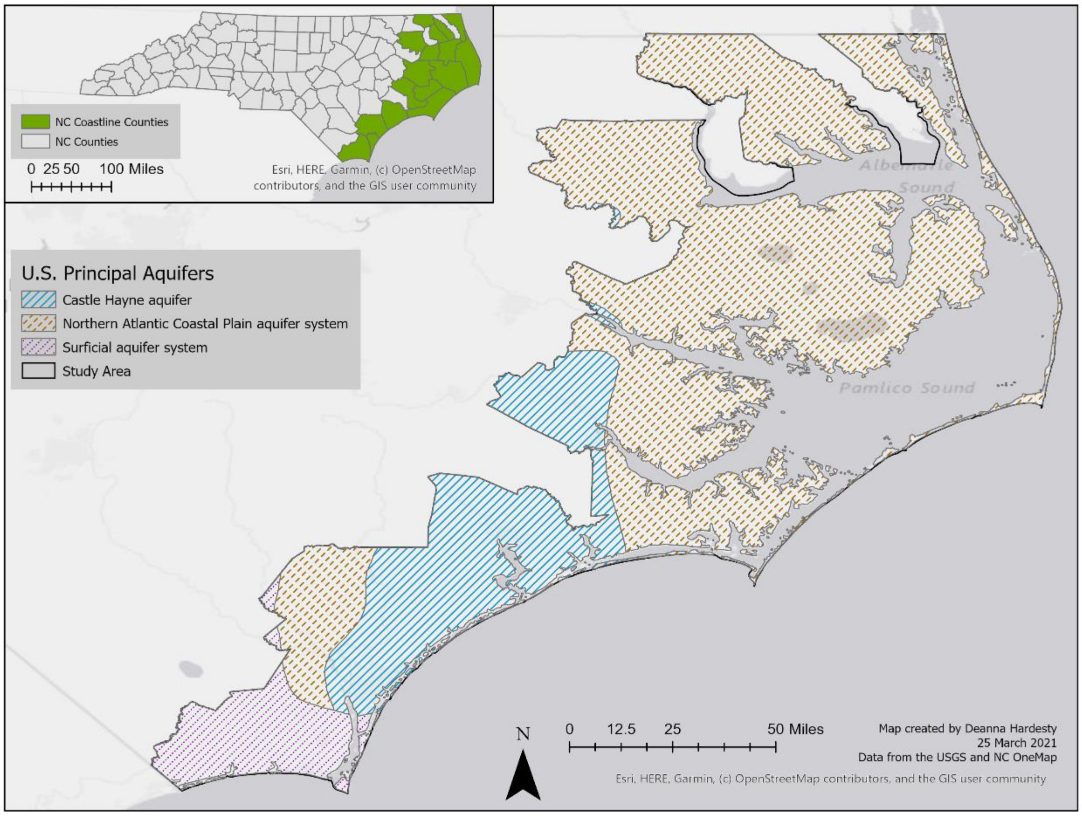

Figure 3: Three United States Principal Aquifers were sampled in this study. This map indicates the spatial location where each aquifer is the shallowest of the three examined within the study area.

Tables

Table 1: Several U.S. Principal Aquifers make up the North Carolina aquifer system. They vary in extent throughout the country and contribute to the water cycle along the entire Atlantic coast. Information adapted from Lyke & Coble (1987), Trapp Jr. & Horn (1997), and Winner & Coble (1989).

U.S Principal Aquifer Name	Extent	Estimated Area (mi^2)	Sediment	Main Uses	Main Threats
Castle Hayne Aquifer	New Jersey to southeastern North Carolina	12,500	Silts and clays to permeable sands	Public withdrawal, industry support	Saltwater intrusion, especially in North Carolina where it is driven by groundwater pumping to support phosphate mines
Northern Atlantic Coastal Plain Aquifer System	New Jersey to the North Carolina/ South Carolina state boundary	50,000	Semi- to unconsolidated clay silt and sand underlain by crystalline rock. Some lignite, gravel, and limestone deposits	Public Supply, Agriculture, industry support (e.g., phosphate mining)	Saltwater intrusion driven by groundwater pumping, agricultural contamination
Surficial Aquifer System	Pennsylvania to North Carolina/South Carolina border	N/A	Unconsolidated sand and gravel	Public and domestic water supplies	Surface contaminants, agricultural runoff, overuse

Table 2: The Coastal Plain aquifer system in North Carolina is composed of 9 local aquifers. These aquifers extend into various portions of the Coastal Plain and vary in areal extent and aquifer thickness. Information from the NCDWR (2021) and Winner (1989).

Aquifer Name	Extent and Type (Confined/Unconfined)	Average Elevation (ft relative to MSL)	Estimated Area (mi^2)	Sediments	Mean Thickness (ft)	Minimum Thickness (ft)	Maximum Thickness
Major Aquifers							
Black Creek	Central and Southwest Coastal Plain, Confined	-138	21,200	Very fine to fine sand	148	14	448
Castle Hayne	Eastern Coastal Plain, Confined	-127	11,500	Limestone, sandy limestone, sand	155	12	755
Lower Cape Fear	Northwestern Coastal Plain, Confined	-767	17,000	Fine to coarse sand	400	23	2730
Peedee	Central to Southeastern Coastal Plain, Confined	-158	13,900	Fine to medium sand	133	8	750
Surficial	Throughout the Coastal Plain, Unconfined	300	25,000	Diverse; includes sand, silt, clay, shell beds, and scattered coarse material	35	3	180
Upper Cape Fear	Western Coastal Plain, Confined	-320	22,200	Very fine to coarse sand, occasionally gravel	165	8	728
Yorktown	Northern Coastal Plain, Confined	-11	11,800	Fine sand, silty sand, clayey sand, shell beds, coarse sand	95	4	922
Minor Aquifers							
Beaufort	Eastern and Central Coastal Plain, Confined	-280	10,700	Fine to medium sand, clayey sand, shell beds, limestone beds	78	8	242
Lower Cretaceous	Northern Coastal Plain, Confined	-701	7,300	Fine to medium sand, occasional coarse sand, limestone beds	142	65	322

Chapter 2: Quantitative Assessment of Groundwater in Eastern North Carolina, USA

Introduction

As mentioned in Chapter 1, sea level rise is a coastal hazard of particular concern in the global coastal zone due to its potential to increase flooding, damage infrastructure, and detrimentally affect the ability of communities to participate in agricultural activities (Befus et al., 2020; Kirwan & Gedan, 2019; Rotzoll & Fletcher, 2012). Sea level rise has the potential to affect both the coastline and inshore systems such as aquifers, as increasing sea level can drive decreased groundwater depth inshore (Befus et al., 2020; Masterson & Garabedian, 2007; Michael et al., 2013; Rotzoll & Fletcher, 2012). North Carolina has historically seen high rates of sea level rise, and these rates are expected to accelerate as climate change drives warmer ocean temperatures and thermal expansion (Kemp et al., 2011; Sallenger et al., 2012). The topography of the North Carolina coastal zone is low-lying with a gradual slope and poorly draining soils, and the area normally experiences a humid climate (Moorhead & Brinson, 1995). Since high rates of sea level rise have been observed in North Carolina, and because of its topographic position and the characteristics of the soils and climate, many areas within the coastal zone are likely to be considered topography-limited and experience an decrease in groundwater depth over time.

This chapter focuses on the question of whether or not there have been there detectable changes groundwater depth in recent decades in North Carolina coastline counties. These counties have historically seen high rates of sea level rise, which has implications for both confined and unconfined aquifers within the study area. Unconfined aquifers are likely to be experiencing high rates of change, as water is able to move more freely though the vadose zone. Confined aquifers may also experience a decrease in groundwater depth, although this depth change may happen at a lower rate due to constraints on water movement through the vadose zone. This research tests the hypothesis that there have been detectable trends in groundwater depth over time using Mann-Kendall trend test methodology. Rate of change of groundwater depth over time are quantified using Linear Regression analysis.

Materials and Methods

Groundwater Data Collection and Analysis

Groundwater data were collected through the NCDWR's Groundwater Levels & Quality data portal (*https://www.ncwater.org/?page=343*). Groundwater data were collected from 257 groundwater monitoring wells in 17 coastal shoreline counties within North Carolina, USA (Appendix 1). Coastal shoreline counties are defined by the National Oceanic and Atmospheric Administration (NOAA) as those counties in the United States "that are directly adjacent to the open ocean, major estuaries, and the Great Lakes" (NOAA, 2010). Data were downloaded using a timeframe of 1 January 2000 to 31 December 2019 to strive for about 20 years of groundwater data. The data reported groundwater depth relative to the fixed datum NAVD88 in feet.

Groundwater depth data included both tape-down and automatic daily recorder measurements. Data were filtered to include only automated recorder measurements because they were more continuous than the sporadic tape-down measurements, and because of the smaller standard error of daily measurements (Figure 4). Automatic measurements were used to construct a time series of groundwater depth relative to the fixed datum NAVD88 for each monitoring well (Figure 5). RStudio version 1.2.5033 was then used to aggregate daily groundwater depth measurements into monthly mean groundwater depth relative to NAVD88 for the years available. The groundwater monitoring well dataset also included measurements from wells at varying depths below the ground surface. Because of this, wells were divided into three depth classes to more accurately be compared and analyzed: a “Shallow” class (10 ft – 206 ft), a “Medium” class (207 ft – 579 ft) and a “Deep” class (580 ft – 1320 ft). A Partitioning Around Medoids (PAM) clustering algorithm was used to define these clusters in RStudio and optimized for three categories.

Measurements of monthly mean groundwater depth relative to NAVD88 in feet were analyzed over time using a seasonal Mann-Kendall trend test in order to determine if there are trends in groundwater depth within the study area. Seasonal Mann-Kendall trend tests were carried out in RStudio using the “SeasonalMannKendall” function within the “kendall” package. The seasonal trend test was chosen as it is designed for non-continuous datasets that exhibit non-normality (Hirsch, 1982; Hirsch & Slack, 1984). Groundwater depth data were not always continuous due to equipment malfunction and tended to be bimodal, which can be attributed to the alternation of seasons (Figure 6). Although the length of the data record was variable across wells, the Mann-Kendall analysis is considered accurate for five or more years of data (Hirsch, 1982; Hirsch & Slack, 1984). Because of this, all sites with five or more years of available data were included in the Mann-Kendall analysis.

The seasonal Mann-Kendall trend test was performed with groundwater depth in feet relative to the fixed datum NAVD88 as the dependent variable, and time as the explanatory variable. The null hypothesis (H_0) of the seasonal Mann-Kendall trend test for each groundwater monitoring well is that there is no monotonic trend in groundwater depth relative to NAVD88 from 2000 to 2019. The alternative hypothesis (H_A) of the seasonal Mann-Kendall trend test for each well is that there is a positive or negative trend in groundwater depth over time. Results were considered significant at the 90% confidence level ($p \leq 0.10$) The sign and magnitude of this trend are reported as Kendall Tau (τ) values. For wells reporting significant positive τ values, we reject H_0 that there is no trend and accept H_A, in which a trend exists within the dataset of decreasing groundwater depth relative to the reference datum. For wells reporting significant negative τ values, we reject H_0 and accept H_A, which for negative values suggests a trend exists within the dataset of increasing groundwater depth relative to the reference datum. For wells reporting no significant τ value, we accept H_0 as there is not enough support to accept H_A.

The rate of change in groundwater depth for each well location was then quantified using a linear regression analysis. This analysis was performed in RStudio version 1.2.5033 and used yearly mean water level in feet relative to NAVD88 as the dependent variable and year as the independent variable. The slope of the relationship (β_1) is then reported as the rate of change in mm/year for each monitoring well, which was converted from ft/year in RStudio after the analysis was performed. Sites were reported according to depth, with "shallow" wells ranging in depth from 10 ft to 206 ft, "medium" wells ranging in depth from 207 ft to 579 ft, and "deep" wells ranging from 580 ft to 1320 ft.

Results

Results of the Mann-Kendall Trend Test

A Mann-Kendall trend test was performed for the time series constructed from each well for 257 site locations, of which 144 (56%) sites reported significant positive Kendall Tau (τ) values ($\bar{x}_\tau = 0.39 \pm 0.23$), 62 sites (24%) reported significant negative τ values ($\bar{x}_\tau = -0.49 \pm 0.30$), and 51 sites (20%) reported no significant τ value at the 90% confidence level (Appendix 2). For all groundwater monitoring sites considered, more sites report a trend of decreasing groundwater table depth relative to the fixed datum NAVD88 than those that report either an increase in groundwater depth relative to NAVD88 or no change in groundwater table depth. Sampling included both confined and unconfined aquifers. Confined aquifers reported 198 wells sampled, with 110 wells (56%) reporting significant positive τ values ($\overline{x}_{\tau}$ = 0.43 ± 0.23), 54 wells (27%) reporting significant negative τ values ($\overline{x}_{\tau}$ = -0.52 ± 0.29), and 34 sites (17%) reporting no significant τ values (Table 3). Unconfined aquifers reported 59 sites sampled, with 34 sites (58%) reporting a significant positive τ value ($\overline{x}_{\tau}$ = 0.26 ± 0.18), 8 sites (14%) reporting a significant negative τ value ($\overline{x}_{\tau}$ = -0.28 ± 0.29), and 17 sites (31%) reporting no significant τ values (Table 3).

As mentioned in the Introduction, both local North Carolina and U.S. Principal Aquifers were sampled in this analysis (Table 3). U.S. Principal Aquifers sampled included the Castle Hayne aquifer, the Northern Atlantic Coastal Plain aquifer system, and the Surficial Aquifer system. The Castle Hayne aquifer reported 69 sites sampled, with 43 sites (62%) reporting significant positive τ values ($\overline{x}_{\tau}$ = 0.38 ± 0.23), 14 sites (20%) reporting significant negative τ values ($\overline{x}_{\tau}$ = -0.43 ± 0.27), and 12 sites reporting no significant τ values. The Northern Atlantic Coastal Plain aquifer system reported 125 sites sampled, with 68 sites (54%) reporting significant positive τ values ($\overline{x}_{\tau}$ = 0.37 ± 0.23), 32 sites (27%) reporting significant negative τ values ($\overline{x}_{\tau}$ = -0.53 ± 0.31), and 25 sites reporting no significant τ values. The Surficial aquifer system reported 63 sites sampled, with 33 sites (52%) reporting significant positive τ values ($\overline{x}_{\tau}$ = 0.43 ± 0.25), 16 sites (25%) reporting significant negative τ values ($\overline{x}_{\tau}$ = -0.46 ± 0.31), and 14 sites (22%) reporting no significant τ values.

Local North Carolina aquifers were also considered in this analysis (Table 3). The Black Creek aquifer reported 18 wells sampled, of which 10 sites (56%) reported significant positive τ values ($\overline{x}_{\tau}$ = 0.40 ± 0.25), 6 sites (33%) reported significant negative τ values ($\overline{x}_{\tau}$ = -0.64 ± 0.34), and 2 sites (11%) reported no significant τ value. The Beaufort aquifer reported 13 sites sampled, of which 5 sites (38%) reported significant positive τ values ($\bar{x}_\tau = 0.37 \pm 0.23$), 4 sites (31%) reported significant negative τ values ($\bar{x}_\tau = -0.46 \pm 0.36$), and 4 sites (31%) reported no significant τ value. The local Castle Hayne aquifer reported 69 sites sampled, with 43 sites (62%) reporting significant positive τ values ($\bar{x}_\tau = 0.38 \pm 0.23$), 14 sites (20%) reporting significant negative τ values ($\bar{x}_\tau = -0.43 \pm 0.27$), and 12 sites (17%) reporting no significant τ value. The Lower Cape Fear aquifer had 8 wells sampled, with 4 sites (50%) reporting significant positive τ values ($\bar{x}_\tau = 0.42 \pm 0.24$), 3 sites (38%) reporting significant negative τ values ($\bar{x}_\tau = -0.79 \pm 0.21$), and 1 site (13%) reporting no significant τ value. The Lower Cretaceous reported 3 wells sampled, with no wells reporting significant positive τ values, 2 sites (66%) reporting significant negative τ values ($\bar{x}_\tau = -0.66 \pm 0.25$), and 1 site (33%) reporting no significant τ value. The Peedee aquifer reported 27 sites sampled, with 14 sites (52%) reporting significant positive τ values ($\bar{x}_\tau = 0.25 \pm 0.22$), 8 sites (30%) reporting significant negative τ values ($\bar{x}_\tau = -0.31 \pm 0.20$), and 5 sites (36%) reporting no significant τ value. The local Surficial aquifer reported 63 sites sampled, with 33 sites (52%) reporting significant positive τ values ($\bar{x}_\tau = 0.43 \pm 0.25$), 16 sites (25%) reporting significant negative τ values ($\bar{x}_\tau = -0.46 \pm 0.31$), and 14 sites (22%) reporting no significant τ values. The Upper Cape Fear aquifer reported 12 sites sampled, with 5 sites (42%) reporting significant positive τ values ($\bar{x}_\tau = 0.57 \pm 0.32$), 6 sites (50%) reporting significant negative τ values ($\bar{x}_\tau = -0.69 \pm 0.30$), and 1 site (8%) reporting no significant τ value. The Yorktown aquifer reported 44 sites sampled, with 30 sites (68%) reporting significant positive τ values ($\bar{x}_\tau = 0.37 \pm 0.19$), 3 sites (7%) reporting significant negative τ values, and 11 sites (25%) reporting no significant τ value.

Linear Regression Analysis

Sites reporting a significant positive trend, which indicates decreasing groundwater table depth relative to NAVD88, on average showed a rate of change of +117.94 ± 71.03 mm/year. Sites reporting a significant negative trend, which indicates increasing groundwater table depth relative to NAVD88, on average showed a rate of change of -149 ± 90.79 mm/year. Although wells that reported negative trends were fewer, these areas are experiencing a higher rate of change than those reporting positive trends. Confined aquifers on average gained height at a higher rate (88.35 mm/yr ± 391.43) than unconfined aquifers (24.69 mm/yr ± 83.77), though the rate of change in groundwater depth across both confined and unconfined aquifers was highly variable (Table 3). Shallow aquifers on average gained 20.88 ± 106.30 mm/year in height, medium aquifers on average gained 98.14 ± 453.71 mm/year in height, and deep aquifers on average gained 180.14 ± 514.81 mm/year in height (Table 3). When separated by U.S. Principal Aquifer, on average the Castle Hayne aquifer gained 117.70 ± 471.70 mm/year in height, the Northern Atlantic Coastal Plain aquifer system gained 42.80 ± 259.59 mm/year, and the Surficial aquifer system gained 86.95 ± 336.62 mm/year (Table 3).

Most local aquifers on average also saw decreasing groundwater depths at rates ranging from 18.79 mm/year to 120.28 mm/year (Table 3). The Beaufort aquifer on average gained 18.79 ± 142.64 mm/year, the Black Creek aquifer on average gained 68.79 ± 290.87 mm/year, the local Castle Hayne aquifer on average gained 117.70 ± 471.70 mm/year, the Peedee aquifer on average gained 11.79 ± 233.61 mm/year, the Surficial aquifer on average gained 86.95 ± 336.62 mm/year, the Upper Cape Fear on average gained 120.28 ± 620.30 mm/year, and the Yorktown aquifer on average gained 56.23 ± 121.32 mm/year. Two aquifers, the Lower Cape Fear (-9.42 ± 150.32 mm/year) and the Lower Cretaceous (-97.58 ± 110.61 mm/year) lost height on average.

Discussion

Overall, Mann Kendall analyses revealed that the majority of wells in North Carolina coastline counties (80%) exhibit a significant trend, both positive and negative. More wells report a positive trend (54%) than report a negative trend (24%). This indicates that more wells are experiencing a decrease in depth to the top of the aquifer than are experiencing an increase in depth to the top of the aquifer. A similar proportion of positive to negative trends at well locations was observed in confined and unconfined aquifers, as well as in each of the U.S. Principal Aquifers examined in this study. Local aquifers show slightly different trends, with two local aquifers reporting a majority negative trends, however, the characteristics of local aquifers are more variable compared to those of aquifer type or U.S. Principal Aquifer. Confined, unconfined, and U.S. Principal Aquifers are sampled throughout the coastal zone, and summaries of measurements associated with these groups integrate patterns of groundwater depth change throughout the coastal plain. Local aquifers, however, are smaller in extent and more limited in depth, and because of this, may only sample a small portion of the North Carolina coastal zone. This could lead to more variable patterns in some parts of the coastal zone, but in not others. Measurements of these aquifers may be useful to gain an understanding of their local extent, while measurements of the Principal aquifers inform patterns in the larger coastal zone.

Regression analyses indicate that sampling positive rates of change in groundwater depth over time were highly variable, from 0.10 mm/year to 3279.65 mm/year. Site locations that reported a larger τ value also typically reported a higher slope coefficient, indicating a higher rate of change. Rates of groundwater depth change were highly variable across all aquifers groupings: Principal and local, unconfined and confined, and shallow, medium, or deep. For groundwater monitoring wells that did report a decrease in groundwater depth (54%) and an associated decrease in groundwater depth, there may be implications for the health of upland plants within the coastal zone. As discussed previously, altered hydrologic regimes can be detrimental to upland plants that are not adapted to saturated and inundated conditions (Barrett-Lennard, 2003; Kirwan et al., 2007). Observations of transitioning ecosystems along the North Carolina coast have led to research into the mechanisms driving this change; identification of altered groundwater hydrology may be important to understanding how the aboveground ecology of the coastal zone will change as sea levels rise.

The coastal zone of North Carolina is unique in that, unlike many other coastal states, its coastline tends to be more rural and contain less hard infrastructure (Bhattachan, Jurjonas, et al., 2018). This lends an increased importance to understanding the potential effects of sea level rise for these rural areas, as the effects of rising aquifers in these regions are not as well understood as in urban coastal zones but will have similar impacts (Befus et al., 2020). The North Carolina coastal plain is especially vulnerable to sea level rise due to its topographic position, but many of the areas that could be affected by sea level rise often do not have the same monetary or social capital possessed by urban areas to mitigate the negative effects (Bhattachan, Jurjonas, et al., 2018; Moorhead & Brinson, 1995; Rowley et al., 2007). Communities in the coastal zone often rely on natural resources for commerce, and the potential for sea level rise to alter the ability to participate in agricultural activities threatens the livelihood of many rural North Carolina communities (Bhattachan, Jurjonas, et al., 2018; Kirwan & Gedan, 2019). Therefore, understanding the changes that the coastal zone is experiencing may inform how we identify and mitigate the effects of sea level rise before they can devastate communities.

Figures and Tables

Figures

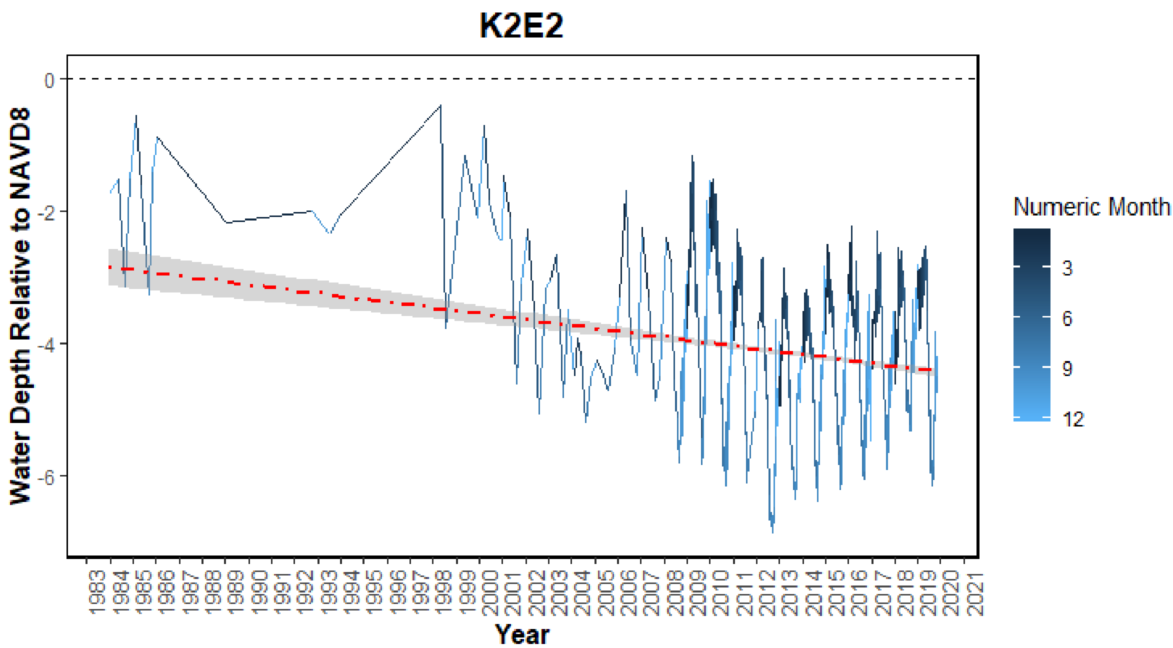

Figure 4: Automatic recorder measurements were used for Mann-Kendall analysis and tape-down measurements were excluded. These measurements were infrequent and raised the standard error of the dataset, while recorder measurements were robust and exhibited low standard error.

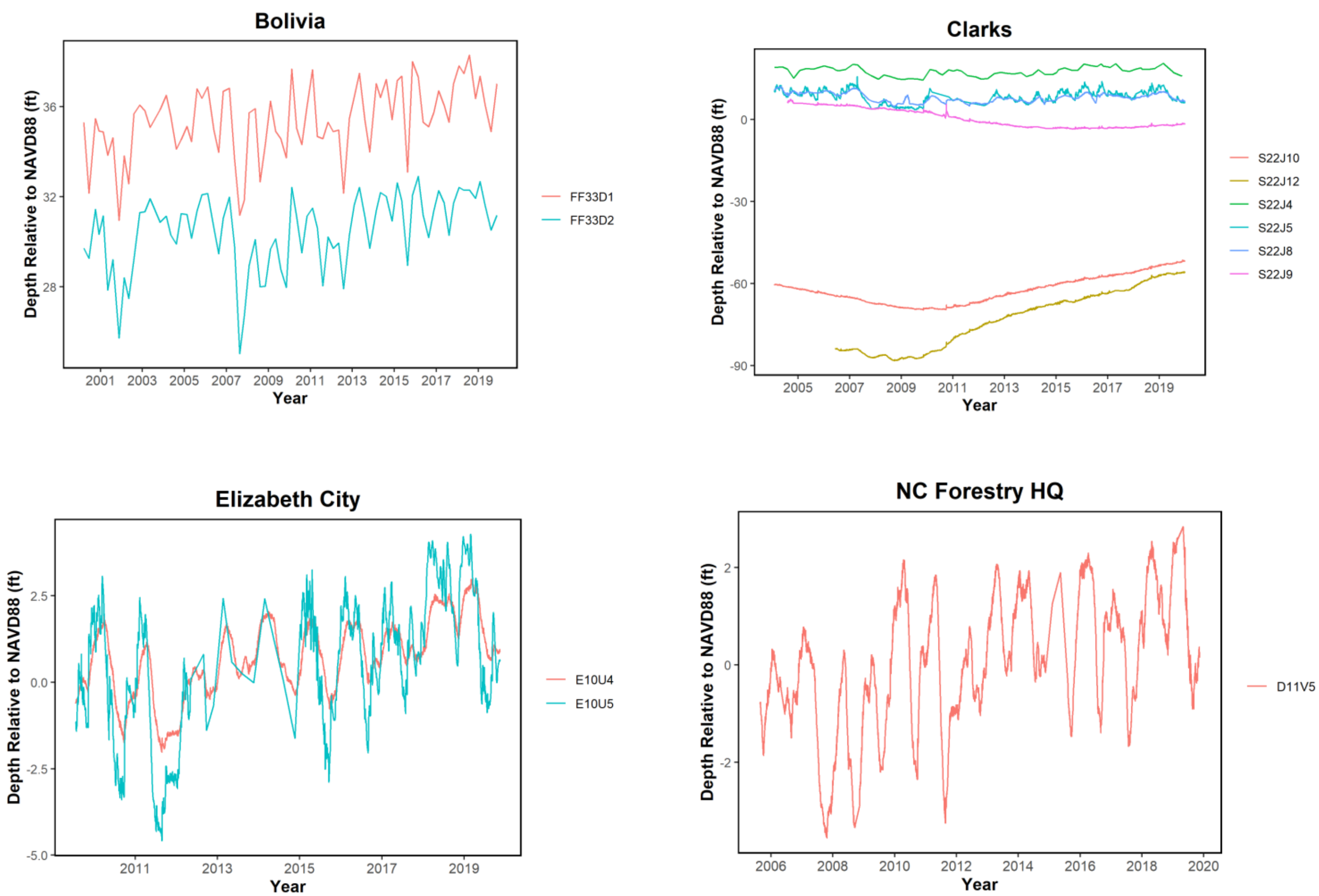

Figure 5: Time series were constructed from automatic groundwater level recorder measurements for groundwater monitoring well locations within the study area. Examples of these time series are shown above for several sites.

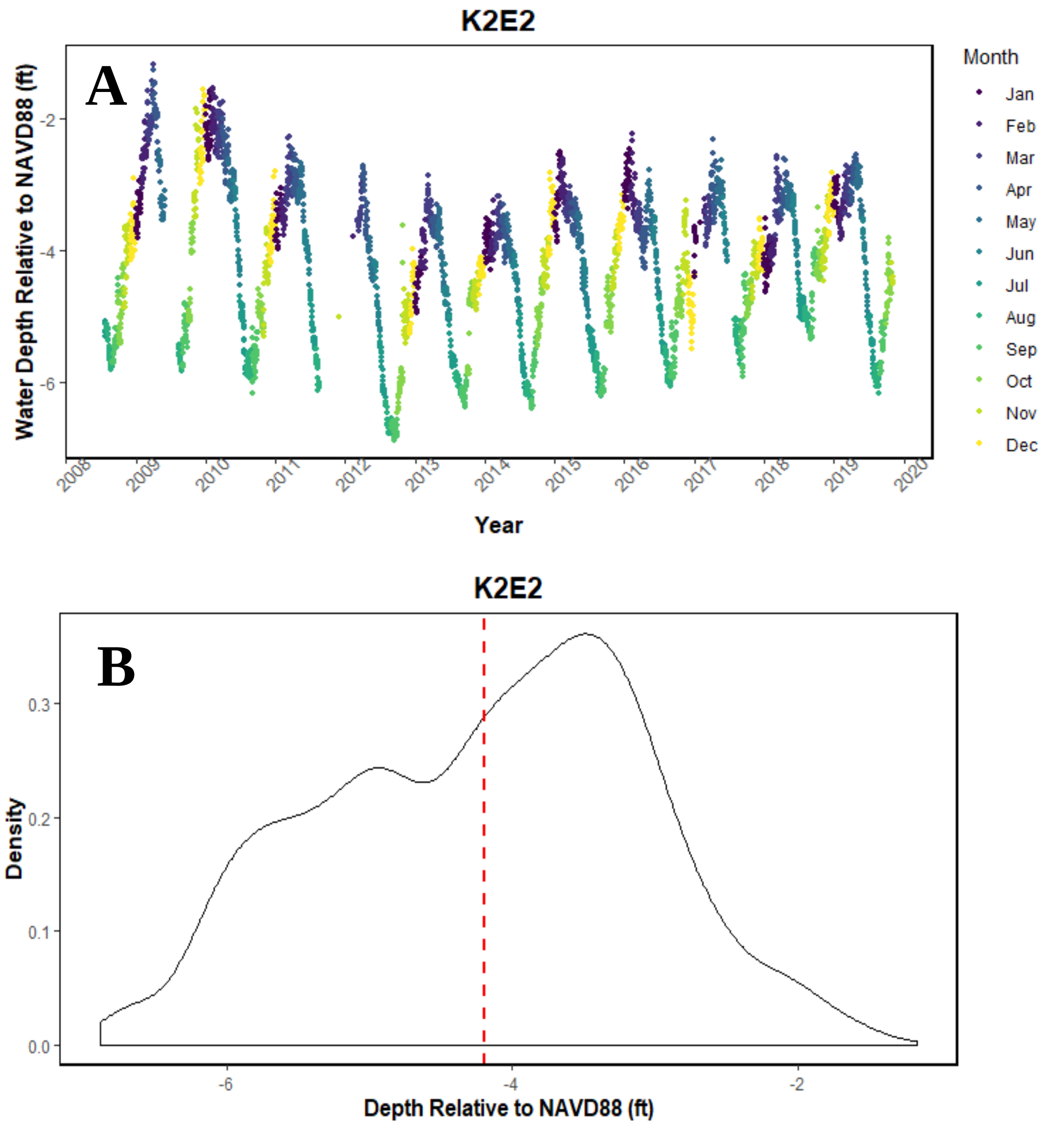

Figure 6: (A) Water level data exhibited a strong pattern of seasonality, as shown for data collected from well K2E2 at Bodie Island in Dare County, NC, USA. Water levels peak in winter months during the dormant season and decrease throughout the growing season, typically reaching a minimum in August/September. (B) This pattern contributed to the non-normal distribution of the data, shown by the density plot above. Mean water level is represented by a red dotted line on the density plot.

Tables

Table 3: Mann-Kendall trend tests were performed on groundwater monitoring well depth to detect any significant trends of increasing or decreasing groundwater depth. Results are displayed alongside average rate of change for U.S. Principal Aquifers, local North Carolina aquifers, counties, and the 5 stratifications: confined aquifers, unconfined aquifers, shallow wells, medium depth wells, and deep wells.

	Average Rate of Depth Change (mm/year)	Average Kendall Tau
U.S Principal Aquifer/Aquifer System		
Castle Hayne aquifer	117.70	0.15
Northern Atlantic Coastal Plain aquifer system	42.80	0.07
Surficial aquifer system	86.95	0.11
Local Aquifer		
Beaufort	18.79	0.02
Black Creek	68.79	0.01
Castle Hayne	117.70	0.15
Lower Cape Fear	-9.42	-0.08
Lower Cretaceous	-97.58	-0.46
Peedee	11.79	0.04
Surficial	86.95	0.11

Table 3 (continued)

Upper Cape Fear	120.28	-0.11
Yorktown	56.23	0.24
County		
Beaufort	169.03	0.13
Bertie	1.88	0.04
Brunswick	-19.55	-0.07
Carteret	19.80	0.25
Craven	138.96	0.10
Currituck	-162.15	-0.99
Dare	11.054	0.20
Gates	273.29	-0.03
Hyde	126.61	0.35
New Hanover	-17.74	-0.06
Onslow	95.17	0.01
Pamlico	114.81	0.36
Pasquotank	-16.21	0.11
Pender	11.73	0.07
Perquimans	-148.00	-0.87
Tyrrell	34.74	0.20

Table 3 (continued)

Washington	11.88	0.07
Depth Cluster		
Shallow (10 ft – 206 ft)	20.88	0.18
Medium (207 ft – 579 ft)	98.14	0.01
Deep (580 ft – 1320 ft)	180.14	0.18
Aquifer Type		
Confined	88.35	0.10
Unconfined	24.69	0.12

Chapter 3: Spatial Analysis of Groundwater Data in Eastern North Carolina, USA

Introduction

As discussed in Chapter 1, groundwater monitoring well measurements have the potential to be highly variable across space and time, as they are sampled from aquifers and geographic locations that are variable. Spatial patterns in these data will be important to identify in order to better understand the effects that a changing hydrologic regime brought on by sea level rise in the coastal zone could have on the surrounding ecosystem and groundwater resources. This chapter examines the questions of whether: (2) groundwater monitoring wells placed by the NCDWR are spatially clustered; (3) areas of high salinity or high rate of groundwater depth change from available groundwater monitoring data are identifiable; and (4) groundwater depth and quality in shallow, unconfined aquifers are correlated with proximity to hydrologic features in the coastal zone.

The NCDWR has stated that groundwater monitoring wells were placed intentionally in areas that were identified as being at risk of aquifer overuse or pollution (NCDWR, 2020). Because of this, I hypothesize that there is significant spatial clustering in groundwater monitoring well locations. Additionally, because of the heterogeneous nature of the North Carolina coastal zone, rates of groundwater depth change and saltwater intrusion are likely to be variable across the study area. I hypothesize that there are areas of significantly high rate of groundwater change, as well as high salinity. Finally, many authors (Masterson & Garabedian 2007, Michael et al. 2013, and Befus et al. 2020) have examined the effects of sea level rise on unconfined, shallow aquifers that are influenced by sea level rise. These studies have found that in topography limited systems, shallow, unconfined aquifers may experience flooding and aquifer salinization due to high rates of seawater intrusion into the aquifer. North Carolina is an area that is likely to be topography-limited in many areas due to its geologic and topographic characteristics and it is experiencing high rates of sea level rise (Kemp et al., 2011; Moorhead & Brinson, 1995; Sallenger et al., 2012). Additionally, aboveground hydrologic features have the ability to influence groundwater depth in shallow, unconfined aquifers, especially in areas in close proximity to these features (Befus et al., 2020; Brinson et al., 1995). Because of this, I hypothesize that measurements of rate of change in groundwater depth and of high salinity in shallow, unconfined aquifers in the coastal zone are correlated to distance from hydrologic features.

Materials and Methods

Spatial Data Collection

Groundwater monitoring well locations across the study area were obtained from the NCDWR Groundwater Data Portal (Figure 7). The number of groundwater monitoring wells per site was not uniform, and density of groundwater wells per site location is visualized in Figure 8. Hydrologic features were downloaded from the USGS National Hydrology Dataset (NHD) for the study area and filtered to include only coastline (Figure 9), stream (Figure 10), and ditch features (Figure 11). Rate of change, obtained from slop (β_1) values of regression analyses performed in Chapter 1 (Table 3), and water quality measurements from groundwater monitoring wells, were used alongside the hydrologic data to assess spatial relationships.

Water Quality Data Collection

Water quality data included measured specific conductance values and derived salinity values, which were collected in the field by the NCDWR using a YSI conductivity and salinity meter. No site reported more than 17 specific conductance measurements or more than 10 salinity measurements from 2000-2019, and not every well that reported groundwater depth data also reported groundwater quality data. The available water quality data are reported in this analysis because salinity has been identified as a driver of forest transition in coastal North Carolina, however the data are not complete enough to derive robust time series (Kirwan & Geden, 2019). Salinity and specific conductance measurements were used to obtain mean salinity and mean specific conductance for each well. Mean salinity and specific conductance were calculated across the study area and interpolated for five groups of wells: those that sampled unconfined aquifers, those that sampled confined aquifers, shallow wells, medium depth wells, and deep wells. Mean water quality measurements were also summarized by U.S. Principal Aquifer.

Water quality data measurements of both salinity and specific conductance were binned into three discrete categories based on the value: fresh, brackish, or saline. Measurements were considered "fresh" at a salinity < 0.50 ppt or specific conductance of < 2,000 μS/cm, "brackish" at a salinity of 0.5-31.9 ppt or specific conductance of 2,001-44,999 μS/cm, and "saline" at a salinity of 32-35 ppt or specific conductance of 45,000-55,000 μS/cm. These categories are based on reported measurements of freshwater, brackish water, and saline water from Millero (2006).

Clustering Analyses

In order to first determine if there was significant clustering in the groundwater monitoring well locations, a Density Based Clustering analysis was run using ArcGIS Pro 2.5.0 using the HBDSCAN methodology. This unsupervised method identifies clusters of input point features based on their spatial location. To then determine whether there was significant clustering in the spatial locations of β_1 values obtained from the regression analyses in Chapter 1, referred to as spatial autocorrelation, a Global Moran's I analysis was run in ArcGIS Pro. The β_1 measurements were analyzed according to aquifer type, either confined or unconfined, as well as aquifer depth. Depth clusters were the same as in the previous chapter, with "Shallow" including wells from 10 ft to 206 ft deep, "Medium" including wells from 207 ft to 579 ft deep, and "Deep" including wells from 580 ft to 1320 ft deep. The water quality dataset contained 196 measurements from confined aquifers, 59 measurements from unconfined aquifers, 130 measurements from shallow wells, 81 measurements from medium wells, and 44 measurements from deep wells.

This test used Euclidian distance as the distance method and inverse distance weight (IDW) as the conceptualization of spatial distance. The IDW conceptualization weighs data based on their spatial location in relation to nearby points. The null hypothesis (H_0) of the Moran's I analysis is that the data points, in this case locations associated with specific β_1 values, are randomly distributed across the study area and do not exhibit spatial autocorrelation. The alternative hypothesis (H_A) is that the spatial locations of β_1 values are not randomly distributed across the study area and are related to each other in some way. A positive z-score in this test suggests that there is a clustered relationship, where data points are spatially close to one another. Results were considered significant at the 90% confidence level. The same method was used to determine the existence of spatial autocorrelation within reported salinity and specific conductance measurements for well sites.

Local clustering was then examined for β_1 values, salinity measurements, and specific conductance measurements using a Getis-Ord Gi* (Hot Spot) analysis in ArcGIS Pro. This analysis again used the Euclidian distance and IDW as distance settings. Significance in this test denotes areas in which high-values or low-values are clustered spatially. Similar to the Moran's I test, the H_0 of the Hot Spot test is that data points are distributed randomly across the study site. The H_A of the test is that there is significant spatial clustering of the data points, which can be high-value clustering or low-value clustering. Positive z-scores suggest high-value clustering while negative z-scores suggest low-value clustering. Results were considered significant at the 90% confidence level.

Interpolation of Rate of Change (β_1), Mean Salinity, and Mean Specific Conductance Values

Rate of change (β_1), mean salinity, and mean specific conductance were interpolated across the study area using Inverse Distance Weighting (IDW) methodology in order to better understand the spatial variation in these measurements visually. Values were again aggregated by aquifer type or aquifer depth for examination using the same depth clusters as mentioned above. Groundwater monitoring locations often contained more than one well, and in the case where more than one well existed in a given cluster and spatial location, all points were considered in the analysis (as opposed to taking a mean, using a maximum, or using a minimum of measurements at each site location). Visual patterns were then quantified using an Ordinary Least Squares (OLS) regression analysis as described below.

Near Analyses

The spatial location of β_1 values, mean salinity, and mean specific conductance of shallow, unconfined wells were then assessed in relation to drainage ditch locations, stream locations, and the coastline location within the study area. A Near analysis was performed on groundwater monitoring well site locations in relation to each hydrologic feature with no defined search radius. The results of these analyses were distance in meters from each groundwater monitoring well location to drainage ditch locations, stream locations, and coastline locations within the study area.

Ordinary Least Squares (OLS) Regression

Distances from the Near analysis were used as the explanatory variable in an Ordinary Least Squares (OLS) regression analysis for measurements from shallow, unconfined aquifers in the study area. These analyses were performed in ArcGIS Pro to determine if there is a relationship between distance to drainage ditches, streams, and coastline and rate of change, mean salinity, and mean specific conductance values reported for each groundwater monitoring well. To examine the relationship between distance to hydrologic feature and rate of change for each well grouping, β_1 value at each well was used as the dependent variable, and distances to the coastline, streams, and drainage ditches were used as explanatory variables. The H_0 of this regression analysis was that there is no spatial relationship between β_1 value and distance to the coastline, distance to streams, or distance to drainage ditches. The H_A of this analysis is that there is a spatial relationship between β_1 value and the coastline, or streams, or drainage ditches, or a combination of these features. The same test was done for the mean salinity and mean specific conductance measurements reported at each groundwater monitoring well.

Results

Water Quality Summary

Groundwater monitoring wells reported a mean specific conductance of $\overline{x}_{nSC} = 3023.54 \pm 6433.19$ μS/cm across the study site and a maximum specific conductance measurement of 48,340.0 μS/cm. Monitoring wells sampled 257 sites for specific conductance, and of these sites

194 (75%) reported specific conductance measurements consistent with freshwater, 62 (24%) reported specific conductance measurements consistent with brackish water, and 1 (1%) reported a specific conductance measurement consistent with saline (sea) water (Appendix 3). Monitoring wells also reported a mean salinity of $\overline{x}_{nSalinity}$ = 3.37 ± 2.00 ppt across the study site and a maximum salinity measurement of 31.5 ppt. Monitoring wells sampled 245 sites for salinity, 156 (64%) of which reported salinities consistent with freshwater and 89 (36%) of which reported salinities consistent with brackish water (Appendix 3). No sites reported salinity measurements consistent with saline (sea) water.

Specific conductance samples were taken from the same three Principal Aquifers examined in Chapter 1 (Appendix 3). Specific conductance measurements were skewed to the right and tended to report low-values (Figure 12). Of 68 sites sampled within the Castle Hayne aquifer ($\overline{x}_{SpecificConductance}$ = 3333.33 ± 7575.44 µS/cm, max_{sc} = 48,340.0 µS/cm), 51 sites (75%) were considered "fresh" ($\overline{x}_{SpecificConductance}$ = 649.56 ± 443.52 µS/cm) 16 sites (24%) were considered "brackish" ($\overline{x}_{SpecificConductance}$ = 9075.95 ± 7809.04 µS/cm) and 1 site (1 %) was considered "saline" ($\overline{x}_{SpecificConductance}$ = 48340.00, no standard deviation due to sampling) (Figure 13). Of 124 sites sampled within the NACP aquifer system ($\overline{x}_{SpecificConductance}$ = 3083.94 ± 6169.28 µS/cm, max_{sc} = 43,930.00 µS/cm), 90 sites (73%) were considered "fresh" ($\overline{x}_{SpecificConductance}$ = 640.87 ± 441.67 µS/cm) 34 sites (27%) were considered "brackish" ($\overline{x}_{SpecificConductance}$ = 9550.88 ± 9053.58) and no sites were considered "saline" (Figure 13). Of 65 sites sampled within the Surficial aquifer system ($\overline{x}_{SpecificConductance}$ = 2584.23 ± 5658.15 µS/cm, max_{sc} = 31,044.33 µS/cm), 53 sites (82%) were considered "fresh" ($\overline{x}_{SpecificConductance}$ = 577.04 ± 385.01 µS/cm) 12 sites (18%) were considered "brackish" ($\overline{x}_{SpecificConductance}$ = 11449.33 ± 8967.72 µ/cm) and no sites were considered "saline" (Figure 13).

Salinity values were derived from specific conductance measurements for the same three Principal Aquifers (Appendix 3): the Castle Hayne aquifer ($\bar{x}_{Salinity}$ = 1.96 ± 4.89 ppt, max_{sal} = 31.5 ppt), the Northern Atlantic Coastal Plain aquifer system ($\bar{x}_{Salinity}$ =1.73 ± 3.89 ppt, max_{sal} = 28.1 ppt), and the Surficial aquifer system ($\bar{x}_{Salinity}$ = 1.38 ± 3.35 ppt, max_{sal} = 19.72 ppt). The distribution of salinity measurements is heavily skewed to the right, with most salinity measurements reporting low-values, though few wells do report high salinity values (Figure 12). Of the 68 sites sampled within the Castle Hayne aquifer, 41 sites (59%) were considered freshwater ($\bar{x}_{Salinity}$ = 0.23 ± 0.12 ppt) , 24 sites (35%) were considered brackish water ($\bar{x}_{Salinity}$ = 4.92 ± 7.21 ppt), and none were considered saline (Figure 14). Three sites did not report salinity data. Of the 124 sites sampled within the NACP aquifer system, 71 sites (57%) were considered freshwater ($\bar{x}_{Salinity}$ = 0.23 ± 0.12 ppt), 48 sites (39%) were considered brackish water ($\bar{x}_{Salinity}$ = 3.96 ± 5.44 ppt), and no sites were considered saline (Figure 14). Five sites did not report salinity data. Of the 65 sites sampled within the Surficial aquifer system, 44 sites (68%) were considered freshwater ($\bar{x}_{Salinity}$ = 0.22 ± 0.11), 17 sites (26%) were considered brackish water ($\bar{x}_{Salinity}$ = 4.37 ± 5.38), and none were considered saline (Figure 14). Four sites did not report salinity measurements.

Clustering Analyses

The Density Based Clustering analysis of groundwater monitoring well locations revealed 7 spatial clusters of well locations (Figure 16). The Moran's Global I analysis revealed significant clustering in β_1 values, salinity measurements, and specific conductance measurements, indicating each dataset exhibits spatial autocorrelation (Table 4).

Getis-Ord (Gi*) Hot Spot analyses were performed on β_1 values for 5 groups: unconfined aquifers, confined aquifers, shallow wells, medium wells, and deep wells. Unconfined aquifers exhibited significant high β_1 value clustering in the southeastern coastal plain, and significant low-value clustering near Aurora, Beaufort County, North Carolina (Figure 16). Confined aquifers exhibited significant high β_1 value clustering in the central coastal plain, around the Pamlico Sound in Beaufort County as well as in Craven and Onslow counties (Figure 16). Shallow wells exhibited significant high β_1 value clustering in the areas surrounding the Pamlico Sound in Beaufort County and Long Bay in New Hanover County, as well as upstream of the New River in Onslow County (Figure 17). Several sites exhibited low-value clustering along the New River. Medium wells exhibited high β_1 value clustering at only one location bordering the Pamlico River in Beaufort County (Figure 17). Deep wells exhibited high β_1 value clustering upstream of the New River in Onslow County (Figure 17).

Getis-Ord (Gi*) Hot Spot analyses were also performed on mean specific conductance measurements for the same five groups examined in the previous Hot Spot analyses on β_1 values (Figure 18). These analyses revealed significant high-value mean specific conductance clustering in confined aquifers along the Albemarle, Pamlico, and Roanoke Sounds in Dare, Pamlico, Pasquotank, and Washington counties. Unconfined aquifer measurements exhibited high-value clustering along the Roanoke and Pamlico sounds in Dare and Beaufort counties (Figure 18). Shallow well water quality measurements exhibited significant high-value clustering along the Albemarle, Pamlico, and Roanoke Sounds in Beaufort, Dare, Hyde, and Pasquotank counties (Figure 19). Medium depth wells exhibited significant high-value mean specific conductance clustering around the Albemarle, Pamlico, and Roanoke Sounds in Dare, Pamlico, and Washington counties (Figure 19). Deep wells exhibited significant high-value clustering around the Albemarle and Pamlico Sounds in Pamlico and Washington counties (Figure 19). Because salinity measurements were derived from specific conductance measurements, salinity hotspots followed the same pattern as mean specific conductance measurements (Figures 20, 21).

Interpolation Analyses

Inverse Distance Weighting (IDW) analysis was used to interpolate rate of change across the study area for 5 groups of measurements: confined aquifer measurements (Figure 22), unconfined aquifer measurements (Figure 22), shallow well measurements (Figure 23), medium depth well measurements (Figure 23), and deep well measurements (Figure 23). Confined aquifer measurements exhibited gains in groundwater depth across the coastal plain, with the exception of some areas around the Albemarle Sound and inshore of Onslow Bay in Onslow County. Unconfined aquifer measurements exhibited consistent gains in groundwater depth across the coastal plain. Shallow well measurements were also consistent across the coastal plain, with most areas exhibiting gains in groundwater depth except for one area inshore of Onslow Bay in Onslow County. Medium depth wells were more variable, with areas central in the coastal plain surrounding the Albemarle and Pamlico Sounds exhibiting gains in groundwater depth, while areas in the southeastern coastal plain and north of the Albemarle Sound exhibited groundwater depth losses. Deep aquifer measurements were the most variable of all classes, with no consistent pattern across the study area.

IDW analysis was then used to interpolate mean specific conductance measurements across the study area for the same 5 classes defined above: confined aquifer measurements (Figure 24), unconfined aquifer measurements (Figure 24), shallow well measurements (Figure 25), medium depth well measurements (Figure 25), and deep well measurements (Figure 25).

Confined aquifers exhibited mean specific conductance measurements that tended to be higher around the Pamlico Sound and lower in the southeastern region of the coastal plain. Unconfined aquifers exhibited mean specific conductance measurements that also tended to be higher around the Pamlico Sound, although measurements were more consistent across the study area than in confined aquifers. Shallow well measurements were variable across the study site, with high-value clusters occurring in Beaufort, Bertie, Craven, and Pamlico counties. Lower mean specific conductance measurements in shallow wells occurred in the southeastern coastal plain surrounding Onslow Bay. Medium depth wells were consistent across the study area, with few lower value areas occurring in Bertie, Brunswick, Onslow, and Pender counties. Deep wells also exhibited higher measurements around the Pamlico Sound, with lower measurements occurring in the areas surrounding Onslow Bay. Mean salinity interpolations followed the same pattern as mean specific conductance interpolations, as salinity was derived from specific conductance.

Ordinary Least Squares (OLS) Regression Analyses

OLS analyses revealed a weak correlation between distance to drainage ditches and rate of change in groundwater depth in shallow, unconfined wells ($\beta = 0.001$, $p = 0.025$, Table 5). However, distance to the coast ($\beta = -0.0002$, $p = 0.471$) and distance to streams ($\beta = 0.0004$, $p = 0.879$) were not significantly correlated with rate of change in groundwater depth. The residuals of this analysis were not significantly spatially autocorrelated (Table 5), suggesting that this model is properly specified. Mean specific conductance values were not significantly correlated with distance to drainage ditches ($\beta = -0.038$, $p = 0.157$), distance to the coast ($\beta = 0.010$, $p = 0.255$) or distance to streams ($\beta = 0.072$, $p = 0.665$) (Table 5). The residuals of this analysis also were not significantly spatially autocorrelated (Table 5), suggesting that this model is properly specified. Mean salinity was also not significantly correlated with distance to drainage ditches (β = -0.00002, p = 0.237), distance to the coast (0.000004, p = 0.467), or distance to streams (β = 0.00002, p = 0.836) (Table 5). The residuals of this model were not significantly spatially autocorrelated (Table 5), suggesting that the model is properly specified.

Discussion

As mentioned in Chapter 1, the NCDWR has placed groundwater monitoring wells with the intent to monitor areas that have been identified as being at risk for aquifer overuse and pollution. To address question (2), if groundwater monitoring wells placed by the NCDWR are spatially clustered, a Density Based Clustering analysis was performed. The hypothesis that accompanied this question was that there is significant spatial clustering in groundwater monitoring well locations throughout the study area. The results of this analysis support this hypothesis, revealing several significant clusters of wells throughout the study area. While a large number of wells is desirable to obtain the most robust dataset possible, this spatial clustering indicates that there are places within the study area that will be more poorly understood than those with a large number of well locations, and that patterns observed in the data could be affected by clustering. These wells are likely sampling similar conditions, and this may be responsible for the observed autocorrelation in the β_1, mean salinity, and mean specific conductance data indicated by the Moran's I analyses.

Question (3) asked if we can identify areas of high salinity as well as high rates of groundwater depth change. Across the five groups examined, confined and unconfined aquifers, as well as shallow, medium depth, and deep wells, there were areas of high rates of change in groundwater depth. Unconfined, shallow aquifers were the most variable. Unconfined aquifers exhibited both areas of high decreasing groundwater depth, as well as areas with high increasing groundwater depth. Most areas reported significant decreases in groundwater depth and were located in southeastern North Carolina. This may indicate that this area is experiencing higher rates of sea level rise, which are driving groundwater depth toward the surface. The HotSpot analysis also identified an area of significant increasing groundwater depth near Aurora, NC. This is likely influenced by the presence of a phosphate mining industry, which is often responsible for pumping water out of aquifers in eastern North Carolina (Trapp Jr. & Horn, 1997). Shallow aquifers exhibited high rates of increasing groundwater depth in areas surrounding the Pamlico Sound, the New River, and southeastern North Carolina. These areas may also be indicative of high rates of sea level rise which are driving higher groundwater depth inshore. Confined aquifers, medium depth wells, and deep wells did exhibit few locations of significant gains in groundwater depth, although these groups typically were only associated with one such instance. These single areas of high rates of groundwater depth change could be indicative of location conditions, such as irrigation, which may influence the local hydrology.

Question (4) asked if groundwater depth and quality in shallow, unconfined aquifers are correlated with proximity to hydrologic features, which include drainage ditches, coastlines, and streams. The analysis revealed only one significant correlation, which was a weak correlation between distance to drainage ditches and rate of change in groundwater depth. Other than this weak correlation, the OLS analyses revealed that there is not a significant relationship between distance to hydrologic feature and rate of change in groundwater depth, mean specific conductance, or mean salinity for our study area. However, we do know from our initial water quality summary and visualization of water quality across the study site that there are spatial and quantitative differences in water quality, and specifically groundwater salinity, across our study site. These results are surprising given the previous work on saltwater intrusion along the coast. However, the size and heterogeneity of the study area may limit the ability of these models to detect local trends. We have discussed the possibility that groundwater aquifers along the coast could be either topography-limited or flux-limited. In flux-limited systems, aquifers are able to resist saltwater intrusion due to an increase in potential energy of the aquifer driven by sea level rise (Befus et al., 2020; Michael et al., 2013). Additionally, precipitation regimes could provide pulses of freshwater that have been shown to allow an aquifer to resist saltwater intrusion (White & Kaplan, 2017). If we are comparing aquifers that respond differently to sea level rise, we may not be able to detect trends as effectively as we could if flux-limited and topography-limited aquifers were isolated. Future research may focus on identifying areas likely to be topography-limited and examining the spatial association within these areas of water quality value and distance to hydrologic feature, as well as local analyses of more homogenous study sites.

Spatial changes in these characteristics are important to understand as they have a direct influence on the aboveground vegetation that inhabit these coastal areas. As mentioned in Chapter 1, increased soil saturation or inundation at the surface can be detrimental to upland plants, leading to reduced plant metabolism, growth, nutrient uptake, and ability to transpire, as well as increased root death and lower recruitment ability (Barrett-Lennard, 2003; Barrett-Lennard et al., 1986, 1988; Else et al., 2008; Huang et al., 1995; Kirwan et al., 2007; Trought & Drew, 1980). When combined with increased salinity, these effects can reduce species richness and cause increased forest mortality (Baldwin & Mendelssohn, 1998; Kirwan & Gedan, 2019; Masterson et al., 2014; Smart et al., 2020). For areas like coastal North Carolina, where flooding and saltwater intrusion may threaten the livelihood of local communities and markets, these influences are important to understand in order to mitigate or adapt to future conditions.

Figures and Tables

Figures

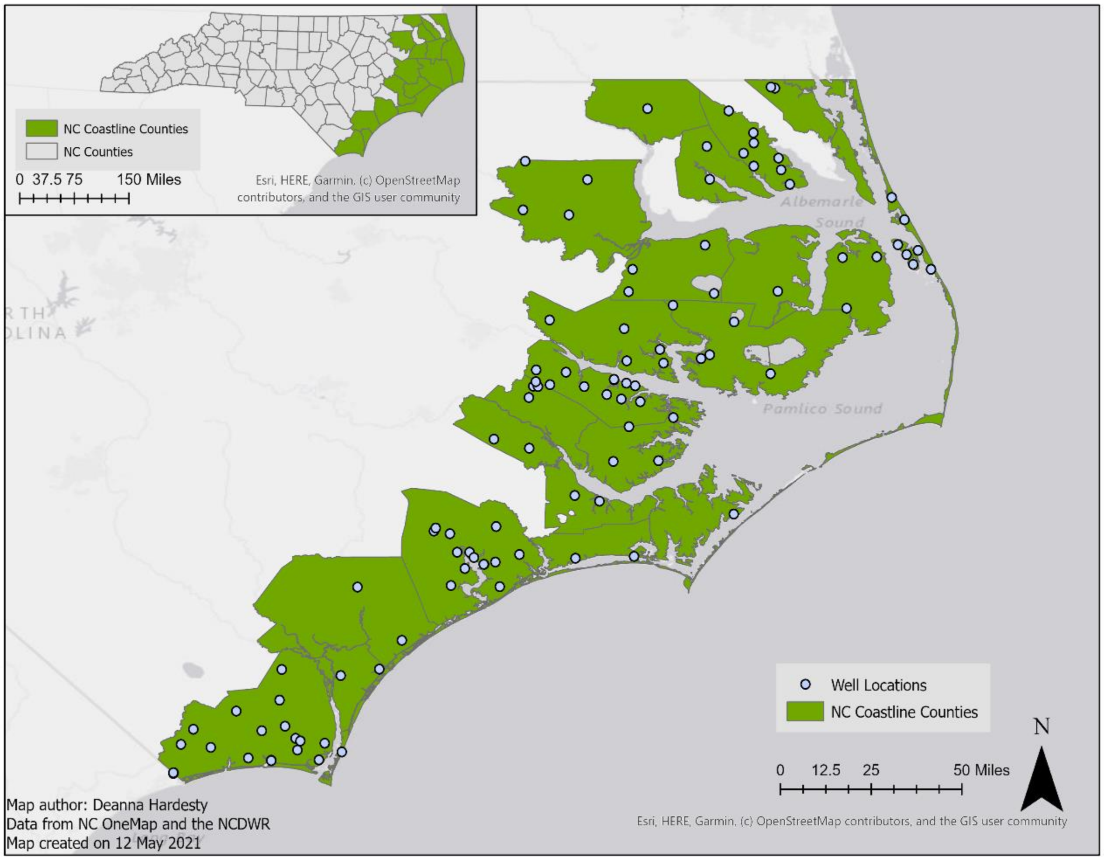

Figure 7: Groundwater monitoring sites are managed and maintained by the North Carolina Department of Water Resources. These monitoring wells are located throughout the state, and wells located within the study area were considered for this analysis. The locations of these sites are shown above.

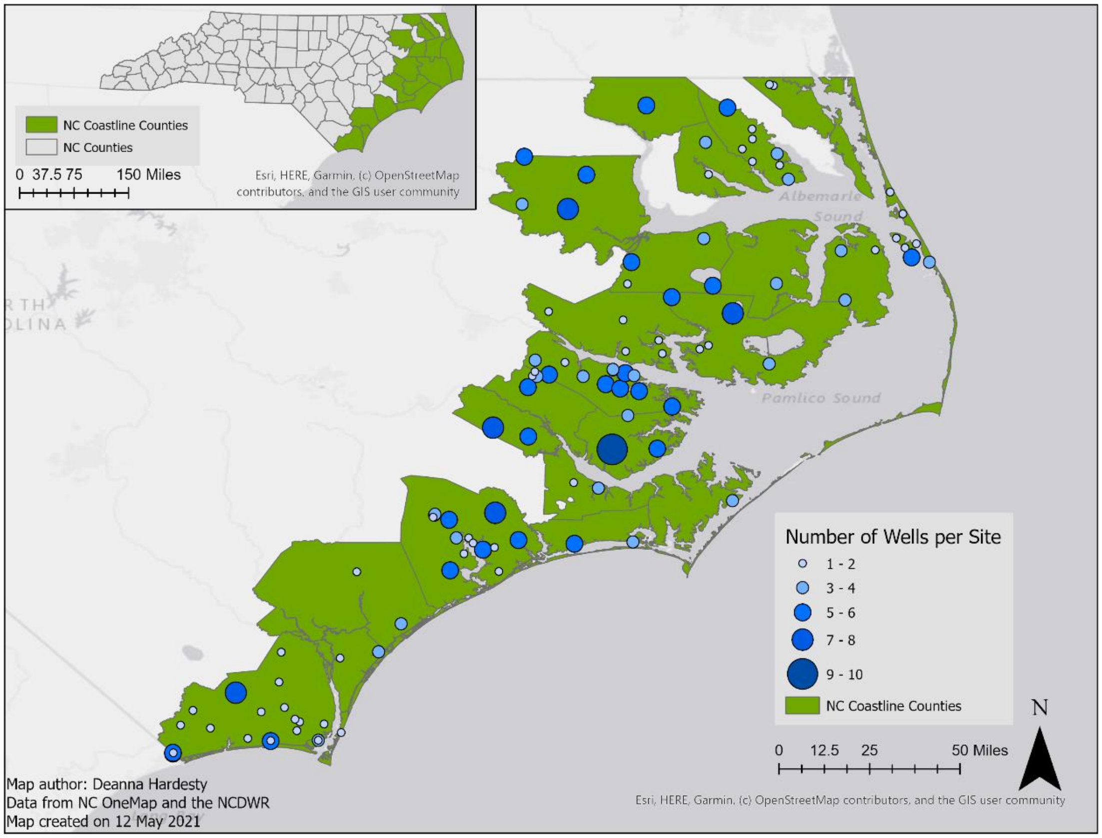

Figure 8: Multiple groundwater monitoring wells often existed in one spatial location, shown above here by plotting wells density per location. Larger circles and darker colors denote site locations with a larger number of wells.

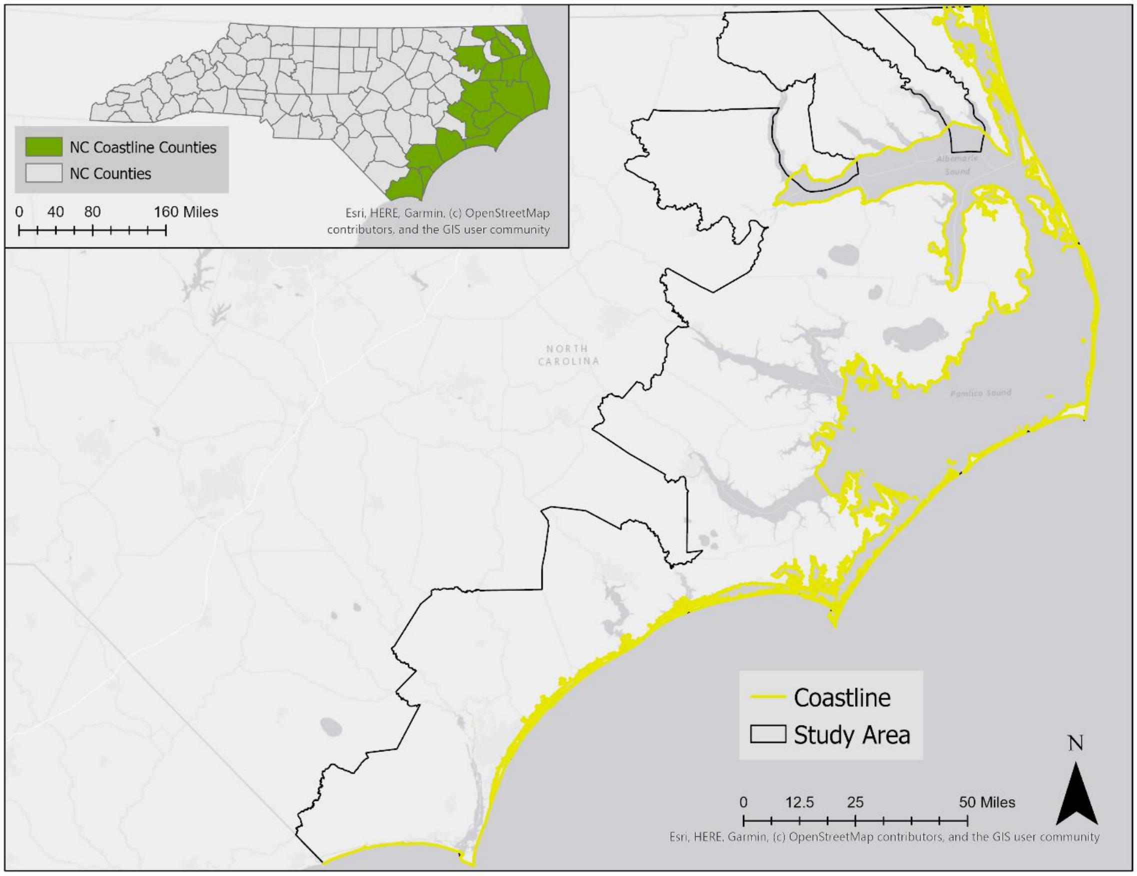

Figure 9: Location of the coastline for the study area of coastline counties in North Carolina, USA.

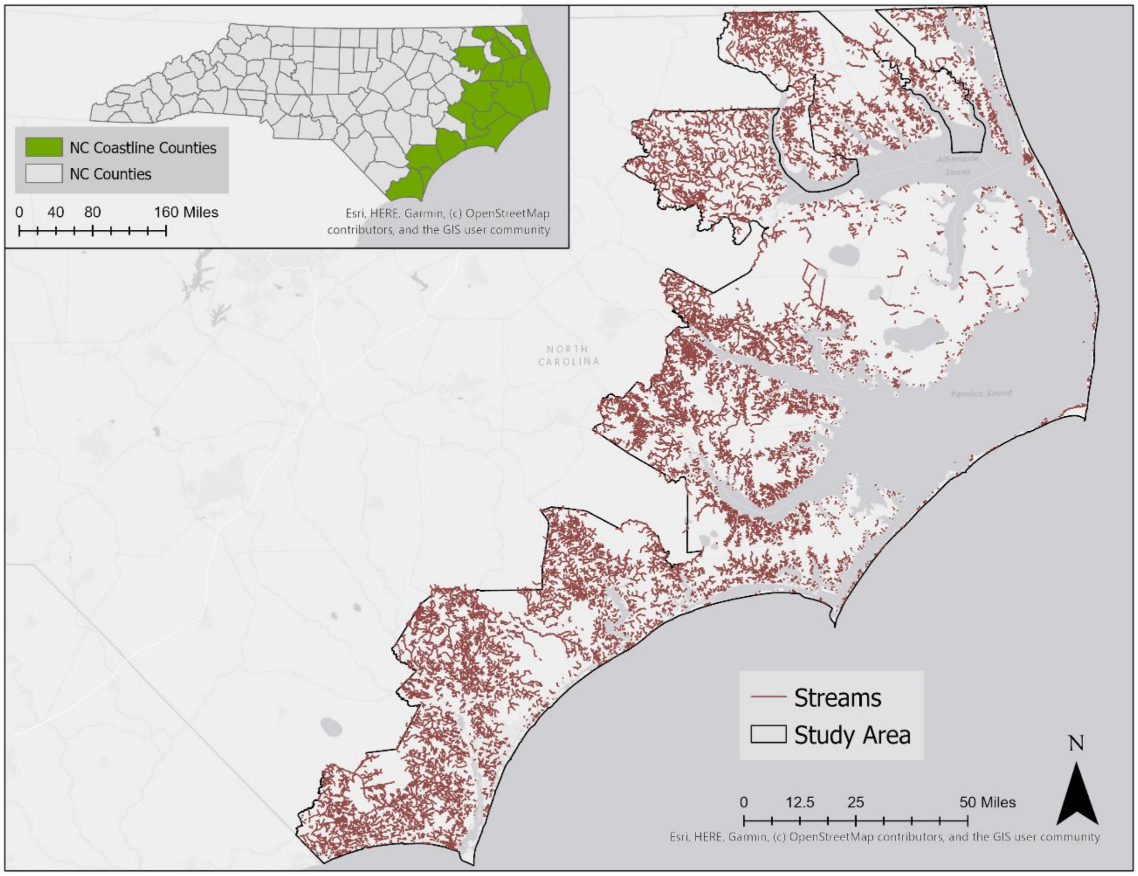

Figure 10: Stream locations within the study area of coastline counties in North Carolina, USA.

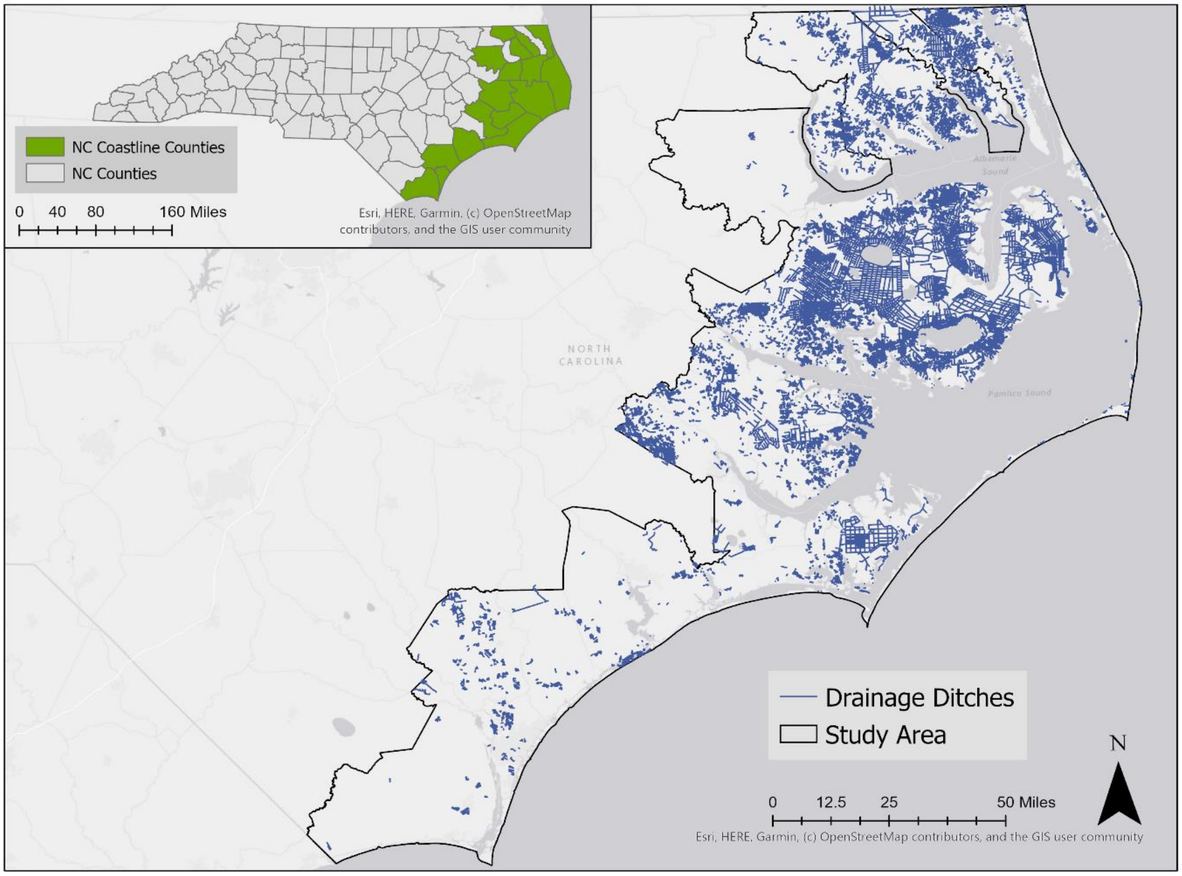

Figure 11: Locations of drainage ditches within the study area of coastline counties in North Carolina, USA.

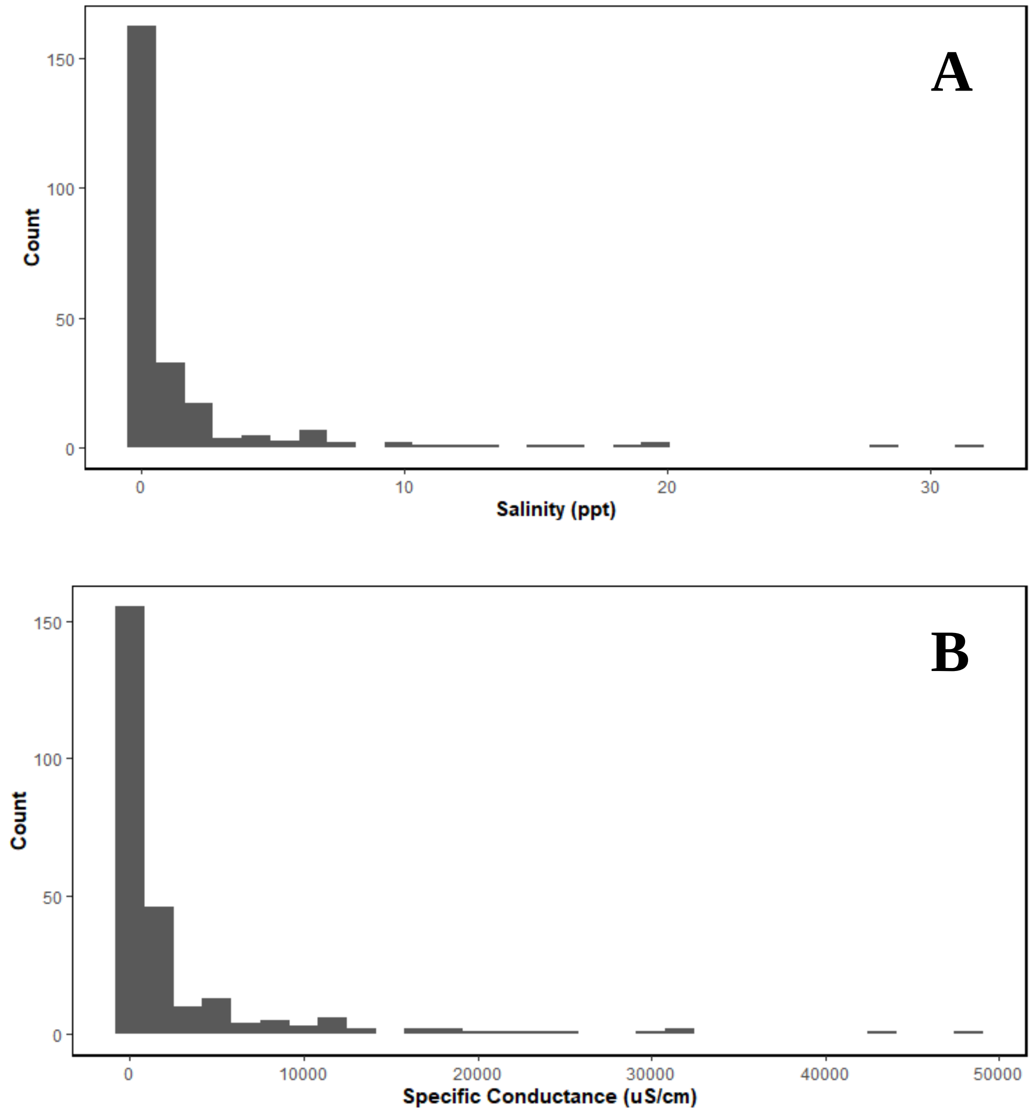

Figure 12: Salinity and specific conductance measurements tended to be low. Histograms show the distribution of (A) salinity (ppt) and (B) specific conductance (μS/cm) for all groundwater monitoring wells in the study site.

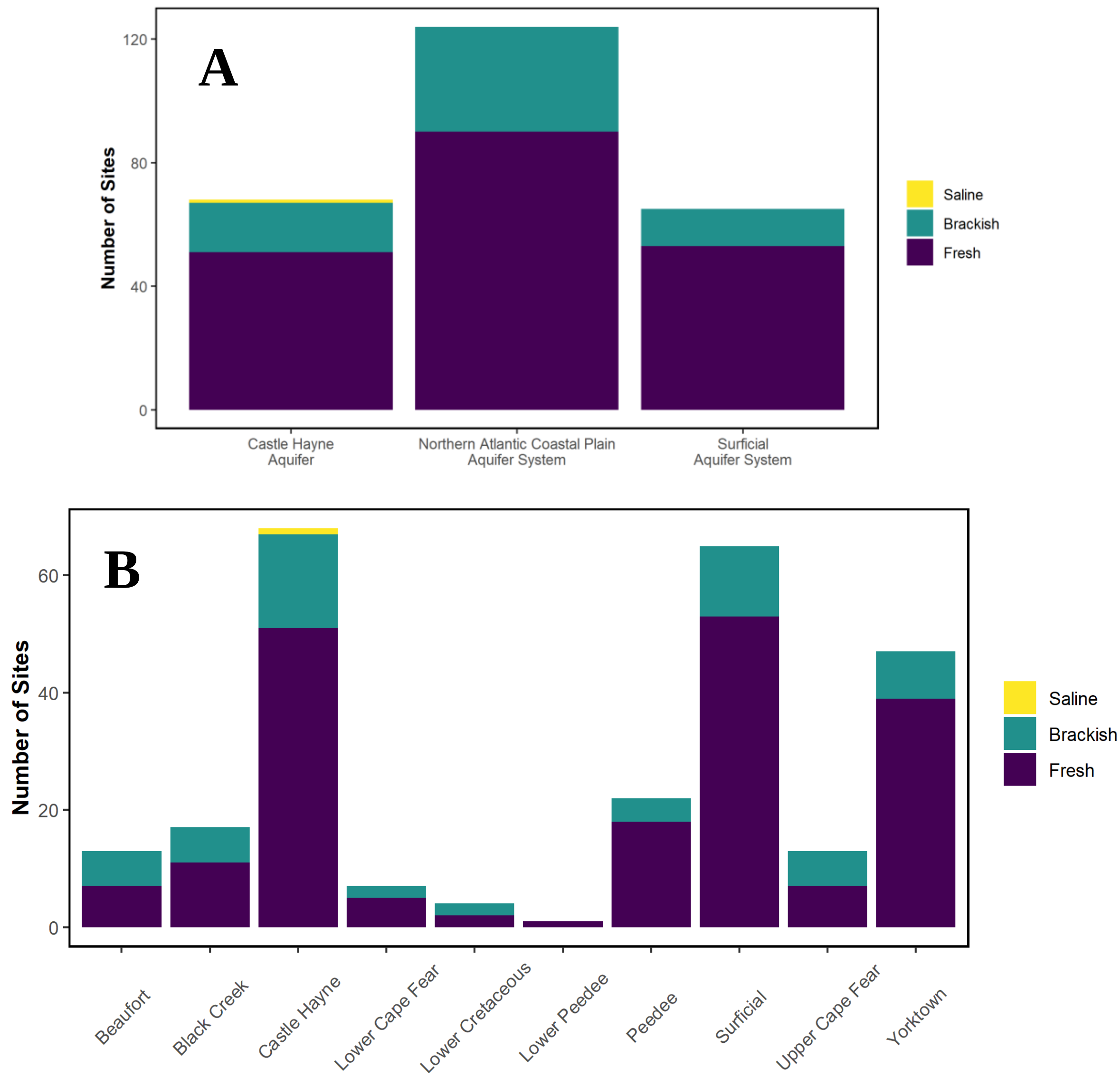

Figure 13: Proportion of specific conductance (μS/cm) levels for (A) Principal aquifers and (B) local aquifers. The majority of sites reported low-salinity measurements that would be considered freshwater. Other sites reported measurements that would be considered brackish. Only one site reported specific conductance measurements that would be considered saline.

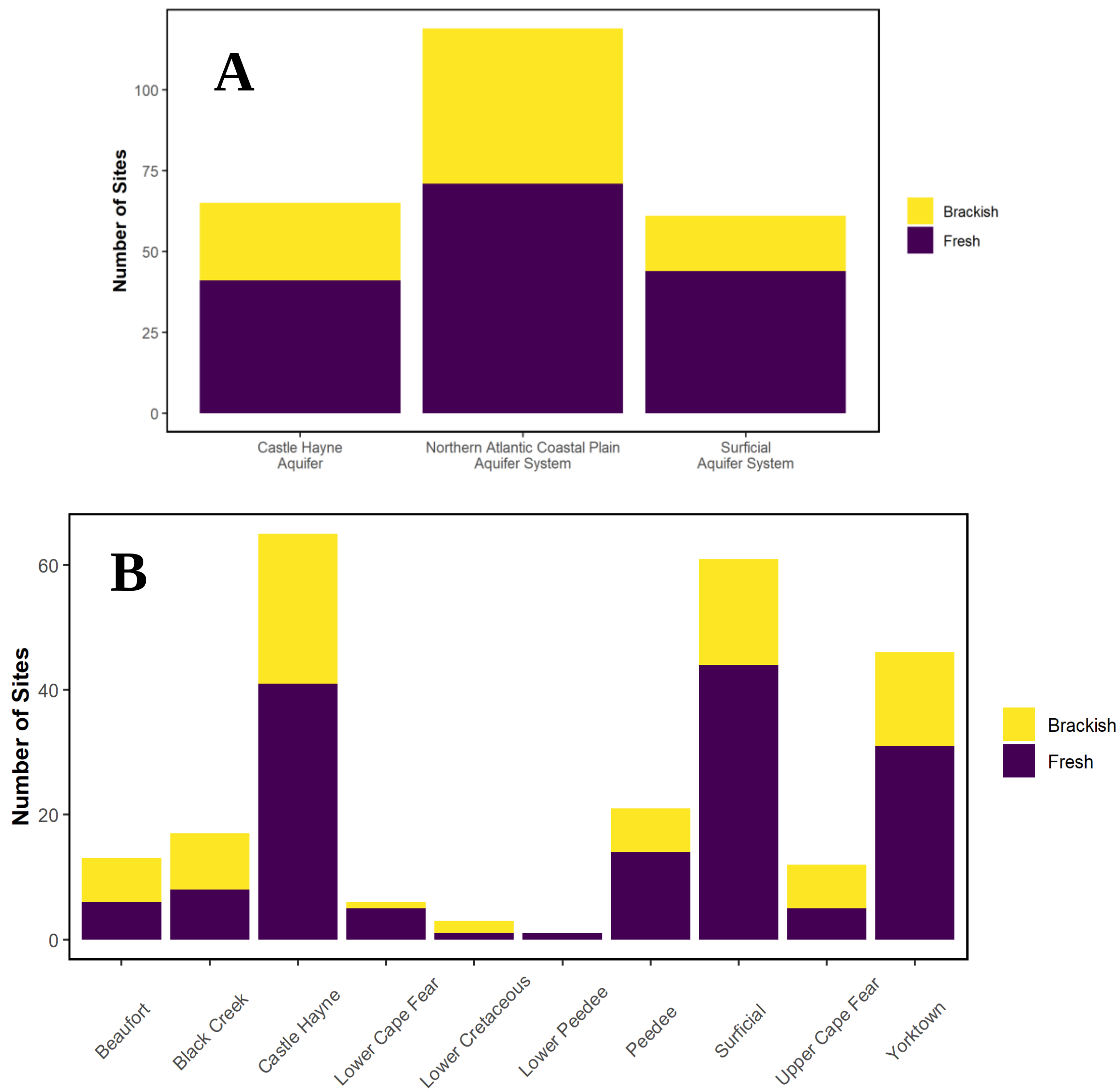

Figure 14: Proportion of salinity (ppt) levels for (A) Principal Aquifers and (B) local aquifers. The majority of sites reported low-salinity measurements that would be considered freshwater. Other sites reported measurements that would be considered brackish. No sites reported salinity measurements that would be considered saline.

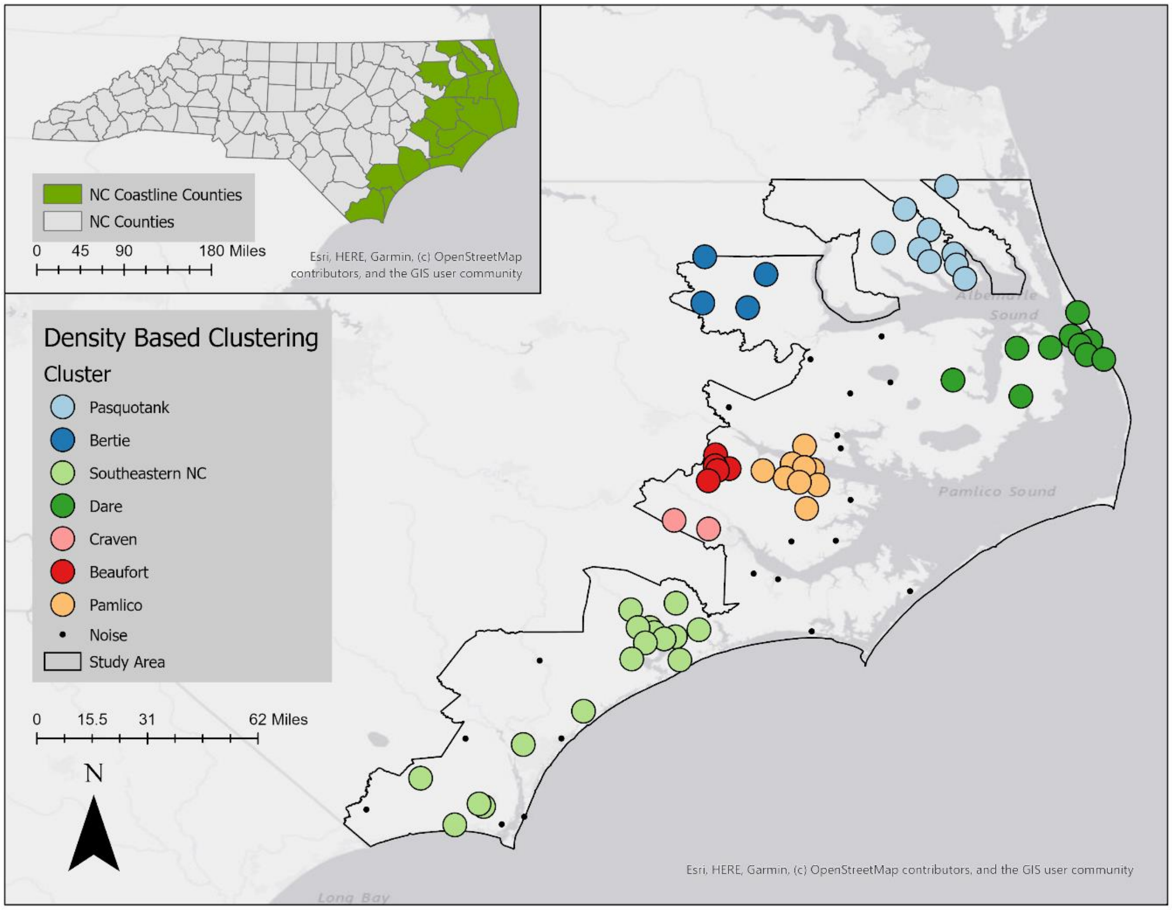

Figure 15: Results of the Density Based Clustering analysis are shown above. The analysis identified 7 clusters based on location: a cluster in Southeastern NC and clusters in Pasquotank, Bertie, Dare, Craven, Beaufort, and Pamlico counties.

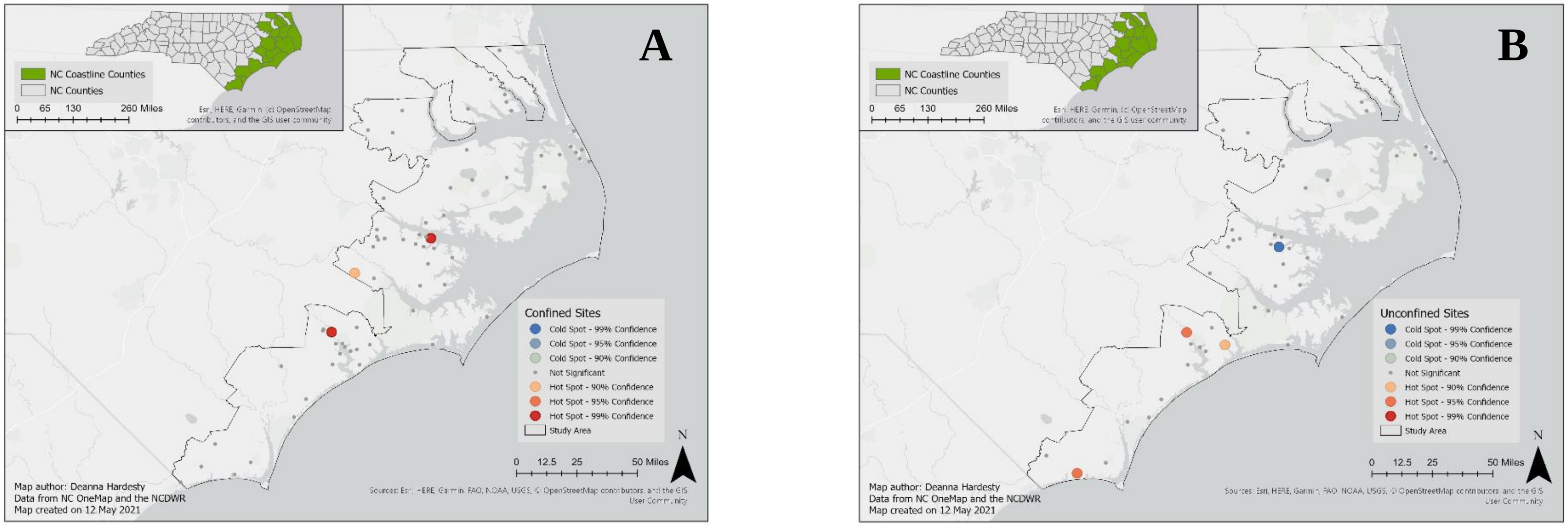

Figure 16: Getis-Ord (Gi*) Hot Spot analyses examining rate of change in groundwater depth (mm/year) for (A) confined and (B) unconfined aquifers revealed several areas of both high and low-value clustering within the study area.

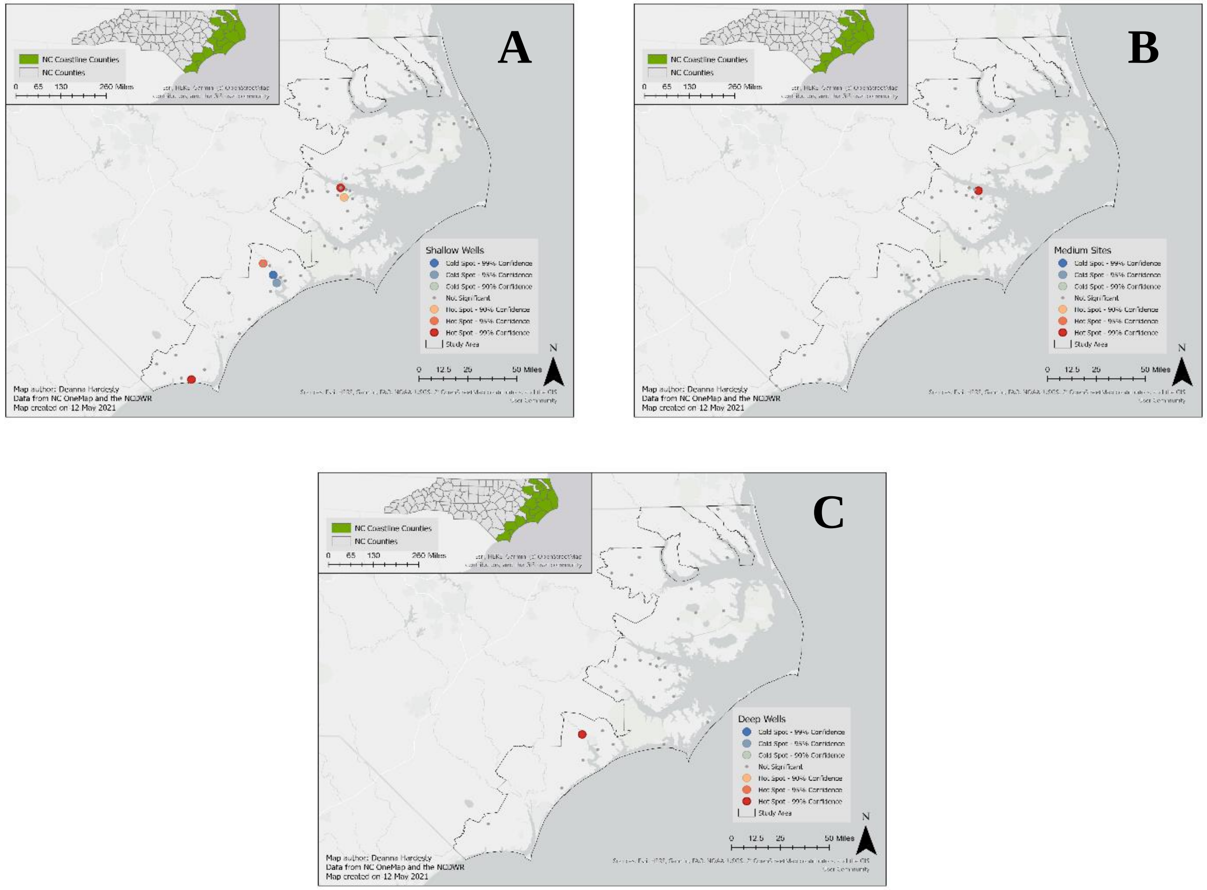

Figure 17: Getis-Ord (Gi*) Hot Spot analyses for (A) shallow wells, (B) medium depth wells, and (C) deep wells revealed locations across the study site that exhibit high and low-value clustering of rate of change of groundwater depth over time.

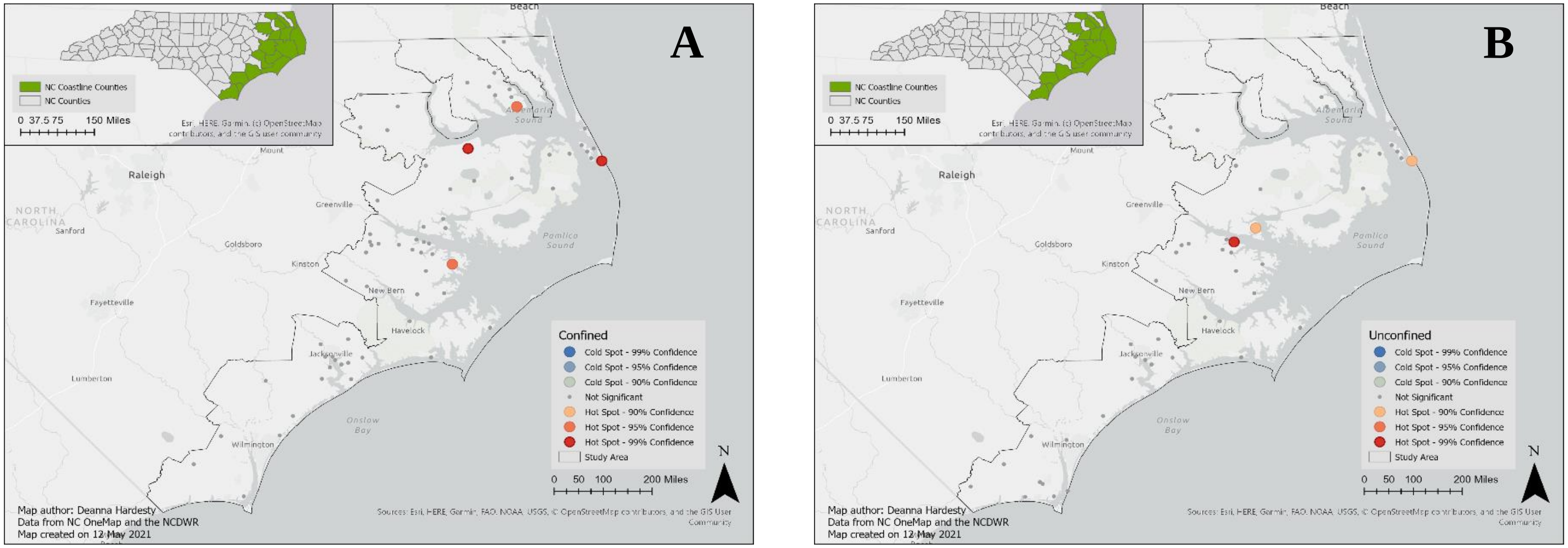

Figure 18: Getis-Ord (Gi*) Hot Spot analyses of mean specific conductance values revealed several locations of significantly high-values in both (A) confined and (B) unconfined aquifers.

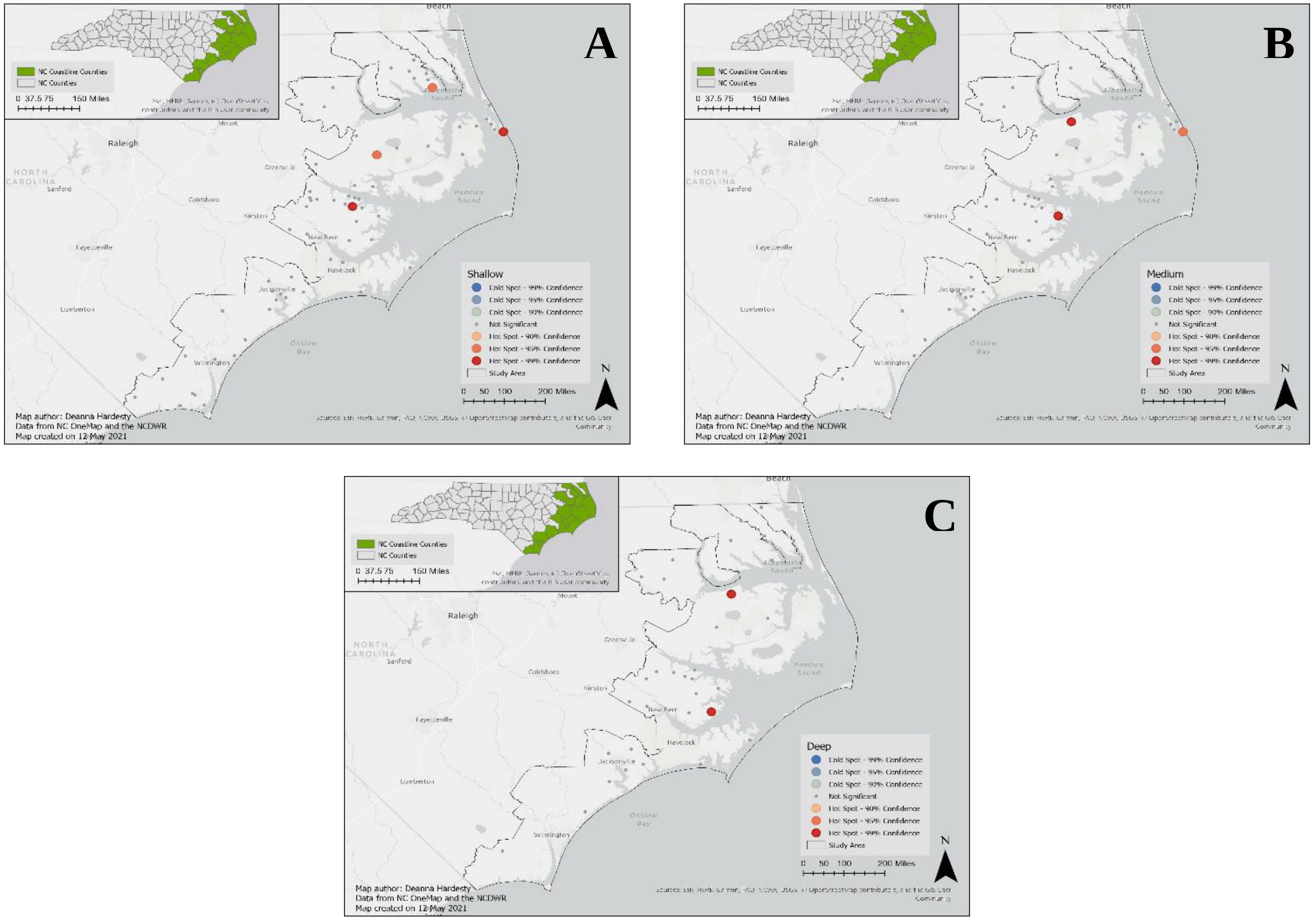

Figure 19: Getis-Ord (Gi*) Hot Spot analyses for mean specific conductance measurements measured at (A) shallow wells, (B) medium depth wells, and (C) deep wells revealed locations across the study site that exhibit high-value clustering.

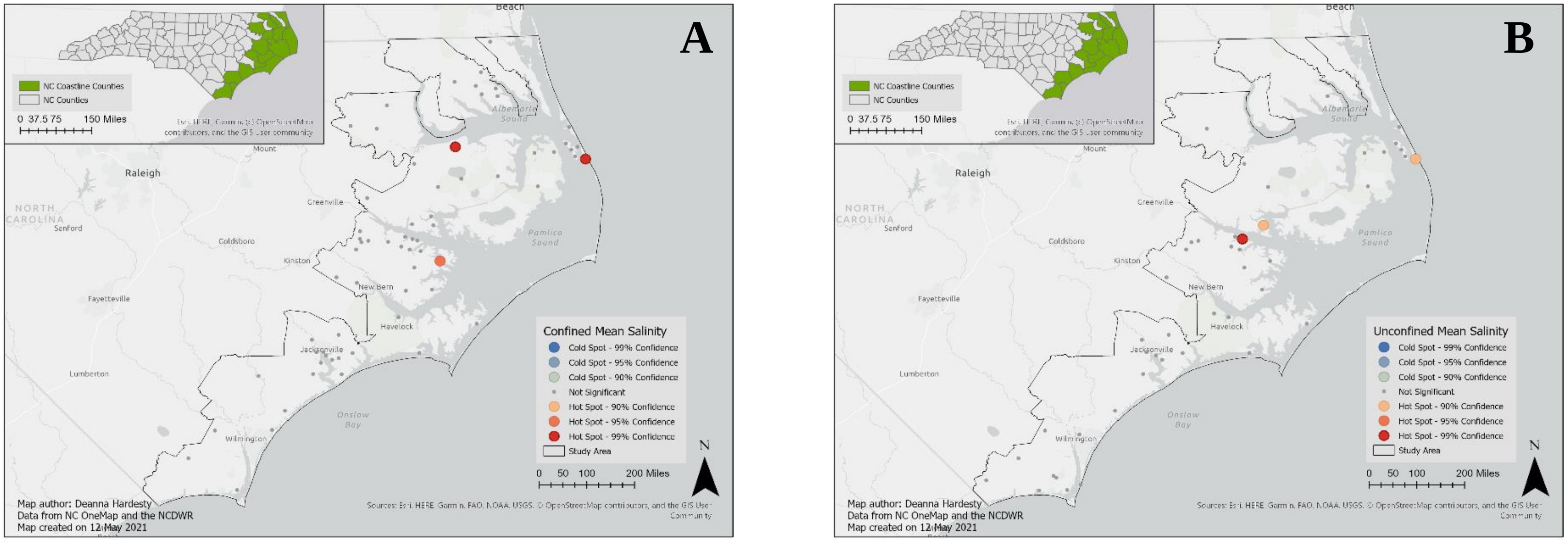

Figure 20: Getis-Ord (Gi*) Hot Spot analyses of mean salinity values revealed several locations of significantly high-values in both (A) confined and (B) unconfined aquifers.

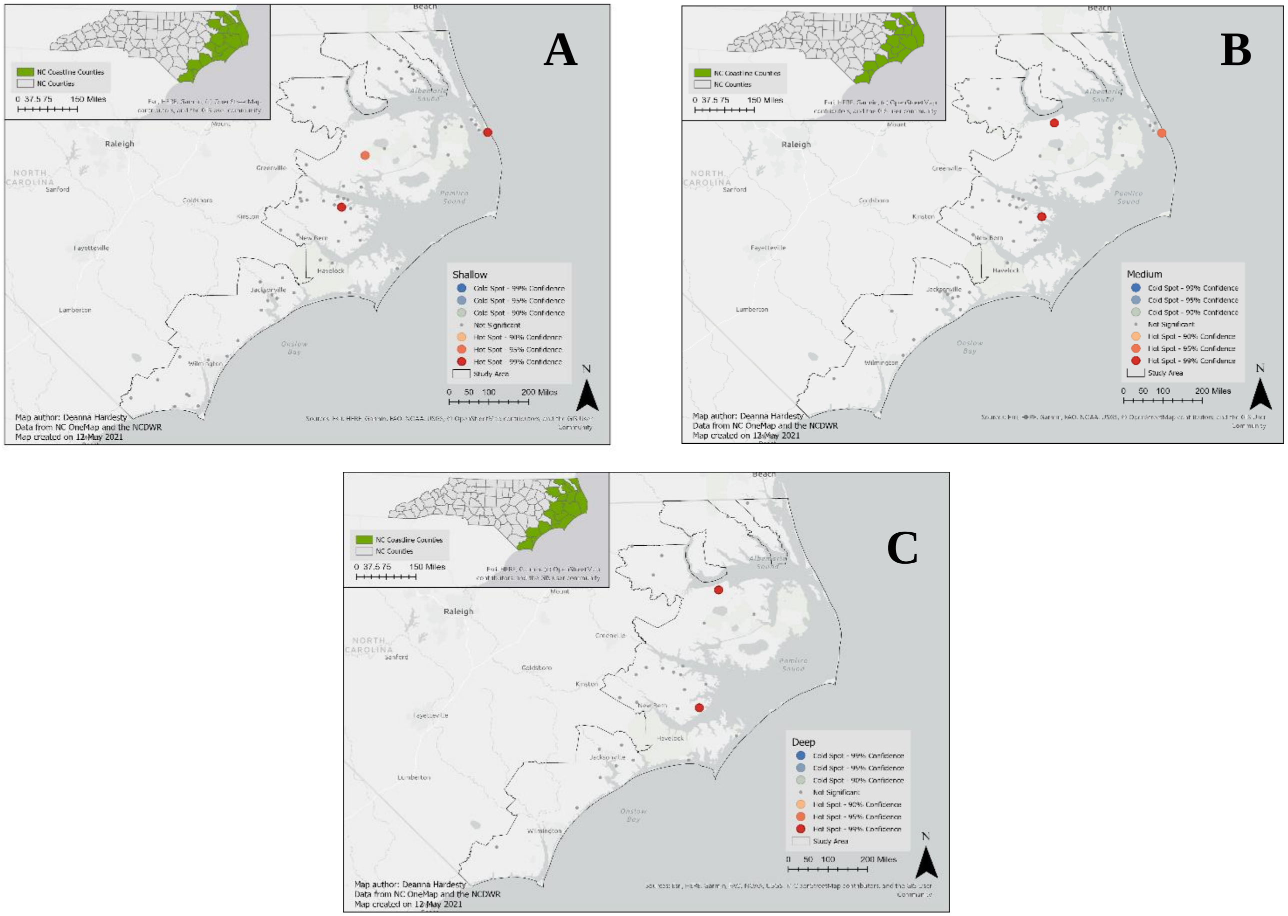

Figure 21: Getis-Ord (Gi*) Hot Spot analyses for mean salinity measurements measured at (A) shallow wells, (B) medium depth wells, and (C) deep wells revealed locations across the study site that exhibit high-value clustering.

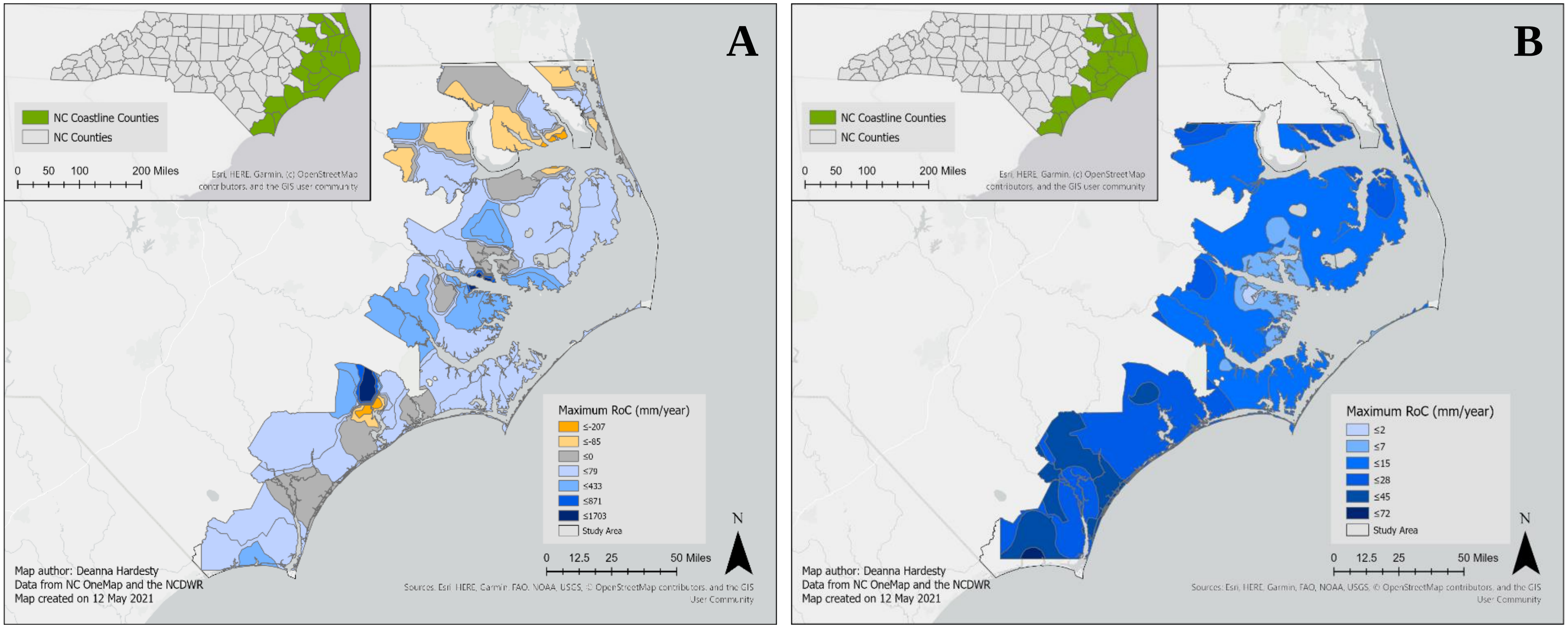

Figure 22: IDW analyses of (A) confined aquifers show a highly variable spatial pattern in rate of change of groundwater depth throughout the study area. Decreased ground water depth is observed across the southeastern and central coastal zone, with some areas in the northern and southern areas exhibiting increases in groundwater depth. (B) Unconfined aquifers consistently decreased in depth across the study area, with rates of change increasing toward the more southern areas of the study area.

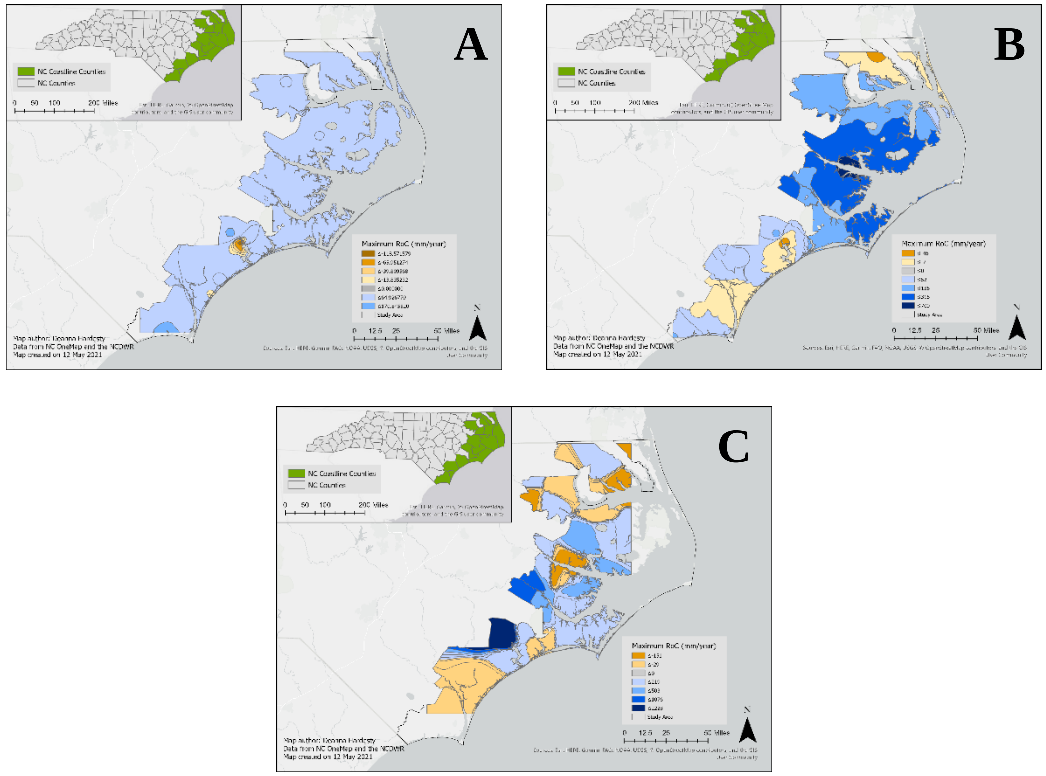

Figure 23: (A) An IDW analysis of shallow well measurements reveals uniform rates of decreasing groundwater depth across the study area, except for the area of increasing depth near Jacksonville, NC, USA. (B) An IDW analysis of medium depth well measurements reveals areas of decreasing groundwater depth surrounding the Pamlico Sound, while increasing depth occurs in the northern and southern areas of the coastal zone. (C) An IDW analysis of deep wells was highly variable across the study site.

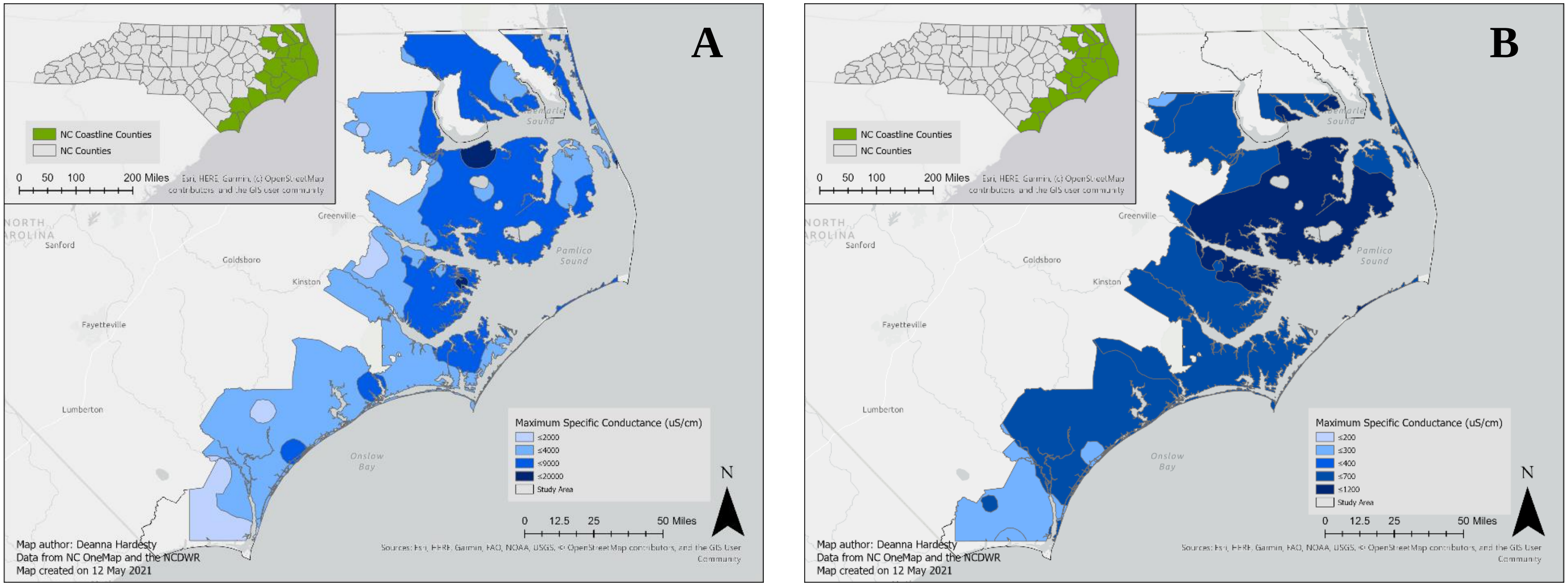

Figure 24: (A) An IDW analysis of mean specific conductance measurements for the confined aquifers within study area reveals consistent decreasing groundwater depth across the study area. (B) An IDW analysis of mean specific conductance measurements for the unconfined aquifers within the study area reveals consistent decreasing groundwater depth across the study site, with areas of higher mean specific conductance occurring in the areas surrounding the Albemarle and Pamlico Sounds.

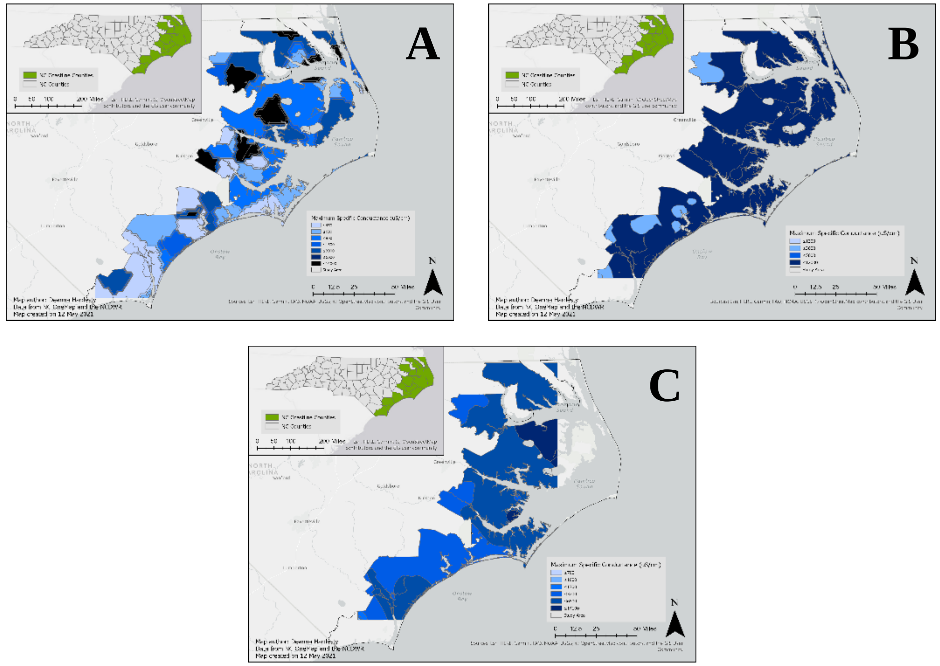

Figure 25: (A) An IDW analysis of mean specific conductance measurements for shallow groundwater monitoring wells within the study area reveals that the spatial pattern is highly variable. Areas in the northern and central counties in the study area exhibit areas of high mean specific conductance. (B) An IDW analysis of mean specific conductance measurements for medium depth groundwater monitoring wells shows uniform mean specific conductance across the study area, with punctuated locations of lower mean specific conductance measurements. (C) AN IDW analysis of deep wells reveals increased specific conductance in the areas surrounding the Albemarle and Pamlico Sounds.

Tables

Table 4: Results of the Moran's Global I (Spatial Autocorrelation) analysis. All datasets reported significant clustering that would be associated with spatial autocorrelation. * denotes a p-value < 0.10 and *** denotes a p-value < 0.01.

Variable	**Moran's Index**	**Expected Index**	**Variance**	**z-score**	**p-value**	**Significance**
β_1	0.259	-0.004	0.002	5.391	0.000	***
Mean Salinity (ppt)	0.092	-0.004	0.003	1.882	0.0599	*
Mean Specific Conductance (µS/cm)	0.090	-0.004	0.002	1.896	0.058	*

Table 5: Ordinary Least Squares regression analyses revealed that rate of change in coastal aquifers was weakly correlated with distance to drainage ditch locations. However, rate of change was not significantly correlated with distance to streams or the coastline. Water quality was also not significantly related to distance to hydrologic features in the study area.

Variable	Coefficient (β)	Standard Error	t-Statistic	Probability (p)	Adjusted R-Squared	Residual Moran's I Index	Residual z-score	Residual p-value	Residual Moran's I Results
Rate of Change (mm/year for Shallow, Unconfined Aquifer Measurements)									
Intercept	13.755	5.948	2.31	0.025 *	0.046	-0.032	-0.113	0.910	Random
Distance to Ditches	0.001	0.0006	2.349	0.023 *					
Distance to the Coast	-0.0002	0.0002	-0.727	0.471					
Distance to Streams	0.0004	0.002	0.152	0.879					
Mean Specific Conductance (µS/cm for Shallow, Unconfined Aquifers)									
Intercept	455.846	247.162	1.844	0.074	-0.005	-0.029	-0.007	0.995	Random
Distance to Ditches	-0.038	0.026	-1.450	0.157					
Distance to the Coast	0.010	0.009	1.158	0.255					
Distance to Streams	0.072	0.165	0.436	0.665					

Table 5 (continued)

Mean Salinity (ppt for Shallow, Unconfined Aquifers									
Intercept	0.259	0.140	1.847	0.074	-0.039	-0.055	-0.295	0.768	Random
Distance to Ditches	-0.00002	0.00001	-1.205	0.237					
Distance to the Coast	0.000004	0.000005	0.737	0.467					
Distance to Streams	0.00002	0.00009	0.209	0.836					

Conclusion

The coastal zone within the United States and around the world is highly populated, and many areas are experiencing high rates of sea level rise (Befus et al., 2020; Kemp et al., 2011; Sallenger et al., 2012). In the United States, the mid-Atlantic coast is experiencing rates of sea level rise that risk drowning more land area than the Gulf or Pacific coasts, and North Carolina has historically experienced high rates of sea level rise relative to eustatic rates (Kemp et al., 2011; Sallenger et al., 2012). These rates of rise are expected to increase as the climate warms, and increasing sea levels have implications for groundwater aquifers along the coast (Befus et al., 2020; Masterson et al., 2014; Masterson & Garabedian, 2007; Michael et al., 2013). Sea level rise increases the hydrostatic pressure applied at the groundwater/seawater interface which can increase the volume of water stored within the aquifer, subsequently decreasing the depth to the top of the groundwater table from the soil surface (Masterson & Garabedian, 2007; Michael et al., 2013). Seawater that infiltrates coastal aquifers and drives this decrease in groundwater depth also has the potential to salinize coastal aquifers and contaminate freshwater supplies on which coastal populations rely (Befus et al., 2020; Michael et al., 2013). Plant communities are also threatened by increased saturation or inundation of the soil surface and increased salinity, as species that are not adapted to survive in these conditions will die off and be replaced by species more adapted to the altered hydrology and soil chemistry of the environment (Barrett-Lennard, 2003; Kirwan et al., 2007). In North Carolina, where coastal ecosystem transition has been observed along the coast, it is possible that this transition is being driven by these altered hydrologic conditions. This research set out to quantify trends of groundwater depth and quality, as well as to discern any spatial patterns in the locations of areas experiencing changes in groundwater depth or quality. In the process, we examined the questions (1) if there are detectable trends in aquifer changing groundwater depth in coastal North Carolina, (2) if groundwater monitoring wells placed by the NCDWR are spatially clustered, (3) if we can identify areas of high salinity, and high rates of groundwater depth change from available groundwater monitoring data and (4) if groundwater depth and quality in shallow, unconfined aquifers are correlated with proximity to hydrologic features within the coastal zone.

In Chapter 1, I hypothesized that due to historic rates of sea level rise in North Carolina, there are detectible trends in groundwater depth data that can be discerned from long term groundwater monitoring well data. The results of this analysis indicate that for a majority of sites (80%), there is a detectable trend in groundwater depth. For the entire study area, 56% of sites reported a decrease in groundwater depth relative to the fixed datum NAVD88, while 20% reported an increase in groundwater depth. This trend was fairly consistent across the five groups into which wells were separated for further analysis: confined and unconfined aquifer measurements, and shallow, medium depth, and deep wells. All groups tended to report about 60% of sites exhibiting a decrease in groundwater depth, and about 25% of sites exhibiting an increase in groundwater depth. U.S. Principal Aquifers followed the same pattern, although local aquifers were more highly variable. This is likely due to the fact that Principal Aquifer measurements were distributed across the entire study area, while local aquifers do not cover the same spatial extent, and variation across the study site is more readily observable in these measurements.

These results show that trends observed elsewhere, such as along the Pacific coast, that areas experiencing sea level rise are also experiencing a decrease in groundwater table depth hold true for areas throughout coastal North Carolina as well ((Befus et al., 2020; Masterson et al., 2014; Michael et al., 2013). This will have implications for communities along the coast, as sea level rise and associated decreases in groundwater depth inshore can drive inland flooding, as well as aquifer salinization (Befus et al., 2020). As discussed throughout this document, this can threaten coastal infrastructure and commerce, and may be detrimental to communities along the coast that rely on natural resources for economic support (Befus et al., 2020; Bhattachan, Jurjonas, et al., 2018; Kirwan & Gedan, 2019). In the interest of understanding the effects that future sea level rise could have on these communities, future research should increase focus on quantifying the relationship between sea level rise and groundwater dynamics in eastern North Carolina to project potential impacts on ecosystems and human communities.

In Chapter 2, I first hypothesized that groundwater monitoring wells are spatially clustered throughout the study area. This research identified seven local clusters of groundwater monitoring well locations. Understanding the spatial relationships of monitoring wells is important, as it can inform our understanding of patterns observed within the data. Since there are local clusters, some locations within the study area may be sampled more robustly than others, leading to knowledge gaps for those areas sampled less frequently or bias toward wells exhibiting certain patterns of groundwater depth and water quality. The non-random, uneven placement of these wells likely leads to the spatial autocorrelations observed in this study across all datasets. This is especially important as the NCDWR has stated that placement of these wells could lead to a bias towards those experiencing a decrease in groundwater depth or reduced water quality (NCDWR, 2020, 2021a). Future groundwater monitoring well placement could focus on more random sampling and dispersed well placement to mediate the potential biases in the groundwater depth and water quality measurements, and add to additional information about changes occurring along the coastal plain.

I then hypothesized that there are areas of high rates of change in groundwater depth and high salinity that can be identified throughout coastal North Carolina. The Hot Spot analyses revealed that across the five groups of wells considered, each group exhibited some Hot Spots of elevated groundwater depth change and salinity. This is important to understanding the dynamics of groundwater depth change and water quality change across the study area, as the coastal zone has a large spatial extent and characteristics like hydrology, soils, and vegetation are not uniform throughout. The identification of these areas may inform where adaptation and mitigation efforts may be focused to protect the economy and ecology of coastal areas that may be affected by rising sea levels.

Which leads into the final hypothesis, that rates of change in groundwater depth and salinity are correlated with distance to hydrologic features in shallow, unconfined aquifers. There was a weak correlation between rate of change in groundwater depth and distance to drainage ditches, however rate of change was not significantly correlated with distance to the coastline or to streams. Neither measurement of water quality, salinity, or specific conductivity was significantly correlated with distance to drainage ditches, the coastline, or streams. From the analyses above, I observed spatial heterogeneity in measurements of rate of change of groundwater depth and aquifer salinity. The results of the regression analyses indicate that there are likely other factors affecting the spatial distribution of those areas experiencing high rates of change in groundwater depth or high salinities. Altered precipitation regimes, population densities, soils, or vegetation may all affect water flow into and out of aquifers, as well as the quality of the water within aquifers. These factors will be important to consider in the future and may inform the spatial variation observed in these data.

Overall, the results of this study indicate that the coastal zone is changing and variable in North Carolina. As the climate continues to warm, the effects of sea level rise are likely to be exacerbated (Kemp et al., 2011; Sallenger et al., 2012). This has implications for communities in this area that have an interest in protecting infrastructure and rely on natural resources for commerce (Bhattachan, Jurjonas, et al., 2018). Flooding and aquifer salinization can be detrimental to plant communities along the coast and have the potential to affect ecosystem health and the viability of cropland (Kirwan & Gedan, 2019). Mitigation and adaptation will be crucial for these communities as they look toward an uncertain future. This study presents a methodology that could be useful in early identification of areas that are experiencing significant rapid change to allow for targeted mitigation efforts. These efforts will be crucial in preserving the ecologic and economic health of the North Carolina coastal zone.

This is not only true for the local study area, but also for the global coastal zone. It is estimated that half of the world's coastline may be at risk of saltwater intrusion due to rising sea levels and decreasing groundwater depth (Befus et al., 2020; Neumann et al., 2015). Understanding this risk and the driving factors behind it will help to identify areas vulnerable to decreased groundwater depth, increased overland flow, and saltwater intrusion. Future research will help to better understand and preserve freshwater resources in the coastal zone.

REFERENCES

Ardón, M., Morse, J. L., Colman, B. P., & Bernhardt, E. S. (2013). Drought-induced saltwater incursion leads to increased wetland nitrogen export. *Global Change Biology*, *19*, 2976–2985. https://doi.org/10.1111/gcb.12287

Baldwin, A. H., & Mendelssohn, I. A. (1998). Effects of salinity and water level on coastal marshes: An experimental test of disturbance as a catalyst for vegetation change. *Aquatic Botany*, *61*, 255–268. https://doi.org/10.1016/S0304-3770(98)00073-4

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169–193.

Barrett-Lennard, E. G. (2003). The interaction between waterlogging and salinity in higher plants: causes, consequences and implications. *Plant and Soil*, *253*(3), 35–54.

Barrett-Lennard, E. G., Leighton, P. D., Buwalda, F., Gibbs, J., Armstrong, W., Thompson, C. J., & Greenway, H. (1988). Effects of Growing Wheat in Hypoxic Nutrient Solutions and of Subsequent Transfer to Aerated Solutions. I. Growth and Carbohydrate Status of Shoots and Roots. *Australian Journal of Plant Physiology*, *15*(4), 585–598. https://www.publish.csiro.au/FP/PP9880585

Barrett-Lennard, E. G., Leighton, P. D., McPharlin, I. R., Setter, T., & Greenway, H. (1986). Methods to experimentally control waterlogging and measure soil oxygen in field trials. *Australian Journal of Soil Research*, *24*, 477–483. https://doi.org/10.1071/SR9860477

Befus, K. M., Barnard, P. L., Hoover, D. J., Finzi Hart, J. A., & Voss, C. I. (2020). Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nature Climate Change*, *10*(10), 946–952. https://doi.org/10.1038/s41558-020-0874-1

Bhattachan, A., Emanuel, R. E., Ardón, M., Bernhardt, E. S., Anderson, S. M., Stillwagon, M. G., Ury, E. A., BenDor, T. K., & Wright, J. P. (2018). Evaluating the effects of land-use change and future climate change on vulnerability of coastal landscapes to saltwater intrusion. *Elementa Science of the Anthropocene*, *6*(62), 1–11. https://doi.org/10.1525/elementa.316

Bhattachan, A., Jurjonas, M. D., Moody, A. C., Morris, P. R., Sanchez, G. M., Smart, L. S., Taillie, P. J., Emanuel, R. E., & Seekamp, E. L. (2018). Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. In *Environmental Science and Policy* (Vol. 90, pp. 122–134). Elsevier. https://doi.org/10.1016/j.envsci.2018.10.006

Brinson, M. M., Christian, R. R., & Blum, L. K. (1995). Multiple states in the sea-level induced transition from terrestrial forest to estuary. *Estuaries*, *18*(4), 648–659. https://doi.org/10.2307/1352383

Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. v., Paruelo, J., Raskin, R. G., Sutton, P., & van den Belt, M. (1998). The value of ecosystem services: Putting the issues in perspective. *Ecological Economics*, *25*, 67–72. https://doi.org/10.1016/S0921-8009(98)00019-6

Daniels, R. B., Gamble, E. E., & Nelson, L. A. (1971). Relations between soil morphology and water-table levels on a dissected North Carolina coastal plain surface. *Soil Science Society of America Journal*, *35*(5), 781–784. https://doi.org/10.2136/sssaj1971.03615995003500050041x

Else, M. A., Coupland, D., Dutton, L., & Jackson, M. B. (2008). Decreased root hydraulic conductivity reduces leaf water potential, initiates stomatal closure and slows leaf expansion in flooded plants of castor oil (Ricinus communis) despite diminished delivery of ABA from the roots to shoots in xylem sap. *Physiologia Plantarum*, *111*(1), 46–54.

Haer, T., Kalnay, E., Kearney, M., & Moll, H. (2013). Relative sea-level rise and the conterminous United States: Consequences of potential land inundation in terms of population at risk and GDP loss. *Global Environmental Change*, *23*(6), 1627–1636. https://doi.org/10.1016/j.gloenvcha.2013.09.005

Hayden, B. P., Santos, M. C. F. V., Shao, G., & Kochel, R. C. (1995). Geomorphological controls on coastal vegetation at the Virginia Coast Reserve. *Geomorphology*, *13*(1–4), 283–300. https://doi.org/10.1016/0169-555X(95)00032-Z

Hirsch, R. M. (1982). *Techniques of Trend Analysis for Monthly Water Quality Data*. *May 2014*. https://doi.org/10.1029/WR018i001p00107

Hirsch, R. M., & Slack, J. R. (1984). A nonparametric trend test for seasonal data with serial dependence. *Water Resources Research*, *20*(6), 727–732.

Huang, B., NeSmith, D. S., Bridges, D. C., & Johnson, J. W. (1995). Responses of Squash to Salinity, Waterlogging, and Subsequent Drainage: II. Root and Shoot Growth. *Journal of Plant Nutrition*, *18*(1), 141–152. https://doi.org/10.1080/01904169509364891

Johnson, S. R., & Young, D. R. (1993). Factors Contributing to the Decline of Pinus taeda on a Virginia Barrier Island. *Bulletin of the Torry Botanical Club*, *120*(4), 431–438. https://www.jstor.org/stable/2996747

Kemp, A. C., Horton, B. P., Donnelly, J. P., Mann, M. E., Vermeer, M., & Rahmstorf, S. (2011). Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(27), 11017–11022. https://doi.org/10.1073/pnas.1015619108

Kirwan, M. L., & Gedan, K. B. (2019). Sea-level driven land conversion and the formation of ghost forests. *Nature Climate Change*, *9*(6), 450–457. https://doi.org/10.1038/s41558-019-0488-7

Kirwan, M. L., Kirwan, J. L., & Copenheaver, C. A. (2007). Dynamics of an Estuarine Forest and its Response to Rising Sea Level. *Journal of Coastal Research*, *232*, 457–463. https://doi.org/10.2112/04-0211.1

Lyke, W. L., & Coble, R. W. (1987). *Regional Study of the Castle Hayne Aquifer of Eastern North Carolina*.

Masterson, J. P., Fienen, M. N., Thieler, E. R., Gesch, D. B., Gutierrez, B. T., & Plant, N. G. (2014). Effects of sea-level rise on barrier island groundwater system dynamics - ecohydrological implications. *Ecohydrology*, *7*(3), 1064–1071. https://doi.org/10.1002/eco.1442

Masterson, J. P., & Garabedian, S. P. (2007). Effects of Sea-Level Rise on Ground Water Flow in a Coastal Aquifer System. *Ground Water*, *45*(2), 209–217. https://doi.org/10.1111/j.1745-6584.2006.00279.x

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, *19*(1), 17–37. https://doi.org/10.1177/0956247807076960

Michael, H. A., Russoniello, C. J., & Byron, L. A. (2013). Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems. *Water Resources Research*, *49*(4), 2228–2240. https://doi.org/10.1002/wrcr.20213

Millero, F. J. (2006). *Chemical Oceanography* (First). Taylor & Francis Group.

Moorhead, K. K., & Brinson, M. M. (1995). *Response of Wetlands to Rising Sea Level in the Lower Coastal Plain of North Carolina*. *5*(1), 261–271.

NCDWR. (2020). *Groundwater Resources Section*. https://deq.nc.gov/about/divisions/water-resources/groundwater-resources-section

NCDWR. (2021a). *Groundwater Quality in North Carolina*. https://www.ncwater.org/?page=740

NCDWR. (2021b). *North Carolina Aquifers*. https://www.ncwater.org/?page=525

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS ONE*, *10*(3). https://doi.org/10.1371/journal.pone.0118571

Nicholls, R. J., & Cazenave, A. (2010). Coastal Zones Sea-Level Rise and Its Impact on. *Science*, *328*(5985), 1517–1520. https://www.jstor.org/stable/40656419

Oude Essink, G. H. P., van Baaren, E. S., & de Louw, P. G. B. (2010). Effects of climate change on coastal groundwater systems : A modeling study in the Netherlands. *Water Resources Research*, *46*, 1–16. https://doi.org/10.1029/2009WR008719

Robichaud, A., & Bégin, Y. (1997). The effects of storms and sea-level rise on a coastal forest margin in New Brunswick, Eastern Canada. *Journal of Coastal Research*, *13*(2), 429–439.

Rotzoll, K., & Fletcher, C. H. (2012). Assessment of groundwater inundation as a consequence of sea-level rise. *Nature Climate Change*, *3*, 477–481. https://doi.org/10.1038/nclimate1725

Rowley, R. J., Kostelnick, J. C., Braaten, D., Li, X., & Meisel, J. (2007). Risk of rising sea level to population and land area. *Eos*, *88*(9), 105–116. https://doi.org/10.1029/2007EO090001

Sallenger, A. H., Doran, K. S., & Howd, P. A. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change*, *2*(12), 884–888. https://doi.org/10.1038/nclimate1597

Smart, L. S., Taillie, P. J., Poulter, B., Vukomanovic, J., Singh, K. K., Swenson, J. J., Mitasova, H., Smith, J. W., & Meentemeyer, R. K. (2020). Aboveground carbon loss associated with the spread of ghost forests as sea levels rise. *Environmental Research Letters*, *15*(10), 104028. https://doi.org/10.1088/1748-9326/aba136

Stocker, T. (2014). *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change.* (T. Stocker, Ed.). Cambridge University Press.

Taillie, P. J., Moorman, C. E., Poulter, B., Ardón, M., & Emanuel, R. E. (2019). Decadal-Scale Vegetation Change Driven by Salinity at Leading Edge of Rising Sea Level. *Ecosystems*, *22*(8), 1918–1930. https://doi.org/10.1007/s10021-019-00382-w

Trapp Jr., H., & Horn, M. A. (1997). Ground Water Atlas of the United States: Segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. *Hydrologic Atlas 730-L*, 24.

Trought, M. C. T., & Drew, M. C. (1980). The development of waterlogging damage in young wheat plants in anaerobic solution cultures. *Journal of Experimental Botany*, *31*(125), 1573–1585. https://doi.org/10.1093/jxb/31.6.1573

White, E., & Kaplan, D. (2017). Restore or retreat? saltwater intrusion and water management in coastal wetlands. *Ecosystem Health and Sustainability*, *3*(1), 1–18. https://doi.org/10.1002/ehs2.1258

Wilson, G. W., & Fischetti, T. R. (2010). Coastline Population Trends in the United States : 1960 to 2008. *U. S. Census Bureau*, *P25-1139*, 1–28.

Winner, M. D., & Coble, R. W. (1989). *Hydrogeologic Framework of the North Carolina Coastal Plain System*.

APPENDICES

Appendix 1: Site information for groundwater wells considered in the Mann-Kendall analysis. Principal aquifers are abbreviated here; CH denotes the Castle Hayne aquifer, NACP denotes the Northern Atlantic Coastal Plain Aquifer System, and S denotes the Surficial aquifer system.

County	Site Name	Site ID	Latitude	Longitude	Well Depth (ft)	Principal Aquifer	Local Aquifer	Aquifer Type
Beaufort	Aurora II	Q17D1	35.3261	-76.803341	168	CH	Castle Hayne	CONFINED
		Q17D2	35.3261	-76.803341	18	S	Surficial	UNCONFINED
		Q17D3	35.3261	-76.803341	80	NACP	Yorktown	CONFINED
		Q17D4	35.3261	-76.803341	1000	NACP	Black Creek	CONFINED
		Q17D5	35.3261	-76.803341	519	NACP	Beaufort	CONFINED
	Bath	O17I1	35.473171	-76.78261	55	NACP	Yorktown	CONFINED
		O17I2	35.473171	-76.78261	190	CH	Castle Hayne	CONFINED
	Bonnerton	P18V3	35.343707	-76.861047	30	S	Surficial	UNCONFINED
		P18V4	35.343707	-76.861047	385	CH	Castle Hayne	CONFINED
		P18V5	35.343707	-76.861047	280	CH	Castle Hayne	CONFINED
		P18V6	35.343707	-76.861047	86	NACP	Yorktown	CONFINED
		P18V7	35.343707	-76.861047	1000	NACP	Black Creek	CONFINED
		P18V8	35.343707	-76.861047	457	NACP	Beaufort	CONFINED

Appendix 1 (continued)

Cox Crossroads	P19M2	35.373479	-76.951008	40	NACP	Yorktown	CONFINED
	P19M4	35.373479	-76.951008	800	NACP	Black Creek	CONFINED
	P19M5	35.373479	-76.951008	390	NACP	Peedee	CONFINED
	P19M6	35.373479	-76.951008	250	CH	Castle Hayne	CONFINED
Godley	Q16G3	35.315752	-76.727595	280	CH	Castle Hayne	CONFINED
	Q16G4	35.315752	-76.727595	500	CH	Castle Hayne	CONFINED
	Q16G5	35.315752	-76.727595	40	NACP	Yorktown	CONFINED
	Q16G6	35.315752	-76.727595	16	S	Surficial	UNCONFINED
	Q16G7	35.315752	-76.727595	810	NACP	Peedee	CONFINED
	Q16G8	35.315752	-76.727595	375	CH	Castle Hayne	CONFINED
Highway 102	O21Q1	35.43746	-77.142706	143	CH	Castle Hayne	CONFINED
	O21Q2	35.43746	-77.142706	12	S	Surficial	UNCONFINED
	O21Q3	35.43746	-77.142706	42	NACP	Yorktown	CONFINED
Hubs Rec	N15X5	35.51658	-76.650011	400	NACP	Beaufort	CONFINED
Lee Creek	P17I12	35.386451	-76.783141	494	NACP	Beaufort	CONFINED
	P17I13	35.386451	-76.783141	41	S	Surficial	UNCONFINED
	P17I6	35.386451	-76.783141	336	CH	Castle Hayne	CONFINED
	P17I7	35.386451	-76.783141	72	NACP	Yorktown	CONFINED

Appendix 1 (continued)

		P17I9	35.38645	-76.783141	946	NACP	Black Creek	CONFINED
	Southside Ferry	P16O2	35.377191	-76.749237	47	NACP	Yorktown	CONFINED
		P16O3	35.377191	-76.749237	370	CH	Castle Hayne	CONFINED
		P16O4	35.377191	-76.749237	250	CH	Castle Hayne	CONFINED
	Washington	M21K2	35.629622	-77.088938	82	CH	Castle Hayne	CONFINED
	Whitley Farms	P17E1	35.400578	-76.832719	186	CH	Castle Hayne	CONFINED
		P17E2	35.400578	-76.832719	370	CH	Castle Hayne	CONFINED
		P17E3	35.400578	-76.832719	49	NACP	Yorktown	CONFINED
		P17E5	35.40096	-76.83281	35	S	Surficial	UNCONFINED
	Wilmar	P21K3	35.381484	-77.087762	29	S	Surficial	UNCONFINED
		P21K4	35.381484	-77.087762	200	CH	Castle Hayne	CONFINED
		P21K5	35.381484	-77.087762	918	NACP	Black Creek	CONFINED
		P21K6	35.381484	-77.087762	200	CH	Castle Hayne	CONFINED
		P21K7	35.381484	-77.087762	320	NACP	Beaufort	CONFINED
		P21K9	35.381484	-77.087762	712	NACP	Black Creek	CONFINED
Bertie	Cremo	F19V2	36.16752	-76.938703	80	NACP	Yorktown	CONFINED
		F19V3	36.16752	-76.938703	225	NACP	Upper Cape Fear	CONFINED

Appendix 1 (continued)

	F19V4	36.16752	-76.938703	1038	NACP	Lower Cretaceous	CONFINED
	F19V5	36.16752	-76.938703	600	NACP	Lower Cape Fear	CONFINED
	F19V6	36.16752	-76.938703	431	NACP	Upper Cape Fear	CONFINED
Lewiston	H22I3	36.051577	-77.194707	20	S	Surficial	UNCONFINED
	H22I4	36.051577	-77.194707	600	NACP	Lower Cretaceous	CONFINED
	H22I5	36.051577	-77.194707	380	NACP	Lower Cape Fear	CONFINED
	H22I6	36.051577	-77.194707	150	NACP	Upper Cape Fear	CONFINED
Roxobel	F22B1	36.238763	-77.18695	325	NACP	Upper Cape Fear	CONFINED
	F22B2	36.238763	-77.18695	441	NACP	Lower Cape Fear	CONFINED
	F22B3	36.238763	-77.18695	40	S	Surficial	UNCONFINED
	F22B5	36.238763	-77.18695	610	NACP	Lower Cretaceous	CONFINED
	F22B7	36.238763	-77.18695	12	S	Surficial	UNCONFINED
Windsor	H20T1	36.03293	-77.01276	1001	NACP	Lower Cretaceous	CONFINED
	H20T2	36.03293	-77.01276	560	NACP	Lower Cape Fear	CONFINED
	H20T3	36.03293	-77.01276	335	NACP	Upper Cape Fear	CONFINED
	H20T4	36.03293	-77.01276	280	NACP	Upper Cape Fear	CONFINED
	H20T6	36.03293	-77.01276	105	NACP	Beaufort	CONFINED
	H20T7	36.03293	-77.01276	60	S	Surficial	UNCONFINED
	H20T8	36.03293	-77.01276	35	S	Surficial	UNCONFINED

Appendix 1 (continued)

		H20T9	36.03293	-77.01276	185	NACP	Black Creek	CONFINED
Brunswick	Bear Pen	EE36K3	34.128756	-78.338547	52	NACP	Peedee	CONFINED
		EE36K4	34.128756	-78.338547	332	NACP	Lower Peedee	CONFINED
		EE36K5	34.128756	-78.338547	654	NACP	Upper Cape Fear	CONFINED
		EE36K6	34.128756	-78.338547	110	NACP	Peedee	CONFINED
	BS RS 2	FF32Y1	34.014423	-78.083039	150	NACP	Peedee	CONFINED
		FF32Y2	34.014423	-78.083039	14	S	Surficial	UNCONFINED
	BR-079	79	33.9411111	-78.198611	102	NACP	Peedee Formation	CONFINED
	BR-080	80	33.9413889	-78.198611	15	S	Post Miocene	UNCONFINED
	BR-081	81	33.9419444	-78.009722	200	NACP	Peedee Formation	CONFINED
	BR-082	82	33.9419444	-78.009722	74	CH	CH Limestone	CONFINED
	BR-083	83	33.9419444	-78.009722	21	S	Post Miocene	UNCONFINED
	BR-100, 15A	15A	33.9802778	-78.095277	158.3	NACP	Peedee Formation	CONFINED
	Calabash	HH39J4	33.892777	-78.589421	516	NACP	Black Creek	CONFINED
		HH39J5	33.892777	-78.589421	358	NACP	Lower Peedee	CONFINED
	Shallotte	GG37B4	33.99	-78.44	70	NACP	Peedee	CONFINED
	Stanbury	GG35R3	33.95	-78.29	25	S	Surficial	UNCONFINED
	Sunset Harbor N.	GG34S4	33.94	-78.2	322	NACP	Peedee	CONFINED

Appendix 1 (continued)

		GG34S5	33.94	-78.2	102	NACP	Peedee	CONFINED
	Waccamaw	FF38J8	34.06	-78.51	40	S	Surficial	UNCONFINED
Carteret	Atlantic	V12I3	34.88528	-76.354791	832	CH	Castle Hayne	CONFINED
		V12I4	34.88528	-76.354791	1140	CH	Castle Hayne	CONFINED
		V12I5	34.88528	-76.354791	17	S	Surficial	UNCONFINED
		V12I6	34.88528	-76.354791	165	NACP	Yorktown	CONFINED
	Camp Glenn	X17J3	34.723029	-76.753385	700	CH	Castle Hayne	CONFINED
		X17J5	34.723029	-76.753385	191	CH	Castle Hayne	CONFINED
		X17J7	34.723018	-76.753503	17	S	Surficial	UNCONFINED
Craven	Cherry Point	U18Q3	34.933879	-76.890064	480	CH	Castle Hayne	CONFINED
		U18Q4	34.933879	-76.890064	250	CH	Castle Hayne	CONFINED
		U18Q5	34.933879	-76.890064	80	NACP	Yorktown	CONFINED
		U18Q6	34.933879	-76.890064	30	S	Surficial	UNCONFINED
	Clarks	S22J10	35.137475	-77.171389	726	NACP	Black Creek	CONFINED
		S22J12	35.137475	-77.171389	1057	NACP	Upper Cape Fear	CONFINED
		S22J5	35.137475	-77.171389	80	CH	Castle Hayne	CONFINED
		S22J8	35.137475	-77.171389	338	NACP	Beaufort	CONFINED
		S22J9	35.137475	-77.171389	530	NACP	Peedee	CONFINED
	Cove City	R23X10	35.172305	-77.311178	1005	NACP	Lower Cape Fear	CONFINED

Appendix 1 (continued)

		R23X4	35.172305	-77.311178	307	NACP	Peedee	CONFINED
		R23X5	35.172305	-77.311178	13	S	Surficial	UNCONFINED
		R23X6	35.172305	-77.311178	101	CH	Castle Hayne	CONFINED
		R23X7	35.172305	-77.311178	213	NACP	Beaufort	CONFINED
		R23X8	35.172305	-77.311178	507	NACP	Black Creek	CONFINED
		R23X9	35.172305	-77.311178	869	NACP	Upper Cape Fear	CONFINED
	Croatan	U19O5	34.956514	-76.988776	80	S	Surficial	UNCONFINED
	Palmetto Swamp	P22U10	35.332429	-77.17249	85	CH	Castle Hayne	CONFINED
		P22U6	35.332429	-77.17249	619	NACP	Black Creek	CONFINED
		P22U7	35.332429	-77.17249	350	NACP	Peedee	CONFINED
		P22U8	35.332429	-77.17249	239	NACP	Peedee	CONFINED
		P22U9	35.332429	-77.17249	25	S	Surficial	UNCONFINED
	Purser	P21N1	35.373997	-77.135278	172	CH	Castle Hayne	CONFINED
		P21N2	35.373997	-77.135278	44	NACP	Yorktown	CONFINED
		P21N3	35.373997	-77.135278	20	S	Surficial	UNCONFINED
	Wilmar FT	P21G1	35.393509	-77.144768	106	CH	Castle Hayne	CONFINED
Currituck	Moyock	B10R1	36.523704	-76.206839	840	NACP	Upper Cape Fear	CONFINED
	Bodie Island	K2E2	35.823721	-75.569477	214	NACP	Yorktown	CONFINED

Appendix 1 (continued)

	K2E3	35.823721	-75.569477	190	NACP	Yorktown	CONFINED
	K2E4	35.823721	-75.569477	134	NACP	Yorktown	CONFINED
	K2E7	35.823721	-75.569477	10	S	Surficial	UNCONFINED
East Lake	J7K5	35.869044	-75.921232	315	NACP	Yorktown	CONFINED
	J7K6	35.869044	-75.921232	195	NACP	Yorktown	CONFINED
	J7K7	35.869044	-75.921232	88	NACP	Yorktown	CONFINED
	J7K8	35.869044	-75.921232	15	S	Surficial	UNCONFINED
Kitty Hawk North	G4X1	36.099542	-75.725501	238	NACP	Yorktown	CONFINED
Manteo Airport	I4W3	35.918385	-75.701641	160	NACP	Yorktown	CONFINED
	I4W5	35.918385	-75.701641	20	S	Surficial	UNCONFINED
Nags Head	J3H3	35.896805	-75.621381	207	NACP	Yorktown	CONFINED
Skyco Road	J3O3	35.880959	-75.665774	220	NACP	Yorktown	CONFINED
	J3O4	35.880944	-75.665799	13	S	Surficial	UNCONFINED
Spencer Creek	J5M2	35.871094	-75.786051	150	NACP	Yorktown	CONFINED
	J5M3	35.871094	-75.786051	24	S	Surficial	UNCONFINED
Stumpy Point	L6Y2	35.674282	-75.905311	300	NACP	Yorktown	CONFINED

Appendix 1 (continued)

		L6Y3	35.674282	-75.905311	145	NACP	Yorktown	CONFINED
	Wanchese	J3X10	35.8423	-75.639888	500	NACP	Yorktown	CONFINED
		J3X11	35.8423	-75.639888	98	NACP	Yorktown	CONFINED
		J3X12	35.8423	-75.639888	84	NACP	Yorktown	CONFINED
		J3X13	35.8423	-75.639888	183	NACP	Yorktown	CONFINED
		J3X9	35.8423	-75.639888	19	S	Surficial	UNCONFINED
	Wright Memorial	H4U2	36.013384	-75.675696	266	NACP	Yorktown	CONFINED
		H4U3	36.013384	-75.675696	23	S	Surficial	UNCONFINED
Hyde	D Canal Road	L15T1	35.68587	-76.5971	110	S	Surficial	UNCONFINED
		L15T2	35.68587	-76.5971	590	NACP	Beaufort	CONFINED
		L15T3	35.68587	-76.5971	28	S	Surficial	UNCONFINED
		L15T4	35.68587	-76.5971	360	CH	Castle Hayne	CONFINED
		L15T5	35.68587	-76.5971	295	CH	Castle Hayne	CONFINED
N. Hanover	Eagle Point	CC29L1	34.289688	-77.767845	105	CH	Castle Hayne	CONFINED
		CC29L2	34.289688	-77.767845	450	NACP	Peedee	CONFINED
		CC29L3	34.289688	-77.767845	24	S	Surficial	UNCONFINED
		CC29L4	34.289688	-77.767845	178	NACP	Peedee	CONFINED

Appendix 1 (continued)

	NH Correctional	CC31U1	34.26499	-77.92259	30	S	Surficial	UNCONFINED
Onslow	Camp Geiger	X25C1	34.738396	-77.457525	68	S	Surficial	UNCONFINED
		X25C2	34.738396	-77.457525	435	NACP	Peedee	CONFINED
		X25C3	34.738396	-77.457525	170	CH	Castle Hayne	CONFINED
	Deppe	V23X1	34.837042	-77.303278	120	S	Surficial	UNCONFINED
		V23X2	34.837042	-77.303278	640	NACP	Peedee	CONFINED
		V23X3	34.837042	-77.303278	300	NACP	Beaufort	CONFINED
		V23X4	34.837042	-77.303278	35	S	Surficial	UNCONFINED
		V23X5	34.837042	-77.303278	225	S	Surficial	UNCONFINED
		V23X6	34.837042	-77.303278	85	S	Surficial	UNCONFINED
		V23X7	34.837042	-77.303278	873	NACP	Black Creek	CONFINED
	Folkstone	Y25Q3	34.611365	-77.482799	240	CH	Castle Hayne	CONFINED
		Y25Q4	34.611365	-77.482799	550	NACP	Peedee	CONFINED
		Y25Q6	34.611365	-77.482799	22	S	Surficial	UNCONFINED
		Y25Q7	34.611365	-77.482799	462	CH	Castle Hayne	CONFINED
		Y25Q8	34.611365	-77.482799	800	NACP	Black Creek	CONFINED
	Hadnot Point	X24S1	34.692198	-77.35118	90	S	Surficial	UNCONFINED
		X24S2	34.692198	-77.35118	918	NACP	Black Creek	CONFINED

Appendix 1 (continued)

	X24S4	34.692738	-77.351433	527	NACP	Peedee	CONFINED
	X24S5	34.692738	-77.351433	380	CH	Castle Hayne	CONFINED
	X24S6	34.692738	-77.351433	130	CH	Castle Hayne	CONFINED
	X24S7	34.692738	-77.351433	40	S	Surficial	UNCONFINED
Montford Point	X24E1	34.738	-77.409222	341	CH	Castle Hayne	CONFINED
	X24E2	34.738056	-77.409139	240	CH	Castle Hayne	CONFINED
Onslow Quarry 14	W26C6	34.828017	-77.545416	105	CH	Castle Hayne	CONFINED
Onslow Quarry 15	W26D1	34.819725	-77.550272	150	CH	Castle Hayne	CONFINED
Paradise Point	X24G1	34.717963	-77.391888	232	CH	Castle Hayne	CONFINED
	X24G2	34.717963	-77.391888	16.4	S	Surficial	UNCONFINED
Parkertown Road	X22H1	34.72964	-77.2104	387	CH	Castle Hanne	CONFINED
	X22H3	34.72964	-77.2104	298	CH	Castle Hayne	CONFINED
	X22H4	34.72964	-77.2104	529	NACP	Beaufort	CONFINED

Appendix 1 (continued)

		X22H5	34.72964	-77.2104	795	NACP	Peedee	CONFINED
		X22H6	34.72964	-77.2104	1043	NACP	Black Creek	CONFINED
	Ragged Point	X25U1	34.676463	-77.427538	180	CH	Castle Hayne	CONFINED
	Sneads Ferry	Y23R2	34.60716	-77.28795	435	NACP	Peedee	CONFINED
	Wallace Creek	X23N1	34.701212	-77.305598	253	CH	Castle Hayne	CONFINED
	Well Field 258	W25F10	34.810394	-77.487225	17	S	Surficial	UNCONFINED
		W25F11	34.810394	-77.487225	303	NACP	Peedee	CONFINED
		W25F12	34.810394	-77.487225	848	NACP	Upper Cape Fear	CONFINED
		W25F6	34.810394	-77.487225	110	S	Surficial	UNCONFINED
		W25F8	34.810394	-77.487225	600	NACP	Black Creek	CONFINED
		W25F9	34.810394	-77.487225	164	S	Surficial	UNCONFINED
Pamlico	Arapahoe	S18U10	35.086676	-76.835587	125	NACP	Yorktown	CONFINED
		S18U11	35.086676	-76.835587	22	S	Surficial	UNCONFINED
		S18U12	35.086676	-76.835587	492	CH	Castle Hayne	CONFINED
		S18U3	35.086676	-76.835587	83	NACP	Yorktown	CONFINED
		S18U4	35.086676	-76.835587	780	NACP	Peedee	CONFINED
		S18U5	35.086676	-76.835587	380	CH	Castle Hayne	CONFINED

Appendix 1 (continued)

		S18U7	35.086676	-76.835587	120	NACP	Yorktown	CONFINED
		S18U9	35.086676	-76.835587	224	CH	Castle Hayne	CONFINED
	Bay City	R17I1	35.219985	-76.773926	76	S	Surficial	UNCONFINED
		R17I2	35.219985	-76.773926	461	CH	Castle Hayne	CONFINED
		R17I3	35.219985	-76.773926	620	CH	Castle Hayne	CONFINED
	Hobucken	Q15U3	35.255031	-76.595863	570	CH	Castle Hayne	CONFINED
		Q15U5	35.255031	-76.595863	740	CH	Castle Hayne	CONFINED
		Q15U6	35.255031	-76.595863	105	NACP	Yorktown	CONFINED
		Q15U7	35.255031	-76.595863	973	NACP	Peedee	CONFINED
		Q15U8	35.255031	-76.595863	25	S	Surficial	UNCONFINED
	Whortonsville	S15Y1	35.089831	-76.655676	59	NACP	Yorktown	CONFINED
		S15Y2	35.089831	-76.655676	1065	NACP	Peedee	CONFINED
		S15Y3	35.089831	-76.655676	590	CH	Castle Hayne	CONFINED
		S15Y4	35.089831	-76.655676	450	CH	Castle Hayne	CONFINED
		S15Y6	35.089831	-76.655676	290	CH	Castle Hayne	CONFINED
		S15Y7	35.089831	-76.655676	14	S	Surficial	UNCONFINED
Pasquotank	Big Flatty Creek	G9C3	36.150033	-76.132485	70	S	Surficial	UNCONFINED

Appendix 1 (continued)

		G9C4	36.150033	-76.132485	622	CH	Castle Hayne	CONFINED
		G9C6	36.150033	-76.132485	105	S	Surficial	UNCONFINED
	Elizabeth City	E10U4	36.250825	-76.177299	145	NACP	Yorktown	CONFINED
		E10U5	36.250825	-76.177299	55	NACP	Yorktown	CONFINED
	Morgans Corner	C12W2	36.431549	-76.375628	40	NACP	Yorktown	CONFINED
		C12W4	36.431549	-76.375628	428	CH	Castle Hayne	CONFINED
		C12W5	36.431549	-76.375628	1308	NACP	Lower Cape Fear	CONFINED
		C12W6	36.431549	-76.375628	648	NACP	Upper Cape Fear	CONFINED
	N.C. Forestry HQ	D11V5	36.347527	-76.277474	130	NACP	Yorktown	CONFINED
	Weeksville	F10K3	36.205757	-76.166895	60	S	Surficial	UNCONFINED
		F10K4	36.205757	-76.166895	75	NACP	Yorktown	CONFINED
Pender	Burgaw	Y30S3	34.604749	-77.85607	145	NACP	Peedee	CONFINED
		Y30S7	34.604749	-77.85607	380	NACP	Black Creek	CONFINED
	Topsail Beach	BB28J2	34.399976	-77.67817	493	NACP	Peedee	CONFINED
		BB28J3	34.399976	-77.67817	612	NACP	Black Creek	CONFINED

Appendix 1 (continued)

		BB28J4	34.399976	-77.67817	160	CH	Castle Hayne	CONFINED
		BB28J5	34.399976	-77.67817	15	S	Surficial	UNCONFINED
Perquimans	Perquimans	F13W1	36.169167	-76.451667	339	CH	Castle Hayne	CONFINED
Tyrrell	Gum Neck	L10A2	35.739773	-76.180591	85	NACP	Yorktown	CONFINED
		L10A3	35.739773	-76.180591	701	CH	Castle Hayne	CONFINED
		L10A5	35.739773	-76.180591	920	CH	Castle Hayne	CONFINED
Washington	Lake Phelps	L13I1	35.730718	-76.43438	510	CH	Castle Hayne	CONFINED
		L13I2	35.730718	-76.43438	130	NACP	Yorktown	CONFINED
		L13I3	35.730718	-76.43438	224	NACP	Yorktown	CONFINED
		L13I4	35.730718	-76.43438	14	S	Surficial	UNCONFINED
		L13I5	35.730718	-76.43438	580	CH	Castle Hayne	CONFINED
	Plymouth	K17A2	35.82388	-76.758325	56	NACP	Yorktown	CONFINED
		K17A4	35.82388	-76.758325	320	NACP	Beaufort	CONFINED
		K17A5	35.82388	-76.758325	230	CH	Castle Hayne	CONFINED
		K17A8	35.82388	-76.758325	185	CH	Castle Hayne	CONFINED
		K17A9	35.82388	-76.758325	18	S	Surficial	UNCONFINED
	Scuppernong	I13X2	35.916795	-76.469963	421	CH	Castle Hayne	CONFINED
		I13X3	35.916795	-76.469963	1320	NACP	Upper Cape Fear	CONFINED
		I13X4	35.916795	-76.469963	557	NACP	Beaufort	CONFINED

Appendix 1 (continued)

	WS-100	100	35.7388889	- 76.7752778	15.53	S	Post Miocene	UNCONFINED

Appendix 2: Mann-Kendall analysis results for 257 sites considered in this research. ** denotes p-value <0.05, *** denotes p-value <0.01.

Site Location	Site Name	Site ID	Kendall Tau	Significance Level	p-value	S	D	VarS
Beaufort County	Aurora II	Q17D1	0.33 ▲	***	<0.01	321	969	3417
		Q17D2	-0.15 ▼	**	0.029	-88	570	1620
		Q17D3	0.19 ▲	**	0.023	67	361	870
		Q17D4	0.11		0.099	72	640	1900
		Q17D5	0.09		0.250	41	477	1269
	Bath	O17I1	0.11 ▲	**	0.029	191	1723	7681
		O17I2	0.03		0.528	-54	1662	7332
	Bonnerton	P18V3	0.11 ▲	**	0.022	214	1878	8678
		P18V4	-0.33 ▼	***	<0.01	-187	571	1627
		P18V5	0.22 ▲	***	<0.01	404	1850	8533
		P18V6	-0.35 ▼	***	<0.01	-212	600	1740
		P18V7	-0.06		0.302	-64	1056	3837
		P18V8	-0.02		0.697	-26	1176	4452

Appendix 2 (continued)

Cox Crossroads	P19M2	0.32 ▲	***	<0.01	542	1692	7501
	P19M4	-0.97 ▼	***	<0.01	-1753	1811	8260
	P19M5	0.16 ▲	***	<0.01	299	1811	8258
	P19M6	0.24 ▲	***	<0.01	283	1191	4537
Godley	Q16G3	-0.09		0.095	-145	1697	7561
	Q16G4	0.09		0.108	112	1250	4866
	Q16G5	0.21 ▲	***	<0.01	263	1277	5006
	Q16G6	0.14 ▲	***	<0.01	251	1761	7948
	Q16G7	0.13 ▲	**	0.035	110	822	2715
	Q16G8	0.21 ▲	***	<0.01	195	909	3136
Highway 102	O21Q1	0.18 ▲	***	<0.01	298	1636	7119
	O21Q2	0.10		0.163	67	701	2306
	O21Q3	0.16 ▲	***	<0.01	279	1721	7658
Hubs Rec	N15X5	-0.19 ▼	***	<0.01	-313	1677	7418
Lee Creek	P17I12	0.67 ▲	***	<0.01	483	717	2234
	P17I13	0.45 ▲	***	<0.01	807	1791	8114

Appendix 2 (continued)

	P17I6	0.05		0.328	78	1486	6348
	P17I7	0.03		0.611	45	1743	7827
	P17I9	-0.82 ▼	***	<0.01	-1359	1655	7334
Southside Ferry	P16O2	0.39 ▲	***	<0.01	219	563	1601
	P16O3	0.82 ▲	***	<0.01	206	252	532
	P16O4	0.55 ▲	***	<0.01	299	543	1521
Washington	M21K2	0.12 ▲	**	0.019	215	1827	8354
Whitley Farms	P17E1	0.50 ▲	***	<0.01	283	561	1587
	P17E2	0.54 ▲	***	<0.01	336	620	1820
	P17E3	0.27 ▲	***	<0.01	153	571	1627
	P17E5	-0.10		0.266	-29	301	679
Wilmar	P21K3	0.14 ▲	***	<0.01	258	1808	8222
	P21K4	0.21 ▲	***	<0.01	264	1264	4941
	P21K5	0.60 ▲	***	<0.01	762	1264	4941
	P21K6	0.24 ▲	***	<0.01	416	1742	7810
	P21K7	0.18 ▲	***	<0.01	281	1599	6957

Appendix 2 (continued)

		P21K9	0.36 ▲	***	<0.01	497	1367	5516
Bertie County	Cremo	F19V2	-0.09		0.104	-132	1552	6592
		F19V3	-0.50 ▼	***	<0.01	-735	1475	6145
		F19V4	-0.21 ▼	***	<0.01	-323	1521	6411
		F19V5	-0.48 ▼	***	<0.01	-494	1028	3689
		F19V6	-0.56 ▼	***	<0.01	-651	1163	4387
	Lewiston	H22I3	-0.05		0.299	-85	1569	6699
		H22I4	-0.42 ▼	***	<0.01	-662	1584	6784
		H22I5	-0.61 ▼	***	<0.01	-697	1149	4378
		H22I6	0.37 ▲	***	<0.01	370	1008	3621
	Roxobel	F22B1	0.42 ▲	***	<0.01	206	486	1302
		F22B2	0.44 ▲	***	<0.01	209	477	1269
		F22B3	0.12		0.121	56	486	1302
		F22B5	0.86 ▲	***	<0.01	495	573	1641
		F22B7	0.08		0.291	40	522	1434
	Windsor	H20T1	-0.33 ▼	***	<0.01	-98	294	658

Appendix 2 (continued)

		H20T2	-0.83 ▼	***	<0.01	-287	345	816
		H20T3	0.59 ▲	***	<0.01	204	346	822
		H20T4	0.63 ▲	***	<0.01	229	361	870
		H20T6	0.48 ▲	***	<0.01	154	322	742
		H20T7	0.10		0.203	37	353	843
		H20T8	0.05		0.558	17	353	843
		H20T9	0.80 ▲	***	<0.01	246	308	700
Brunswick County	Bear Pen	EE36K3	0.16		0.059	50	308	700
		EE36K4	-0.82 ▼	***	<0.01	-264	322	742
		EE36K5	-0.96 ▼	***	<0.01	-283	295	663
		EE36K6	0.17 ▲	**	0.047	54	322	742
	Boiling Springs RS 2	FF32Y1	0.28 ▲	***	<0.01	392	1402	5749
		FF32Y2	0.10		0.052	150	1445	5983
	BR-079	79	0.11 ▲	***	<0.01	1266	11643	123225
	BR-080	80	0.16 ▲	***	<0.01	858	5431	40667
	BR-081	81	-0.68 ▼	***	<0.01	-1516	2226	11042

Appendix 2 (continued)

	BR-082	82	-0.25	▼	***	<0.01	-553	2225	11028
	BR-083	83	0.04			0.421	100	2804	15431
	BR-100	15A	-0.22	▼	***	<0.01	-536	2460	12720
	Calabash	HH39J4	-0.32	▼	***	<0.01	-1233	3865	25212
		HH39J5	0.06			0.094	379	6315	51071
	Shallotte	GG37B4	0.22	▲	**	0.012	662	280	616
	Stanbury	GG35R3	0.16			0.269	11	69	99
	Sunset Harbor North	GG34S4	-0.06			0.489	-17	275	605
		GG34S5	0.55	▲	***	<0.01	151	275	605
	Waccamaw School	FF38J8	0.10			0.081	127	1324	5300
Carteret County	Atlantic	V12I3	-0.06			0.221	-107	1703	7630
		V12I4	0.31	▲	***	<0.01	303	979	3456
		V12I5	0.14			0.089	47	329	763
		V12I6	0.21	▲	***	<0.01	189	893	3044
	Camp Glenn	X17J3	0.51	▲	***	<0.01	130	254	542
		X17J5	0.61	▲	***	<0.01	685	1121	4163

Appendix 2 (continued)

		X17J7	0.03			0.697	10	294	658
Craven County	Cherry Point	U18Q3	-0.39	▼	***	<0.01	-665	1717	7710
		U18Q4	-0.34	▼	***	<0.01	-477	13958	5674
		U18Q5	0.13	▲	**	0.043	103	797	2593
		U18Q6	-0.04			0.509	-49	1365	5495
	Clarks	S22J10	0.50	▲	***	<0.01	717	1425	5835
		S22J12	0.89	▲	***	<0.01	859	967	3398
		S22J5	0.16	▲	***	0.002	265	1643	7202
		S22J8	-0.02			0.696	-25	1095	4089
		S22J9	-0.78	▼	***	<0.01	-791	1047	3808
	Cove City	R23X10	0.51	▲	***	<0.01	689	1351	5420
		R23X4	-0.47	▼	***	<0.01	-625	1337	5346
		R23X5	0.12	▲	**	0.042	132	1126	4211
		R23X6	0.10			0.065	141	1425	5835
		R23X7	-0.13	▼	**	0.018	-169	1291	5080
		R23X8	0.71	▲	***	<0.01	1206	1688	7454

Appendix 2 (continued)

		R23X9	0.84 ▲	***	<0.01	1017	1209	4652
	Croatan	U19O5	-0.23 ▼	***	<0.01	-150	650	2015
	Palmetto Swamp	P22U10	0.08		0.154	108	1410	5750
		P22U6	0.70 ▲	***	<0.01	964	1380	5580
		P22U7	-0.32 ▼	***	<0.01	-457	1425	5835
		P22U8	0.13 ▲	**	0.013	188	1410	5750
		P22U9	0.00		0.989	1	1309	5196
	Purser	P21N1	0.08		0.131	125	1591	6864
		P21N2	0.07		0.214	86	1236	4791
		P21N3	0.32 ▲	***	<0.01	467	1475	6155
	Wilmar Fire Tower	P21G1	0.01		0.822	18	1522	6423
Currituck County	Moyock	B10R1	-1.00 ▼	***	<0.01	-60	60	84
Dare County	Bodie Island	K2E2	-0.01		0.927	-4	642	1915
		K2E3	-0.08		0.236	-52	642	1922
		K2E4	0.49 ▲	***	<0.01	348	714	2217
		K2E7	0.33 ▲	***	<0.01	242	726	2266

Appendix 2 (continued)

East Lake	J7K5	0.53 ▲	***	<0.01	330	624	1850
	J7K6	0.57 ▲	***	<0.01	333	585	1702
	J7K7	0.21 ▲	***	<0.01	154	736	2313
	J7K8	0.29 ▲	***	<0.01	214	748	2361
Kitty Hawk North	G4X1	0.08		0.596	5	63	89
Manteo Airport	I4W3	-0.01		0.842	-16	1522	6422
	I4W5	0.22 ▲	***	<0.01	335	1537	6507
Nags Head	J3H3	0.08		0.132	108	1296	5131
Skyco Road	J3O3	-0.17 ▼	***	<0.01	-254	1506	6326
	J3O4	0.17 ▲	***	<0.01	269	1569	6699
Spencer Creek	J5M2	0.22 ▲	***	<0.01	128	586	1704
	J5M3	0.49 ▲	***	<0.01	339	685	2098
Stumpy Point	L6Y2	-0.11		0.515	-5	45	59
	L6Y3	0.51 ▲	***	<0.01	23	45	59
Wanchese	J3X10	0.30 ▲	***	<0.01	94	314	720
	J3X11	0.34 ▲	***	<0.01	103	301	679

Appendix 2 (continued)

		J3X12	0.33 ▲	***	<0.01	100	302	684
		J3X13	0.26 ▲	***	<0.01	80	308	700
		J3X9	0.19 ▲	**	0.023	60	308	700
	Wright Memorial	H4U2	-0.44 ▼	***	<0.01	-236	536	1501
		H4U3	0.11		0.192	35	315	721
Gates County	Sunbury	C15S4	0.93 ▲	***	<0.01	255	275	605
		C15S6	-0.99 ▼	***	<0.01	-267	269	589
		C15S7	0.19 ▲	***	<0.01	523	2803	15717
Hyde County	D Canal Road	L15T1	-0.19		0.098	-26	140	247
		L15T2	0.80 ▲	***	<0.01	98	122	207
		L15T3	-0.20		0.075	-28	140	247
		L15T4	0.69 ▲	***	<0.01	91	131	227
		L15T5	0.63 ▲	***	<0.01	88	140	247
New Hanover County	Eagle Point	CC29L1	0.07		0.452	16	222	452
		CC29L2	-0.25 ▼	**	0.012	-52	212	429
		CC29L3	0.18		0.060	10	222	452

Appendix 2 (continued)

		CC29L4	-0.27 ▼	***	<0.01	-57	211	424
	NH Correctional	CC31U1	-0.03		0.788	-6	240	500
Onslow County	Camp Geiger	X25C1	0.09		0.295	26	280	616
		X25C2	-0.99 ▼	***	<0.01	-244	246	516
		X25C3	-0.54 ▼	***	<0.01	-141	259	553
	Deppe	V23X1	0.00		0.934	-6	1320	5249
		V23X2	-0.90 ▼	***	<0.01	-1094	1220	4697
		V23X3	-0.54 ▼	***	<0.01	-742	1380	5580
		V23X4	0.14		0.051	75	533	1481
		V23X5	0.23 ▲	***	<0.01	129	561	1587
		V23X6	0.13		0.076	70	552	1554
		V23X7	0.77 ▲	***	<0.01	391	505	1375
	Folkstone	Y25Q3	-0.18 ▼	**	0.015	-100	570	1685
		Y25Q4	-0.42 ▼	***	<0.01	-214	508	1449
		Y25Q6	0.14 ▲	**	0.044	83	577	1706
		Y25Q7	-0.12		0.059	-90	726	2266

Appendix 2 (continued)

	Y25Q8	-0.04		0.521	-29	673	2043
Hadnot Point	X24S1	-0.09		0.178	-64	710	2259
	X24S2	0.27 ▲	***	<0.01	138	506	1463
	X24S4	-0.35 ▼	***	<0.01	-84	240	500
	X24S5	0.38 ▲	***	<0.01	109	287	637
	X24S6	0.53 ▲	***	<0.01	157	293	657
	X24S7	0.30 ▲	***	<0.01	177	595	1806
Montford Point	X24E1	-0.60 ▼	***	<0.01	-144	240	500
	X24E2	-0.56 ▼	***	<0.01	-128	228	468
Onslow Quarry 14	W26C6	0.34 ▲	***	<0.01	138	410	1299
Onslow Quarry 15	W26D1	0.39 ▲	***	<0.01	242	620	2001
Paradise Point	X24G1	-0.47 ▼	***	<0.01	-70	150	270
	X24G2	0.07		0.524	10	140	247
Parkertown Road	X22H1	-0.01		0.844	-9	685	2098
	X22H2	0.37 ▲	***	<0.01	225	697	2153
	X22H3	0.01		0.829	10	696	2146

Appendix 2 (continued)

		X22H4	0.04		0.575	26	696	2146
		X22H5	-0.85	***	<0.01	-583	685	2105
		X22H6	-0.34	***	<0.01	-251	737	2314
	Ragged Point	X25U1	-0.22	**	0.017	-54	246	516
	Sneads Ferry	Y23R2	0.05		0.688	6	130	223
	Wallace Creek	X23N1	0.06		0.592	8	130	223
	Well Field 258	W25F10	0.11		0.052	137	1265	4951
		W25F11	0.61	***	<0.01	757	1233	4761
		W25F12	0.99	***	<0.01	855	865	2896
		W25F6	0.22	***	<0.01	291	1323	5271
		W25F8	0.85	***	<0.01	1113	1307	5176
		W25F9	0.62	***	<0.01	810	1308	5186
Pamlico County	Arapahoe	S18U10	0.54	***	<0.01	160	296	668
		S18U11	0.07		0.428	18	246	516
		S18U12	0.63	***	<0.01	394	630	1860
		S18U3	0.60	***	<0.01	344	570	1620

Appendix 2 (continued)

	S18U4	0.59 ▲	***	<0.01	348	590	1700
	S18U5	0.14 ▲	***	<0.01	256	1814	8297
	S18U7	0.58 ▲	***	<0.01	364	630	1860
	S18U9	0.48 ▲	***	<0.01	302	630	1860
Bay City	R17I1	0.22 ▲	***	<0.01	383	1717	7706
	R17I2	0.07		0.149	123	1647	72480
	R17I3	0.37 ▲	***	<0.01	187	499	1362
Hobucken	Q15U3	-0.02		0.765	-20	1148	4493
	Q15U5	0.63 ▲	***	<0.01	278	442	1143
	Q15U6	0.42 ▲	***	<0.01	192	452	1183
	Q15U7	0.56 ▲	***	<0.01	250	444	1156
	Q15U8	0.17 ▲	**	0.023	82	486	1302
Whortonsville	S15Y1	-0.09		0.304	-28	322	742
	S15Y2	0.78 ▲	***	<0.01	255	329	763
	S15Y3	-0.07		0.155	-128	1768	8029
	S15Y4	0.79 ▲	***	<0.01	237	301	679

Appendix 2 (continued)

		S15Y6	0.49 ▲	***	<0.01	424	866	3905
		S15Y7	-0.12		0.07354354	-78	640	1900
Pasquotank County	Big Flatty Creek	G9C3	0.46 ▲	***	<0.01	222	486	1302
		G9C4	-0.97 ▼	***	<0.01	-455	469	1242
		G9C6	0.38 ▲	***	<0.01	111	295	663
	Elizabeth City	E10U4	0.59 ▲	***	<0.01	348	590	1700
		E10U5	0.46 ▲	***	<0.01	192	418	1087
	Morgans Corner	C12W2	0.19 ▲	***	<0.01	215	1137	4256
		C12W4	-0.98 ▼	***	<0.01	-1204	1232	4751
		C12W5	0.89 ▲	***	<0.01	675	759	2409
		C12W6	-0.86 ▼	***	<0.01	-624	726	2266
	NC Forestry HQ	D11V5	0.52 ▲	***	<0.01	540	1032	3726
	Weeksville Elem	F10K3	0.30 ▲	***	<0.01	75	253	537
		F10K4	0.31 ▲	***	<0.01	79	259	553
Pender County	Burgaw	Y30S3	0.21 ▲	**	0.019	59	287	637
		Y30S7	0.81 ▲	***	<0.01	201	249	531

Appendix 2 (continued)

	Topsail Beach	BB28J2	-0.16 ▼	***	<0.01	-641	3934	25300
		BB28J3	-0.94 ▼	***	<0.01	-1005	1071	3981
		BB28J4	0.26 ▲	***	<0.01	357	1395	5665
		BB28J5	0.24 ▲	**	<0.01	322	1334	5324
Perquimans County	Perquimans	F13W1	-0.87 ▼	***	<0.01	-55	63	89
Tyrrell County	Gum Neck	L10A2	0.11 ▲	**	0.027	197	1763	7972
		L10A3	0.92 ▲	***	<0.01	110	120	200
		L10A5	-0.44 ▼	***	<0.01	-800	1806	8288
Washington County	Lake Phelps	L13I1	-0.13 ▼	***	<0.01	-225	1681	7466
		L13I2	0.28 ▲	***	<0.01	332	1176	4452
		L13I3	0.30 ▲	***	<0.01	93	315	721
		L13I4	0.09		0.080	153	1711	7636
		L13I5	0.61 ▲	***	<0.01	169	275	605
	Plymouth	K17A2	0.12 ▲	**	0.017	233	2019	9602
		K17A4	0.34 ▲	***	<0.01	551	1615	7053
		K17A5	0.37 ▲	***	<0.01	681	1845	8474

Appendix 2 (continued)

		K17A8	0.49 ▲	***	<0.01	262	532	1474
		K17A9	0.14 ▲	***	<0.01	269	1910	8869
	Scuppernong	I13X2	0.02		0.736	30	1758	7909
		I13X3	-0.99 ▼	***	<0.01	-691	695	2138
		I13X4	-0.55 ▼	***	<0.01	-369	673	2043
	WS100	WS100	-0.11 ▼	***	<0.01	-691	6272	49258

Appendix 3: Salinity (ppt) and specific conductance (μS/cm) measurements by Principal and local aquifer. Values colored from green to orange indicate increasing mean salinity and mean specific conductance measurements.

Aquifer Name	Local Aquifer Name	Mean Sal (ppt)	n Sal	Mean SC (uS/cm)	n SC
Castle Hayne aquifer	Castle Hayne	0.00	2	71.17	3
		0.07	3	672.50	3
		0.07	6	141.04	7
		0.10	1	178.40	1
		0.10	3	379.33	3
		0.10	1	270.30	1
		0.10	8	234.51	8
		0.10	4	171.90	4
		0.10	1	270.00	1
		0.10	0	253.50	1
		0.10	2	151.36	14
		0.11	7	192.26	7
		0.17	6	291.53	6
		0.19	8	424.89	8
		0.20	1	358.20	1
		0.20	1	397.00	1
		0.20	1	478.00	1
		0.20	1	397.10	1
		0.20	2	427.00	2
		0.20	6	401.37	6
		0.20	6	349.05	6
		0.20	8	432.20	8

Appendix 3 (continued)

	0.25	6	532.05	6
	0.27	7	555.06	7
	0.27	6	538.00	6
	0.29	7	563.37	7
	0.30	1	674.00	1
	0.30	6	630.12	6
	0.30	1	460.00	1
	0.30	3	623.67	3
	0.32	6	628.33	6
	0.34	7	695.64	7
	0.36	5	739.20	5
	0.36	9	699.77	10
	0.37	3	745.67	3
	0.40	1	776.00	1
	0.40	6	742.67	6
	0.40	1	769.00	1
	0.40	3	757.33	3
	0.43	7	850.29	7
	0.44	7	686.73	7
	0.50	3	917.67	3
	0.57	9	1119.33	9
	0.60	1	1188.00	1
	0.71	9	1379.60	10
	0.71	7	1400.13	8
	0.96	8	1873.00	8
	0.98	9	1839.67	9

Appendix 3 (continued)

		0.98	8	1887.50	8
		1.18	8	2235.88	8
		1.30	3	2226.00	3
		1.60	6	2494.95	6
		1.93	6	3649.17	6
		2.40	3	4237.00	3
		2.57	7	4808.13	8
		2.80	1	5235.00	1
		2.93	3	5091.67	3
		4.71	7	8480.43	7
		5.27	7	9367.29	7
		6.90	1	12050.00	1
		6.97	6	12157.00	6
		7.10	2	12336.50	2
		14.79	7	24196.86	7
		18.03	3	29433.33	3
		31.50	1	48340.00	1
		N/A	N/A	473.00	1
		N/A	N/A	1440.00	1
		N/A	N/A	7200.00	1
Northern Atlantic Coastal Plain	Beaufort	0.10	1	151.60	1
		0.21	8	321.08	8
		0.30	5	526.48	5
		0.31	8	655.26	9
		0.37	10	697.92	12
		0.40	3	811.33	3

Appendix 3 (continued)

	0.84	9	1654.44	9
	1.63	6	3091.50	6
	2.25	6	4017.17	6
	2.70	9	4767.20	10
	9.35	6	15911.17	6
	9.40	1	13230.00	1
	28.10	1	43930.00	1
Black Creek	0.10	2	206.37	3
	0.13	8	203.08	9
	0.15	6	301.18	6
	0.16	7	275.26	8
	0.30	2	565.00	2
	0.33	8	605.00	12
	0.34	8	694.13	8
	0.40	8	820.25	8
	0.76	5	1536.60	5
	0.83	10	1629.10	10
	0.88	8	1733.88	8
	1.09	9	2101.40	10
	1.14	8	2184.75	8
	2.43	9	4448.00	9
	4.99	7	8918.71	7
	5.00	2	8765.00	2
	7.00	8	11749.62	8
Lower Cape Fear	0.10	4	136.30	4
	0.30	2	632.00	2

Appendix 3 (continued)

		0.32	5	690.68	5
		0.33	8	694.61	8
		0.33	8	677.17	10
		1.93	7	3658.29	7
		N/A	N/A	6700.00	1
	Lower Cretaceous	0.15	2	314.25	2
		1.30	8	2222.10	10
		3.12	5	5767.80	5
				190.00	1
	Lower Peedee	0.06	5	137.10	5
	Peedee	0.10	1	172.50	1
		0.10	1	221.70	1
		0.10	1	160.70	1
		0.10	1	98.70	1
		0.10	7	187.00	7
		0.16	5	355.82	5
		0.16	8	311.36	9
		0.20	1	351.50	1
		0.20	5	453.76	5
		0.28	6	640.33	6
		0.30	1	3887.44	9
		0.30	6	608.88	6
		0.30	2	531.00	2
		0.40	3	829.00	3
		0.50	1	979.00	1
		0.53	7	1032.34	7

Appendix 3 (continued)

	0.60	1	1190.00	1
	0.80	1	1634.00	1
	3.85	6	6988.67	6
	6.72	5	11790.20	5
	19.78	8	31338.00	8
	N/A	N/A	582.00	1
Upper Cape Fear	0.10	1	203.40	1
	0.24	8	457.30	8
	0.25	6	535.35	6
	0.30	5	606.20	5
	0.42	6	879.33	6
	0.91	8	1787.00	8
	2.09	7	4003.57	7
	2.35	8	4347.50	8
	3.82	6	6872.14	7
	4.09	7	8148.67	9
	4.33	3	7848.00	3
	12.54	10	20611.30	10
	N/A	N/A	100.00	2
Yorktown	0.07	7	190.69	8
	0.10	5	186.98	6
	0.10	2	202.00	2
	0.10	4	173.28	5
	0.10	5	354.54	5
	0.11	9	207.31	9
	0.15	6	282.11	7

Appendix 3 (continued)

0.16	5	310.78	5
0.16	5	411.13	6
0.16	5	311.67	6
0.17	7	374.93	8
0.18	5	336.14	5
0.18	5	378.81	7
0.20	6	464.73	6
0.22	6	473.13	6
0.22	5	513.48	8
0.22	5	455.90	6
0.22	5	521.85	6
0.22	6	425.73	7
0.25	6	511.55	6
0.26	5	585.00	11
0.30	7	669.71	7
0.30	2	654.50	2
0.31	7	665.29	7
0.32	5	690.17	
0.38	6	800.50	6
0.38	8	728.50	8
0.40	7	772.00	7
0.40	6	832.50	7
0.40	1	756.00	1
0.40	5	825.67	6
0.50	1	983.00	1
0.55	8	1109.80	8

Appendix 3 (continued)

		0.64	5	1206.33	6
		0.68	10	1299.90	10
		0.76	7	1545.88	8
		0.78	5	1532.40	5
		0.80	6	1534.00	7
		0.81	7	1632.14	7
		1.24	7	2211.50	8
		1.52	5	3290.14	7
		2.11	7	4241.75	8
		2.51	9	4562.78	9
		6.28	5	9878.00	6
		6.87	6	11999.83	6
		16.16	5	23197.67	6
		N/A	N/A	18050.00	4
Surficial aquifer system	Surficial	0.00	1	61.70	1
		0.10	4	167.26	5
		0.10	1	155.80	1
		0.10	1	173.70	1
		0.10	1	274.00	1
		0.10	1	176.65	2
		0.10	5	248.40	6
		0.10	1	250.90	1
		0.10	5	184.52	5
		0.10	2	244.00	2
		0.10	2	238.25	2
		0.10	6	279.38	6

Appendix 3 (continued)

	0.13	8	264.39	9
	0.14	9	363.13	11
	0.17	7	356.29	7
	0.18	9	330.01	9
	0.19	7	809.73	7
	0.20	1	433.60	1
	0.20	5	510.65	6
	0.20	4	329.10	4
	0.20	4	411.08	4
	0.20	4	388.55	4
	0.20	1	211.20	1
	0.21	8	439.91	8
	0.22	6	452.17	6
	0.23	4	488.08	4
	0.24	5	454.90	17
	0.26	7	531.09	7
	0.27	6	563.12	6
	0.29	9	570.67	9
	0.30	1	705.00	1
	0.31	8	637.86	9
	0.32	5	628.14	7
	0.33	3	695.00	3
	0.33	10	684.18	11
	0.33	3	706.20	3
	0.34	5	506.06	16
	0.35	6	715.67	6

Appendix 3 (continued)

	0.38	8	788.36	9
	0.38	8	713.50	8
	0.38	5	750.20	5
	0.41	8	869.63	8
	0.42	6	887.17	6
	0.45	8	898.00	8
	0.50	5	935.67	6
	0.50	8	1018.25	8
	0.56	9	1105.22	9
	0.84	7	1667.00	7
	0.89	7	1766.88	8
	0.92	5	1407.25	16
	1.84	5	3512.17	6
	1.88	6	3597.33	6
	1.96	8	3706.91	8
	2.20	1	4221.00	1
	2.64	5	4859.20	5
	2.90	1	5372.00	1
	6.10	2	10743.00	2
	7.70	6	13288.67	6
	10.63	3	17348.67	3
	12.44	5	21198.67	6
	19.72	6	31044.33	6
	N/A	N/A	1500.00	1
	N/A	N/A	336.69	10
	N/A	N/A	18500.00	1

Appendix 3 (continued)

	N/A	N/A		299.00	1